WATER TREATMENT PRIMER 4

CONTINUING EDUCATION
PROFESSIONAL DEVELOPMENT COURSE

Technical Learning College
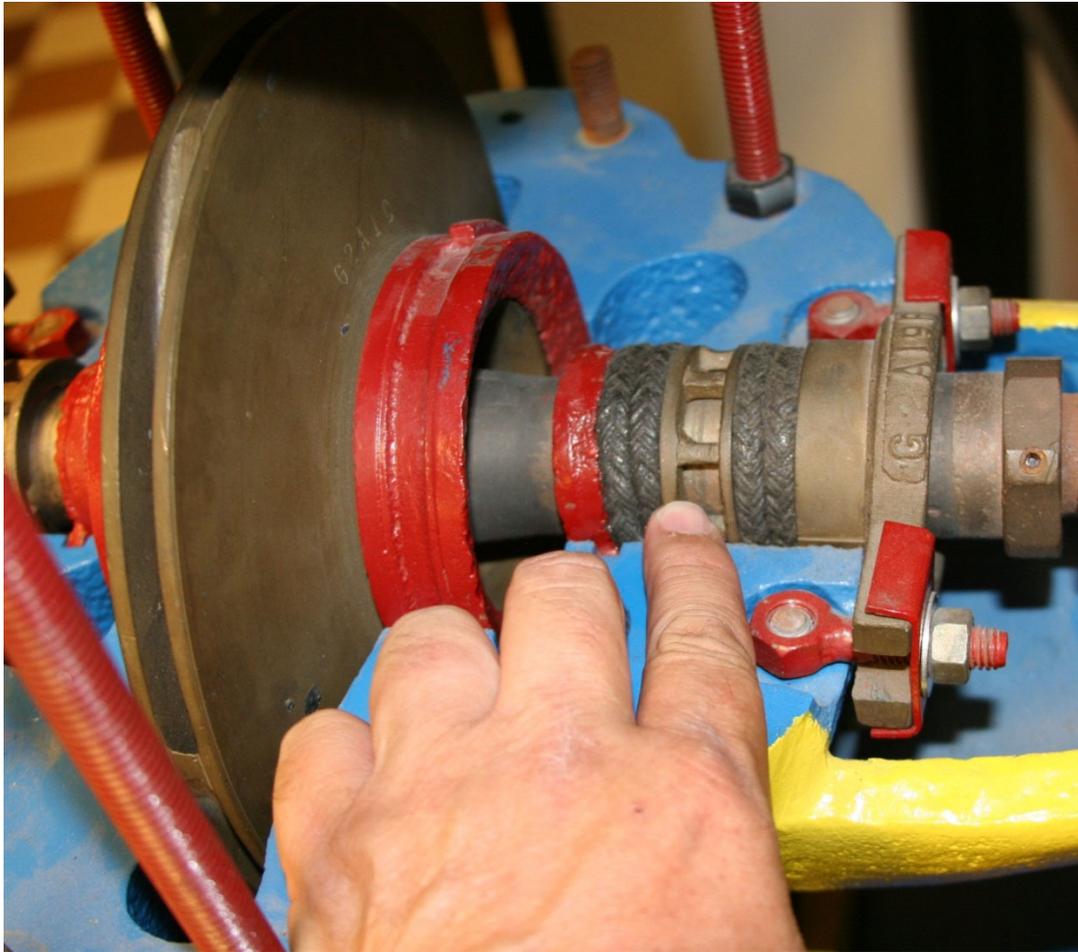
Printing and Saving Instructions

TLC recommends that you download and save this pdf document and assignment to your computer desktop and open it with Adobe Acrobat DC reader.

Adobe Acrobat DC reader is a free computer software program and you can find it at Adobe Acrobat's website.

You can complete the course by viewing the course on your computer or you can print it out. This course booklet does not have the assignment. Please visit our website and download the assignment (the test).

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Internet Link to Assignment…
http://www.abctlc.com/downloads/PDF/WTPrimer4ASS.pdf

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All downloads are electronically tracked and monitored for security purposes.
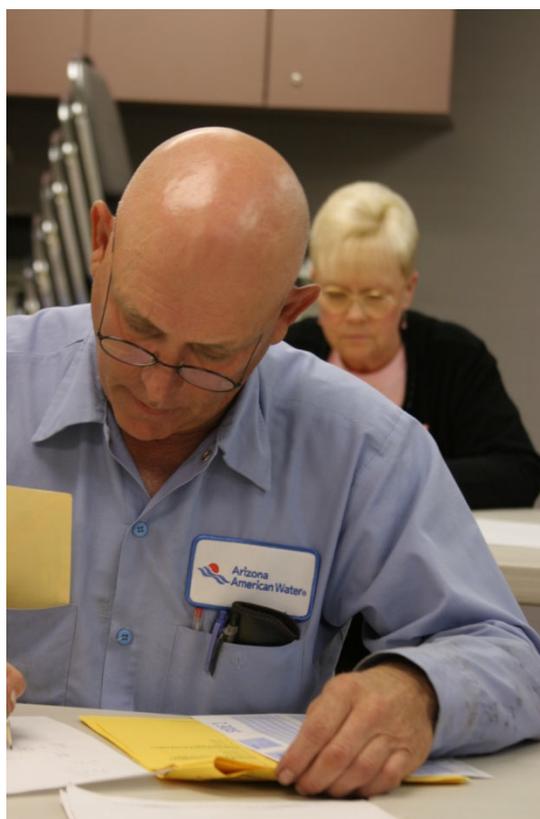
Some States and many employers require the final exam to be proctored.

Do not solely depend on TLC's Approval list for it may be outdated.

A second certificate of completion for a second State Agency $50 processing fee.

Most of our students prefer to do the assignment in Word and e-mail or fax the assignment back to us. We also teach this course in a conventional hands-on class. Call us and schedule a class today.

Responsibility
This course contains EPA's federal rule requirements. Please be aware that each state implements drinking water//safety regulations that may be more stringent than EPA's or OSHA's regulations. Check with your state environmental agency for more information. You are solely responsible in ensuring that you abide with your jurisdiction or agency's rules and regulations.

Copyright Notice

Contributing Editors

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Dr. Pete Greer S.M.E., Retired biology instructor, chemistry and biological review.

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Important Information about this Manual

Disclaimer
This CEU training manual has been prepared to assist employees in the general awareness of the water distribution system and groundwater production system, complex pumping ideas, dangerous excavation techniques, water regulatory sampling and dealing with often-complex procedures and requirements for safely handling hazardous and toxic materials. The scope of the material is quite large, requiring a major effort to bring it under control. Employee health and safety, as well as that of the public, depend upon careful application of federal and state regulations and safe working procedures.

This manual will cover general laws, regulations, required procedures and work rules relating to water distribution and sampling. It should be noted, however, that the federal and state regulations are an ongoing process and subject to change over time. For this reason, a list of resources and hyperlinks is provided to assist in obtaining the most up-to-date information on various subjects. You can find these on our website or in this manual.

This manual is a guidance document for employees who are involved with water distribution, water quality and pollution control. It is not designed to meet the full requirements of the United States Environmental Protection Agency (EPA) or the Department of Labor-Occupational Safety and Health Administration (OSHA) rules and regulations.

This course manual will provide general guidance and should not be used as a preliminary basis for developing general water/wastewater sampling plans or water distribution safety plans or procedures.

This document is not a detailed water/wastewater textbook or a comprehensive source book on water/wastewater/safety rules and regulations. Technical Learning College makes no warranty, guarantee or representation as to the absolute correctness or appropriateness of the information in this manual and assumes no responsibility in connection with the implementation of this information.

It cannot be assumed that this manual contains all measures and concepts required for specific conditions or circumstances. This document should be used for guidance and is not considered a legal document. Individuals who are responsible for water distribution, production and/or sampling and the health and safety of workers at hazardous waste sites should obtain and comply with the most recent federal, state, and local regulations relevant to these sites and are urged to consult with OSHA, the EPA and other appropriate federal, state, and local agencies.

Technical Learning College's Scope and Function

Welcome to the Program,

Technical Learning College (TLC) offers affordable continuing education for today's working professionals who need to maintain licenses or certifications. TLC holds several different governmental agency approvals for granting of continuing education credit.

TLC's delivery method of continuing education can include traditional types of classroom lectures and distance-based courses or independent study. TLC's distance based or independent study courses are offered in a print - based distance educational format. We will beat any other training competitor's price for the same CEU material or classroom training.

Our courses are designed to be flexible and for you do finish the material on your leisure. Students can also receive course materials through the mail. The CEU course or e-manual will contain all your lessons, activities and instruction to obtain the assignments. All of TLC's CEU courses allow students to submit assignments using e-mail or fax, or by postal mail. (See the course description for more information.)

Students have direct contact with their instructor—primarily by e-mail or telephone. TLC's CEU courses may use such technologies as the World Wide Web, e-mail, CD-ROMs, videotapes and hard copies. (See the course description.) Make sure you have access to the necessary equipment before enrolling, i.e., printer, Microsoft Word and/or Adobe Acrobat Reader. Some courses may require proctored closed-book exams depending upon your state or employer requirements.

Flexible Learning
At TLC, there are no scheduled online sessions or passwords you need contend with, nor are you required to participate in learning teams or groups designed for the "typical" younger campus based student. You can work at your own pace, completing assignments in time-frames that work best for you. TLC's method of flexible individualized instruction is designed to provide each student the guidance and support needed for successful course completion.

Course Structure
TLC's online courses combine the best of online delivery and traditional university textbooks. You can easily find the course syllabus, course content, assignments, and the post-exam (Assignment). This student friendly course design allows you the most flexibility in choosing when and where you will study.

Classroom of One
TLC offers you the best of both worlds. You learn on your own terms, on your own time, but you are never on your own. Once enrolled, you will be assigned a personal Student Service Representative who works with you on an individualized basis throughout your program of study. Course specific faculty members (S.M.E.) are assigned at the beginning of each course providing the academic support you need to successfully complete each course. Please call or email us for assistance.

Satisfaction Guaranteed

We have many years of experience, dealing with thousands of students. We assure you, our customer satisfaction is second to none. This is one reason we have taught more than 20,000 students.
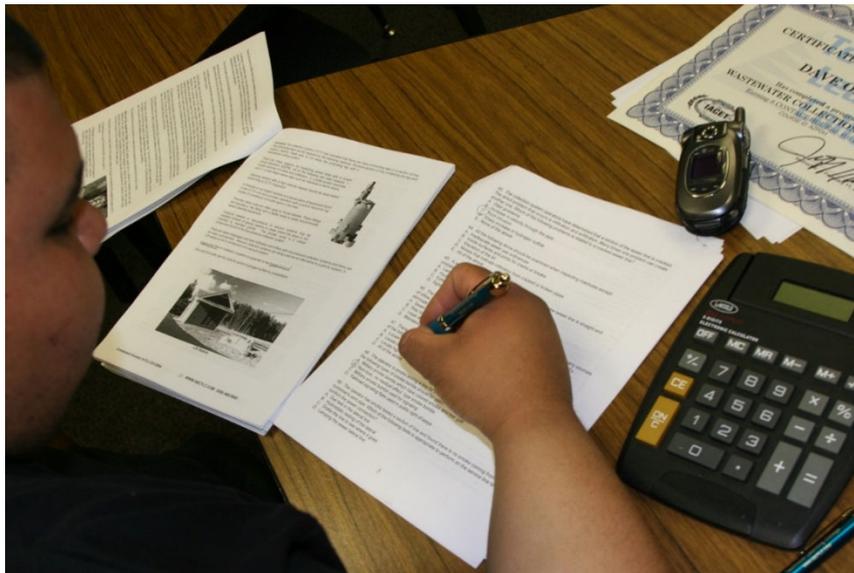
We welcome you to do the electronic version of the assignment and submit the answer key and registration to us either by fax or e-mail. If you need this assignment graded and a certificate of completion within a 48-hour turn around, prepare to pay an additional rush charge of $50.

We welcome you to complete the assignment in Word.

Once we grade it, we will mail a certificate of completion to you. Call us if you need any help.

<div align="center">

Contact Numbers
Fax (928) 468-0675
Email   Info@tlch2o.com
Telephone (866) 557-1746

</div>

CEU Course Description

WATER TREATMENT PRIMER 4 CEU TRAINING COURSE
This is an 8 hour continuing education review of various water distribution components and systems. This course will cover the basic requirements of the Safe Drinking Water Act, water sampling, safety, pumps, and general water distribution principles. You will not need any other materials for this course.

Water Distribution, Well Drillers, Pump Installers, Water Treatment Operators.
The target audience for this course is the person interested in working in a water treatment or distribution facility and/or wishing to maintain CEUs for certification license or to learn how to do the job safely and effectively, and/or to meet education needs for promotion.

Final Examination for Credit
Opportunity to pass the final comprehensive examination is limited to three attempts per course enrollment.

Course Procedures for Registration and Support
All of Technical Learning College's correspondence courses have complete registration and support services offered. Delivery of services will include, e-mail, web site, telephone, fax and mail support. TLC will attempt immediate and prompt service.

When a student registers for a distance or correspondence course, he/she is assigned a start date and an end date. It is the student's responsibility to note dates for assignments and keep up with the course work.

If a student falls behind, he/she must contact TLC and request an end date extension in order to complete the course. It is the prerogative of TLC to decide whether to grant the request. All students will be tracked by a unique number assigned to the student.

Instructions for Written Assignments
The Distribution Primer III training CEU course uses a multiple choice answer key. If you should need any assistance, please email all concerns and the final test to: info@tlch2o.com.

You may write your answers or type out your own answer key. TLC would prefer that you utilize the answer key found on the TLC website under Assignments and e-mail the answer key to TLC, but it is not required. You may also fax the answer key. Please call us a couple hours later to ensure we received your information.

Feedback Mechanism (examination procedures)
Each student will receive a feedback form as part of their study packet. You will be able to find this form in the front of the course assignment or lesson.

Security and Integrity
All students are required to do their own work. All lesson sheets and final exams are not returned to the student to discourage sharing of answers. Any fraud or deceit and the student will forfeit all fees and the appropriate agency will be notified.

Grading Criteria

TLC will offer the student either pass/fail or a standard letter grading assignment. If TLC is not notified, you will only receive a pass/fail notice.

Required Texts

The Distribution Primer III training CEU course will not require any other materials. This course comes complete. No other materials are needed.

Recordkeeping and Reporting Practices

TLC will keep all student records for a minimum of seven years. It is the student's responsibility to give the completion certificate to the appropriate agencies.

ADA Compliance

TLC will make reasonable accommodations for persons with documented disabilities. Students should notify TLC and their instructors of any special needs. Course content may vary from this outline to meet the needs of this particular group.

You will have 90 days from receipt of this manual to complete it in order to receive your Continuing Education Units (**CEUs**) or Professional Development Hours (**PDHs**). A score of 70% or better is necessary to pass this course.

Educational Mission

The educational mission of TLC is:

To provide TLC students with comprehensive and ongoing training in the theory and skills needed for the environmental education field,

To provide TLC students with opportunities to apply and understand the theory and skills needed for operator certification,

To provide opportunities for TLC students to learn and practice environmental educational skills with members of the community for the purpose of sharing diverse perspectives and experience,

To provide a forum in which students can exchange experiences and ideas related to environmental education,

To provide a forum for the collection and dissemination of current information related to environmental education, and to maintain an environment that nurtures academic and personal growth.

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DISCHARGE

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IMPELLER
ASSEMBLY

**VERTICAL TURBINE
PUMP**

SUCTION

Common Hydraulic Terms

Head
The height of a column or body of fluid above a given point expressed in linear units. Head is often used to indicate gauge pressure. Pressure is equal to the height times the density of the liquid.

Head, Friction
The head required to overcome the friction at the interior surface of a conductor and between fluid particles in motion. It varies with flow, size, type, and conditions of conductors and fittings, and the fluid characteristics.

Head, static
The height of a column or body of fluid above a given point.

Hydraulics
Engineering science pertaining to liquid pressure and flow.

Hydrokinetics
Engineering science pertaining to the energy of liquid flow and pressure.

Pascal's Law
A pressure applied to a confined fluid at rest is transmitted with equal intensity throughout the fluid.

Pressure
The application of continuous force by one body upon another that it is touching; compression. Force per unit area, usually expressed in pounds per square inch (Pascal or bar).

Pressure, Absolute
The pressure above zone absolute, i.e. the sum of atmospheric and gauge pressure. In vacuum related work it is usually expressed in millimeters of mercury. (mmHg).

Pressure, Atmospheric
Pressure exported by the atmosphere at any specific location. (Sea level pressure is approximately 14.7 pounds per square inch absolute, 1 bar = 14.5psi.)

Pressure, Gauge
Pressure differential above or below ambient atmospheric pressure.

Pressure, Static
The pressure in a fluid at rest.

NEUTRAL WIRE IS USUALLY GROUNDED AT THE POLE AND THE HOME AND IT ACTS AS SUPPORT FOR 2 "HOT" WIRES

TRANSFORMER

SERVICE DROP LINES

TO GROUND

SERVICE PANEL

BLACK NEUTRAL RED

120 VOLTS
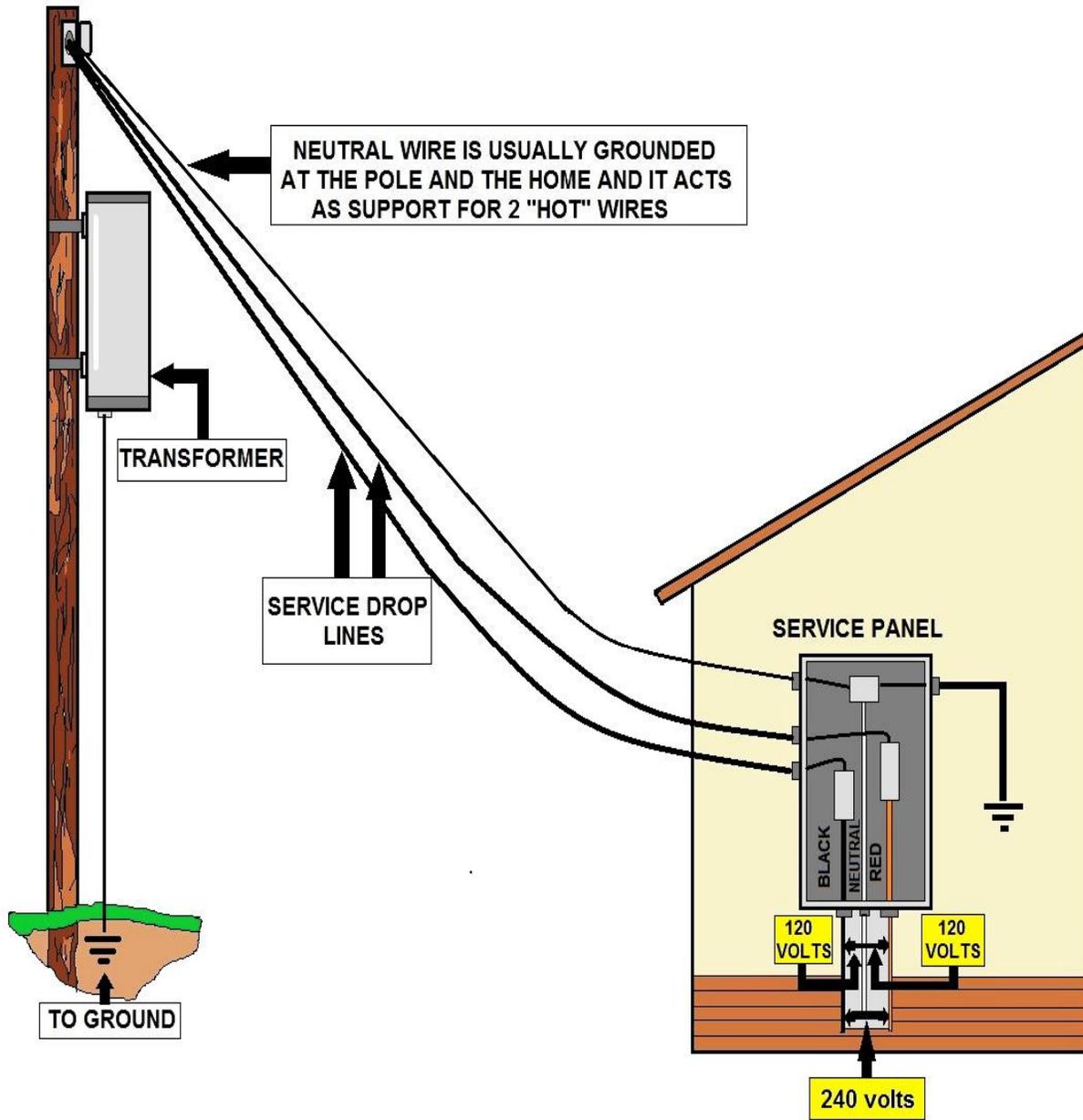
120 VOLTS

240 volts

BASIC HOME ELECTRICITY
(120/240 volts)

ARMATURE

MAGNET

MAGNET

BRUSH

COMMUTATOR

PARTS OF A DC MOTOR

STATOR MAGNET

WINDINGS

COMMUTATOR

BRUSH

ARMATURE

− +

TERMINALS

BRUSHED DC MOTOR

ROTATION OF LOOP

BRUSH   BRUSH

N   S

SPLIT RING COMMUTATOR

DC POWER SUPPLY
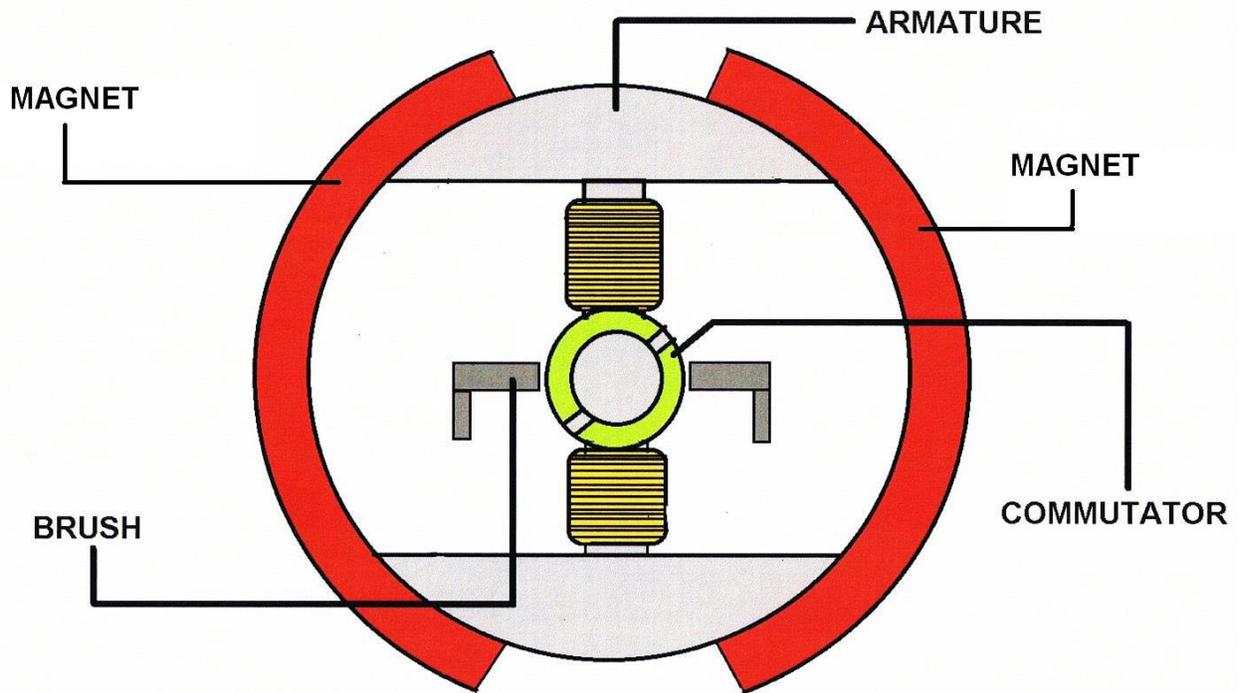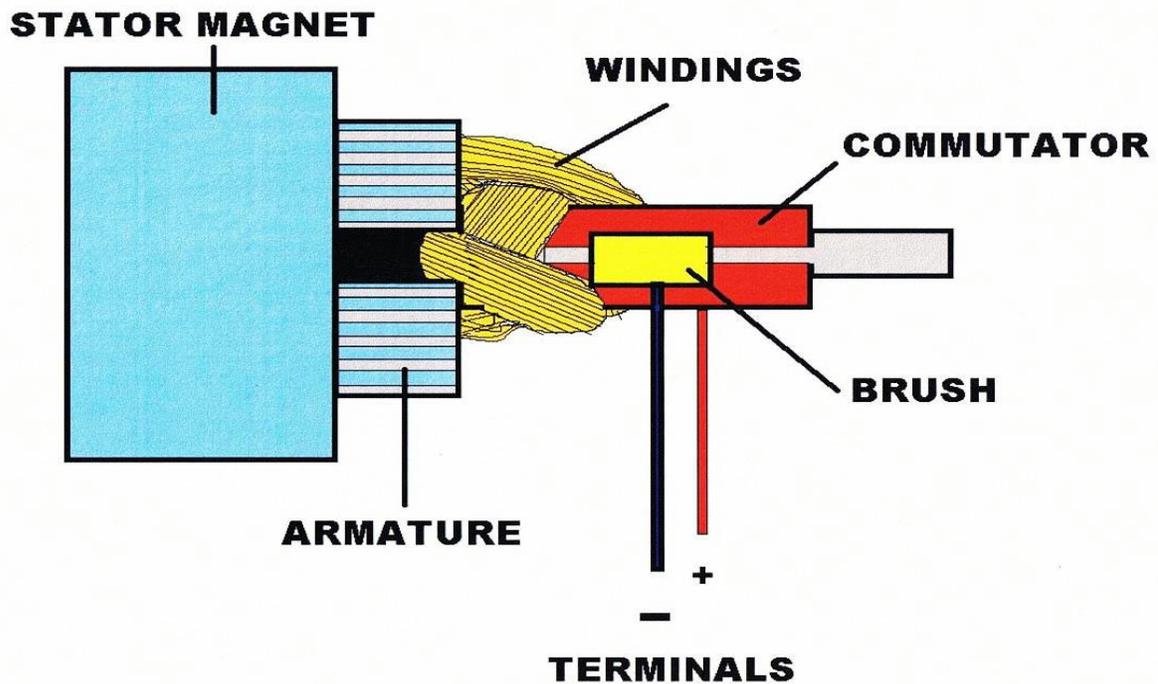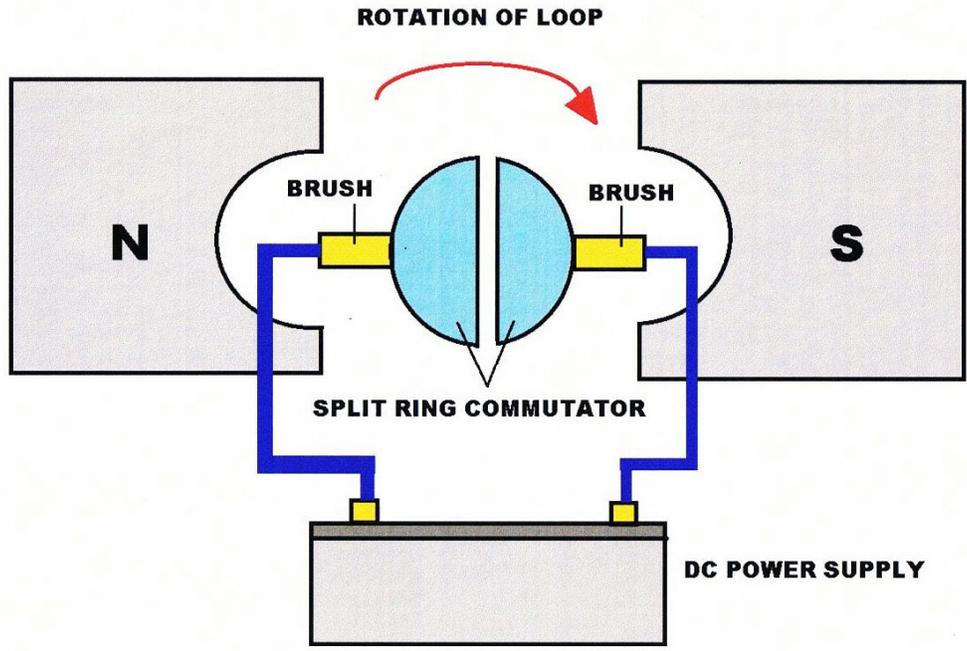
DC MOTOR

WHEN ELECTRIC CURRENT PASSES
THROUGH A COIL IN A MAGNETIC FIELD,
THE MAGNETIC FORCE PRODUCES A
TORQUE WHICH TURNS THE DC MOTOR

S   N

THE COMMUTATOR REVERSES THE
CURRENT EACH HALF REVOLUTION
TO KEEP THE TORQUE TURNING THE
COIL IN THE SAME DIRECTION

ELECTRIC CURRENT
SUPPLIED EXTERNALLY
THROUGH A
COMMUTATOR
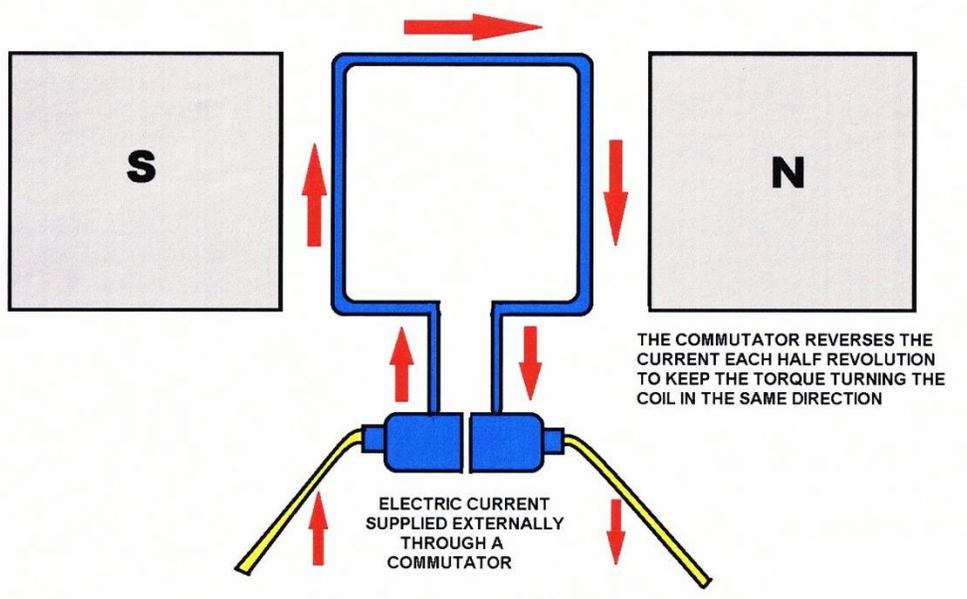
Motor Section

We will now refer to the motor, coupling, and bearings. The power source of the pump is usually an electric motor. The motor is connected by a coupling to the pump shaft. The purpose of the bearings is to hold the shaft firmly in place, yet allow it to rotate. The bearing house supports the bearings and provides a reservoir for the lubricant. An impeller is connected to the shaft. The pump assembly can be a vertical or horizontal set-up; the components for both are basically the same.

Motors

The purpose of this discussion on pump motors is to identify and describe the main types of motors, starters, enclosures, and motor controls, as well as to provide you with some basic maintenance and troubleshooting information. Although pumps could be driven by diesel or gasoline engines, pumps driven by electric motors are commonly used in our industry.

There are two general categories of electric motors:
- D-C motors, or direct current
- A-C motors, or alternating current

You can expect most motors at facilities to be A-C type.

D-C Motors
The important characteristic of the D-C motor is that its speed will vary with the amount of current used. There are many different kinds of D-C motors, depending on how they are wound and their speed/torque characteristics.

A-C Motors
There are a number of different types of alternating current motors, such as Synchronous, Induction, wound rotor, and squirrel cage. The synchronous type of A-C motor requires complex control equipment, since they use a combination of A-C and D-C. This also means that the synchronous type of A-C motor is used in large horsepower sizes, usually above 250 HP. The induction type motor uses only alternating current. The squirrel cage motor provides a relatively constant speed. The wound rotor type could be used as a variable speed motor.
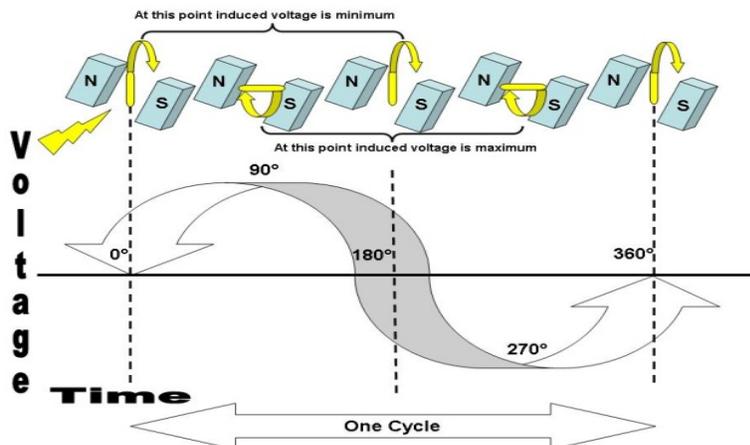
Define the Following Terms:

Voltage:

EMF:

Power:

Current:

Resistance:

Conductor:

Phase:

Single Phase:

Three Phase:

Hertz:

Motor Starters

All electric motors, except very small ones such as chemical feed pumps, are equipped with starters, either full voltage or reduced voltage. This is because motors draw a much higher current when they are starting and gaining speed. The purpose of the reduced voltage starter is to prevent the load from coming on until the amperage is low enough.

How do you think keeping the discharge valve closed on a centrifugal pump could reduce the start-up load?

Motor Enclosures

Depending on the application, motors may need special protection. Some motors are referred to as open motors. They allow air to pass through to remove heat generated when current passes through the windings. Other motors use specific enclosures for special environments or safety protection.

Can you think of any locations within your facility that requires special enclosures?

Two Types of Totally Enclosed Motors Commonly Used are:

- ☞ **TENV**, or totally enclosed non-ventilated motor
- ☞ **TEFC**, or totally enclosed fan cooled motor

Totally enclosed motors include dust-proof, water-proof and explosion-proof motors. An explosion proof enclosure must be provided on any motor where dangerous gases might accumulate.

Motor Controls

All pump motors are provided with some method of control, typically a combination of manual and automatic. Manual pump controls can be located at the central control panel at the pump or at the suction or discharge points of the liquid being pumped.

There are a number of ways in which automatic control of a pump motor can be regulated:

- ☞ Pressure and vacuum sensors
- ☞ Preset time intervals
- ☞ Flow sensors
- ☞ Level sensors

Two typical level sensors are the float sensor and the bubble regulator. The float sensor is pear-shaped and hangs in the wet well. As the height increases, the float tilts, and the mercury in the glass tube flows toward the end of the tube that has two wires attached to it. When the mercury covers the wires, it closes the circuit.

A low pressure air supply is allowed to escape from a bubbler pipe in the wet well. The back-pressure on the air supply will vary with the liquid level over the pipe.

Sensitive air pressure switches will detect this change and use this information to control pump operation.

Motor Maintenance

Motors should be kept clean, free of moisture, and lubricated properly. Dirt, dust, and grime will plug the ventilating spaces and can actually form an insulating layer over the metal surface of the motor.

What condition would occur if the ventilation becomes blocked?

Moisture

Moisture harms the insulation on the windings to the point where they may no longer provide the required insulation for the voltage applied to the motor. In addition, moisture on windings tend to absorb acid and alkali fumes, causing damage to both insulation and metals. To reduce problems caused by moisture, the most suitable motor enclosure for the existing environment will normally be used. It is recommended to run stand by motors to dry up any condensation which accumulates in the motor.

Motor Lubrication

Friction will cause wear in all moving parts, and lubrication is needed to reduce this friction. It is very important that all your manufacturer's recommended lubrication procedures are strictly followed. You have to be careful not to add too much grease or oil, as this could cause more friction and generate heat.

To grease the motor bearings, this is the usual approach:

1. Remove the protective plugs and caps from the grease inlet and relief holes.
2. Pump grease in until fresh starts coming from the relief hole.

If fresh grease does not come out of the relief hole, this could mean that the grease has been pumped into the motor windings. The motor must then be taken apart and cleaned by a qualified service representative.

To change the oil in an oil lubricated motor, this is the usual approach:

1. Remove all plugs and let the oil drain.
2. Check for metal shearing.
3. Replace the oil drain.
4. Add new oil until it is up to the oil level plug.
5. Replace the oil level and filter plug.

Never mix oils, since the additives of different oils when combined can cause breakdown of the oil.

STATOR

S

N

ARMATURE

BUSHES

SLIP RINGS

GALVOMETER

PRODUCTION OF AC CURRENT

N

A   B

C   C

B   A

S
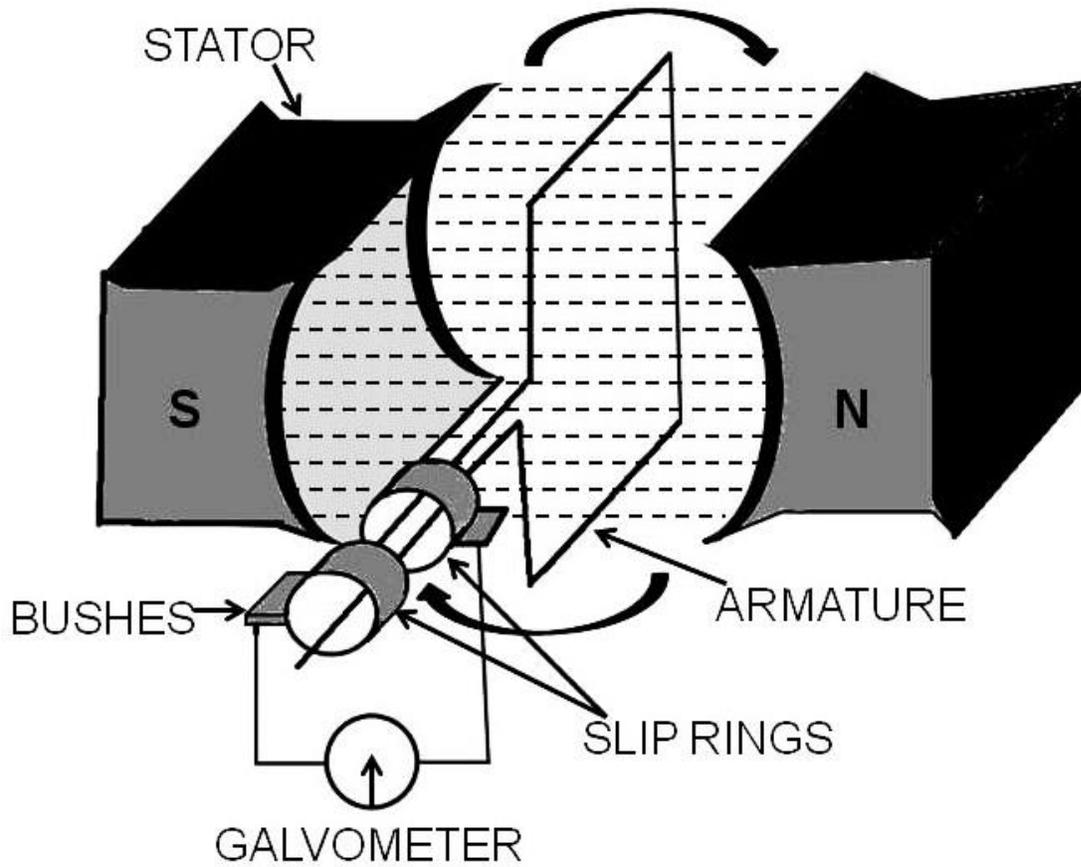
FLOW OF WATER ➡️

+   **HEIGHT**   **–**
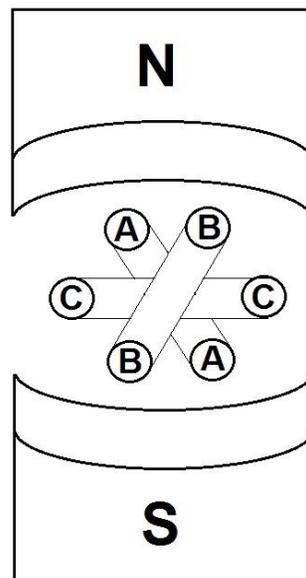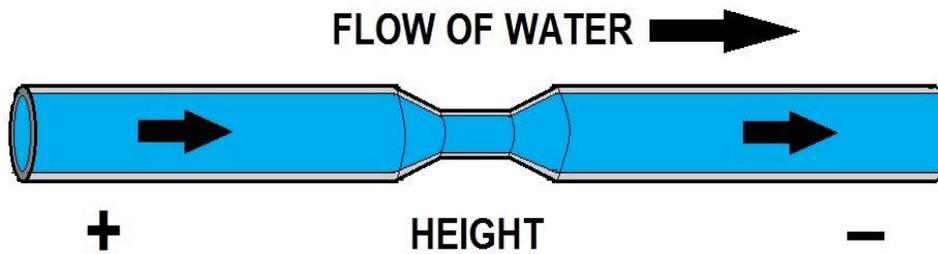
> **Electricity flow can be compared to flow of water:**
> - When pressure is applied at one end of a pipe (or wire) then, water (or electricity) will come out the other end.

(Flow of electrons (electricity) along a wire)

+   **FLOW OF ELECTRICAL CHARGE**   **–**
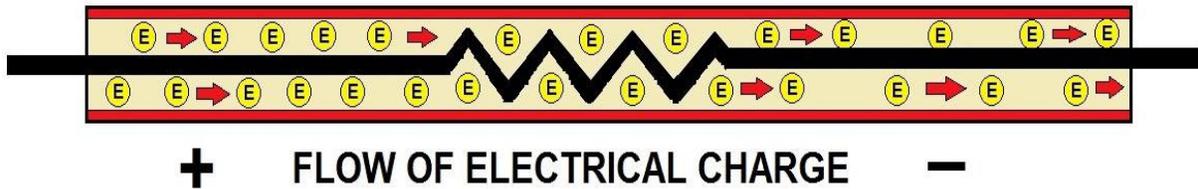
BASIC ELECTRICITY CONCEPT

More Detailed Information on Motors

SHAFT

FAN

WINDINGS

FIELD POLES

COMMUTATOR
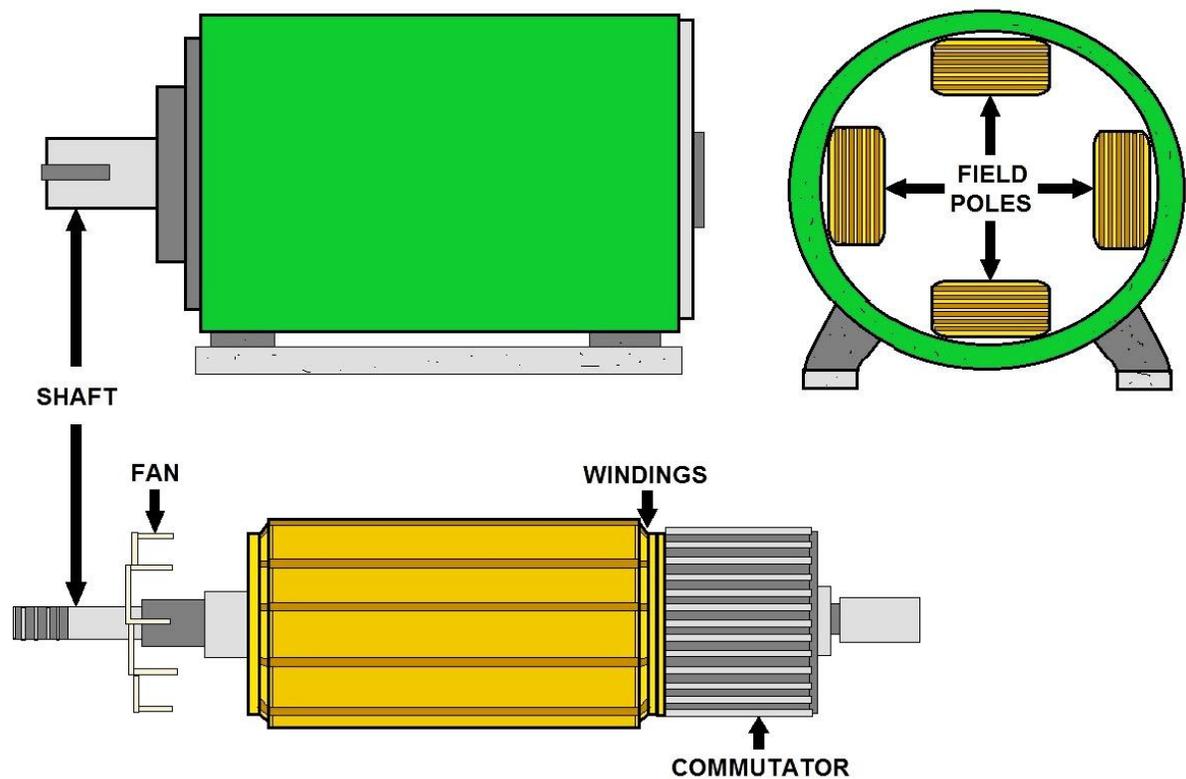
DC ELECTRIC MOTOR DIAGRAM

The classic division of electric motors has been that of Direct Current (DC) types vs. Alternating Current (AC) types. This is more a de facto convention, rather than a rigid distinction. For example, many classic DC motors run happily on AC power.

The ongoing trend toward electronic control further muddles the distinction, as modern drivers have moved the commutator out of the motor shell. For this new breed of motor, driver circuits are relied upon to generate sinusoidal AC drive currents, or some approximation of. The two best examples are: the brushless DC motor and the stepping motor, both being polyphase AC motors requiring external electronic control.

There is a clearer distinction between a synchronous motor and asynchronous types. In the synchronous types, the rotor rotates in synchrony with the oscillating field or current (e.g. permanent magnet motors). In contrast, an asynchronous motor is designed to slip; the most ubiquitous example being the common AC induction motor which must slip in order to generate torque.

A DC motor is designed to run on DC electric power. Two examples of pure DC designs are Michael Faraday's homopolar motor (which is uncommon), and the ball bearing motor, which is (so far) a novelty. By far the most common DC motor types are the brushed and brushless types, which use internal and external commutation respectively to create an oscillating AC current from the DC source -- so they are not purely DC machines in a strict sense.

Brushed DC motors
The classic DC motor design generates an oscillating current in a wound rotor with a split ring commutator, and either a wound or permanent magnet stator. A rotor consists of a coil wound around a rotor, which is then powered by any type of battery. Many of the limitations of the classic commutator DC motor are due to the need for brushes to press against the commutator. This creates friction. At higher speeds, brushes have increasing difficulty in maintaining contact. Brushes may bounce off the irregularities in the commutator surface, creating sparks. This limits the maximum speed of the machine.

The current density per unit area of the brushes limits the output of the motor. The imperfect electric contact also causes electrical noise. Brushes eventually wear out and require replacement, and the commutator itself is subject to wear and maintenance. The commutator assembly on a large machine is a costly element, requiring precision assembly of many parts.
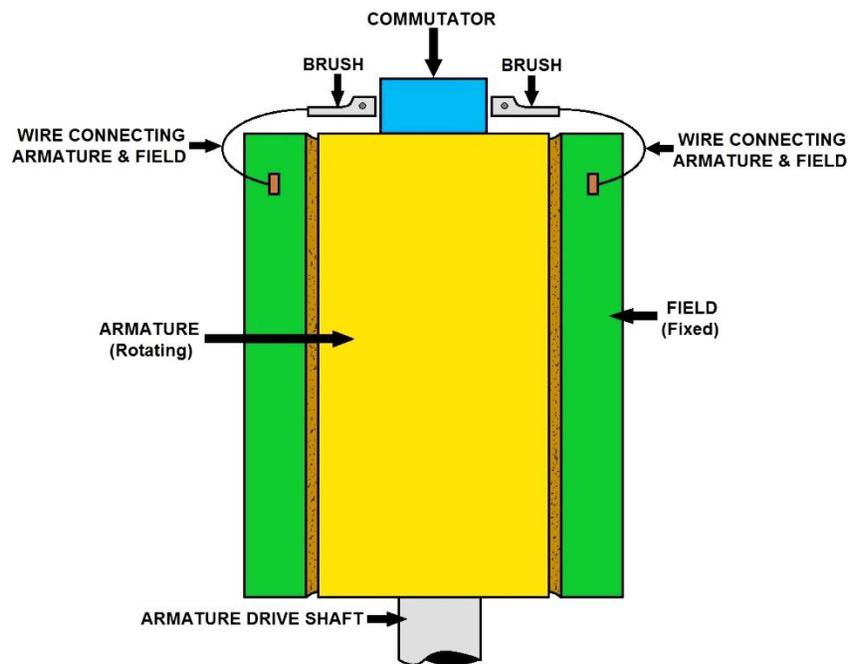
DIAGRAM SHOWING MECHANICAL CONSTRUCTION OF A DC SERIES WOUND MOTOR

Brushless DC motors
Some of the problems of the brushed DC motor are eliminated in the brushless design. In this motor, the mechanical "rotating switch" or commutator/brush gear assembly is replaced by an external electronic switch synchronized to the rotor's position. Brushless motors are typically 85-90% efficient, whereas DC motors with brush gear are typically 75-80% efficient.

Midway between ordinary DC motors and stepper motors lies the realm of the brushless DC motor. Built in a fashion very similar to stepper motors, these often use a permanent magnet external rotor, three phases of driving coils, one or more Hall Effect sensors to sense the position of the rotor, and the associated drive electronics.

The coils are activated one phase after the other by the drive electronics, as cued by the signals from the Hall Effect sensors. In effect, they act as three-phase synchronous motors containing their own variable-frequency drive electronics.

Brushless DC motors are commonly used where precise speed control is necessary, as in computer disk drives or in video cassette recorders, the spindles within CD, CD-ROM (etc.) drives, and mechanisms within office products such as fans, laser printers, and photocopiers.

They have several advantages over conventional motors:
* Compared to AC fans using shaded-pole motors, they are very efficient, running much cooler than the equivalent AC motors. This cool operation leads to much-improved life of the fan's bearings.
* Without a commutator to wear out, the life of a DC brushless motor can be significantly longer compared to a DC motor using brushes and a commutator. Commutation also tends to cause a great deal of electrical and RF noise; without a commutator or brushes, a brushless motor may be used in electrically sensitive devices like audio equipment or computers.
* The same Hall Effect sensors that provide the commutation can also provide a convenient tachometer signal for closed-loop control (servo-controlled) applications. In fans, the tachometer signal can be used to derive a "fan OK" signal.
* The motor can be easily synchronized to an internal or external clock, leading to precise speed control.
* Brushless motors have no chance of sparking, unlike brushed motors, making them better suited to environments with volatile chemicals and fuels.
* Brushless motors are usually used in small equipment such as computers, and are generally used to get rid of unwanted heat.
* They are also very quiet motors, which is an advantage if being used in equipment that is affected by vibrations.

Modern DC brushless motors range in power from a fraction of a watt to many kilowatts. Larger brushless motors up to about 100 kW rating are used in electric vehicles. They also find significant use in high-performance electric model aircraft.

Coreless DC Motors
Nothing in the design of any of the motors described above requires that the iron (steel) portions of the rotor actually rotate; torque is exerted only on the windings of the electromagnets. Taking advantage of this fact is the coreless DC motor, a specialized form of a brush or brushless DC motor. Optimized for rapid acceleration, these motors have a rotor that is constructed without any iron core.

The rotor can take the form of a winding-filled cylinder inside the stator magnets, a basket surrounding the stator magnets, or a flat pancake (possibly formed on a printed wiring board) running between upper and lower stator magnets. The windings are typically stabilized by being impregnated with electrical epoxy potting systems. Filled epoxies that have moderate mixed viscosity and a long gel time. These systems are highlighted by low shrinkage and low exotherm.

Because the rotor is much lighter in weight (mass) than a conventional rotor formed from copper windings on steel laminations, the rotor can accelerate much more rapidly, often achieving a mechanical time constant under 1 ms. This is especially true if the windings use aluminum rather than the heavier copper. But because there is no metal mass in the rotor to act as a heat sink, even small coreless motors must often be cooled by forced air.

These motors were commonly used to drive the capstan(s) of magnetic tape drives and are still widely used in high-performance servo-controlled systems, like radio-controlled vehicles/aircraft, humanoid robotic systems, industrial automation, medical devices, etc.

Labels from the diagram:

SOLENOID

DRIVE PINION

END COVER

COMMUTATOR

BEARING CAP
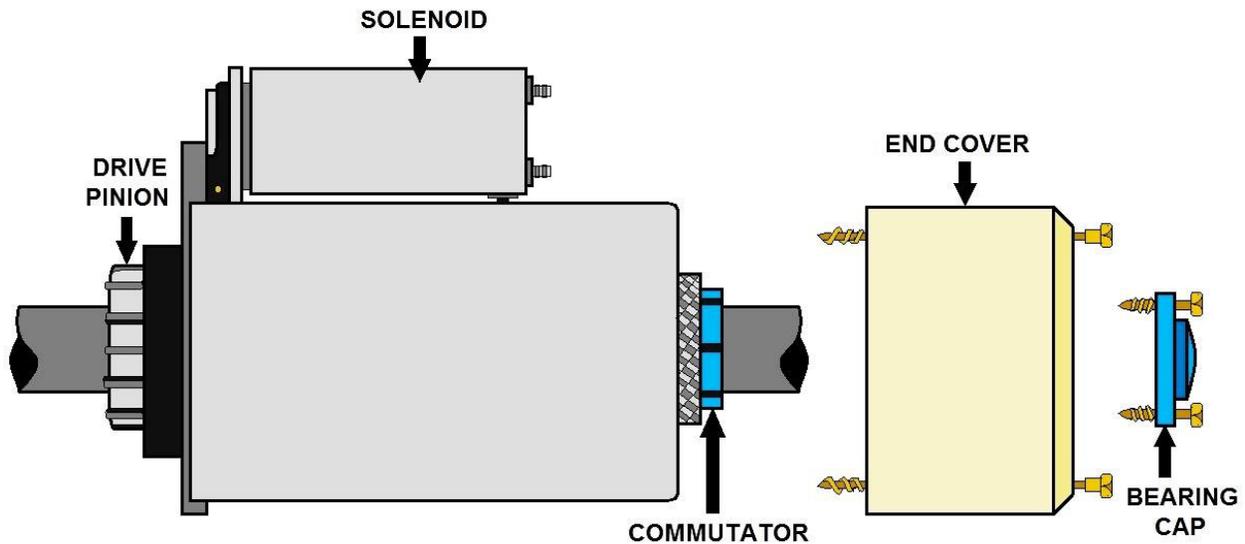
STARTER MOTOR

Universal Motors

A variant of the wound field DC motor is the universal motor. The name derives from the fact that it may use AC or DC supply current, although in practice they are nearly always used with AC supplies.

The principle is that in a wound field DC motor the current in both the field and the armature (and hence the resultant magnetic fields) will alternate (reverse polarity) at the same time, and hence the mechanical force generated is always in the same direction. In practice, the motor must be specially designed to cope with the AC current (impedance must be taken into account, as must the pulsating force), and the resultant motor is generally less efficient than an equivalent pure DC motor.

Operating at normal power line frequencies, the maximum output of universal motors is limited and motors exceeding one kilowatt are rare. But universal motors also form the basis of the traditional railway traction motor in electric railways. In this application, to keep their electrical efficiency high, they were operated from very low frequency AC supplies, with 25 Hz and 16 2/3 hertz operation being common. Because they are universal motors, locomotives using this design were also commonly capable of operating from a third rail powered by DC.

The advantage of the universal motor is that AC supplies may be used on motors which have the typical characteristics of DC motors, specifically high starting torque and very compact design if high running speeds are used.

The negative aspect is the maintenance and short life problems caused by the commutator. As a result, such motors are usually used in AC devices such as food mixers and power tools, which are used only intermittently.

Continuous speed control of a universal motor running on AC is very easily accomplished using a thyristor circuit, while stepped speed control can be accomplished using multiple taps on the field coil. Household blenders that advertise many speeds frequently combine a field coil with several taps and a diode that can be inserted in series with the motor (causing the motor to run on half-wave rectified AC).

Universal motors can rotate at relatively high revolutions per minute (rpm). This makes them useful for appliances such as blenders, vacuum cleaners, and hair dryers where high-speed operation is desired. Many vacuum cleaner and weed trimmer motors exceed 10,000 rpm; Dremel and other similar miniature grinders will often exceed 30,000 rpm. Motor damage may occur due to overspeed (rpm in excess of design specifications) if the unit is operated with no significant load. On larger motors, sudden loss of load is to be avoided, and the possibility of such an occurrence is incorporated into the motor's protection and control schemes. Often, a small fan blade attached to the armature acts as an artificial load to limit the motor speed to a safe value, as well as provide cooling airflow to the armature and field windings.

With the very low cost of semiconductor rectifiers, some applications that would have previously used a universal motor now use a pure DC motor, sometimes with a permanent magnet field.

AC Motors
In 1882, Nicola Tesla identified the rotating magnetic field principle, and pioneered the use of a rotary field of force to operate machines. He exploited the principle to design a unique two-phase induction motor in 1883. In 1885, Galileo Ferraris independently researched the concept. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin.

Introduction of Tesla's motor from 1888 onwards initiated what is sometimes referred to as the Second Industrial Revolution, making possible the efficient generation and long distance distribution of electrical energy using the alternating current transmission system, also of Tesla's invention (1888). Before the invention of the rotating magnetic field, motors operated by continually passing a conductor through a stationary magnetic field (as in homopolar motors). Tesla had suggested that the commutators from a machine could be removed and the device could operate on a rotary field of force. Professor Poeschel, his teacher, stated that would be akin to building a perpetual motion machine.

Components
A typical AC motor consists of two parts:
1. An outside stationary stator having coils supplied with AC current to produce a rotating magnetic field, and;
2. An inside rotor attached to the output shaft that is given a torque by the rotating field.

Torque Motors
A torque motor is a specialized form of induction motor which is capable of operating indefinitely at stall (with the rotor blocked from turning) without damage. In this mode, the motor will apply a steady stall torque to the load (hence the name). A common application of a torque motor would be the supply- and take-up reel motors in a tape drive. In this application, driven from a low voltage, the characteristics of these motors allow a relatively-constant light tension to be applied to the tape whether or not the capstan is feeding tape past the tape heads. Driven from a higher voltage, (and so delivering a higher torque), the torque motors can also achieve fast-forward and rewind operation without requiring any additional mechanics such as gears or clutches. In the computer world, torque motors are used with force feedback steering wheels.

Slip Ring

The slip ring or wound rotor motor is an induction machine where the rotor comprises a set of coils that are terminated in slip rings to which external impedances can be connected. The stator is the same as is used with a standard squirrel cage motor. By changing the impedance connected to the rotor circuit, the speed/current and speed/torque curves can be altered.

The slip ring motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range. By correctly selecting the resistors used in the secondary resistance or slip ring starter, the motor is able to produce maximum torque at a relatively low current from zero speed to full speed. A secondary use of the slip ring motor is to provide a means of speed control.

Because the torque curve of the motor is effectively modified by the resistance connected to the rotor circuit, the speed of the motor can be altered. Increasing the value of resistance on the rotor circuit will move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced.

When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner, the slip losses are dissipated in the secondary resistors and can be very significant. The speed regulation is also very poor.

Stepper Motors

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a large iron core with salient poles is controlled by a set of external magnets that are switched electronically.

A stepper motor may also be thought of as a cross between a DC electric motor and a solenoid. As each coil is energized in turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the motor may not rotate continuously; instead, it "steps" from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. Computer controlled stepper motors are one of the most versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle with ease, and hence stepper motors are used in pre-gigabyte era computer disk drives, where the precision they offered was adequate for the correct positioning of the read/write head of a hard disk drive. As drive density increased, the precision limitations of stepper motors made them obsolete for hard drives, thus newer hard disk drives use read/write head control systems based on voice coils. Stepper motors were up-scaled to be used in electric vehicles under the term SRM (switched reluctance machine).

Reviewing A-C Motors

AC Motor History
In 1882, Nikola Tesla discovered the rotating magnetic field, and pioneered the use of a rotary field of force to operate machines. He exploited the principle to design a unique two-phase induction motor in 1883. In 1885, Galileo Ferraris independently researched the concept. In 1888, Ferraris published his research in a paper to the Royal Academy of Sciences in Turin. Tesla had suggested that the commutators from a machine could be removed and the device could operate on a rotary field of force. Professor Poeschel, his teacher, stated that would be akin to building a perpetual motion machine.

Michail Osipovich Dolivo-Dobrovolsky later developed a three-phase "cage-rotor" in 1890. This type of motor is now used for the vast majority of commercial applications.

An AC motor has two parts: a stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and a rotor attached to the output shaft that is given a torque by the rotating field.

AC Motor with Sliding Rotor
A conical-rotor brake motor incorporates the brake as an integral part of the conical sliding rotor. When the motor is at rest, a spring acts on the sliding rotor and forces the brake ring against the brake cap in the motor, holding the rotor stationary. When the motor is energized, its magnetic field generates both an axial and a radial component. The axial component overcomes the spring force, releasing the brake; while the radial component causes the rotor to turn. There is no additional brake control required.

Synchronous Electric Motor
A synchronous electric motor is an AC motor distinguished by a rotor spinning with coils passing magnets at the same rate as the alternating current and resulting magnetic field which drives it. Another way of saying this is that it has zero slip under usual operating conditions. Contrast this with an induction motor, which must slip to produce torque.

One type of synchronous motor is like an induction motor except the rotor is excited by a DC field. Slip rings and brushes are used to conduct current to the rotor. The rotor poles connect to each other and move at the same speed hence the name synchronous motor.

Another type, for low load torque, has flats ground onto a conventional squirrel-cage rotor to create discrete poles. Yet another, such as made by Hammond for its pre-World War II clocks, and in the older Hammond organs, has no rotor windings and discrete poles. It is not self-starting. The clock requires manual starting by a small knob on the back, while the older Hammond organs had an auxiliary starting motor connected by a spring-loaded manually operated switch.

Finally, hysteresis synchronous motors typically are (essentially) two-phase motors with a phase-shifting capacitor for one phase. They start like induction motors, but when slip rate decreases sufficiently, the rotor (a smooth cylinder) becomes temporarily magnetized. Its distributed poles make it act like a permanent-magnet-rotor synchronous motor.

The rotor material, like that of a common nail, will stay magnetized, but can also be demagnetized with little difficulty. Once running, the rotor poles stay in place; they do not drift.

Low-power synchronous timing motors (such as those for traditional electric clocks) may have multi-pole permanent-magnet external cup rotors, and use shading coils to provide starting torque. Telechron clock motors have shaded poles for starting torque, and a two-spoke ring rotor that performs like a discrete two-pole rotor.

Induction Motor

An induction motor is an asynchronous AC motor where power is transferred to the rotor by electromagnetic induction, much like transformer action. An induction motor resembles a rotating transformer, because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Polyphase induction motors are widely used in industry.

Induction motors may be further divided into squirrel-cage motors and wound-rotor motors. Squirrel-cage motors have a heavy winding made up of solid bars, usually aluminum or copper, joined by rings at the ends of the rotor. When one considers only the bars and rings as a whole, they are much like an animal's rotating exercise cage, hence the name.

Currents induced into this winding provide the rotor magnetic field. The shape of the rotor bars determines the speed-torque characteristics. At low speeds, the current induced in the squirrel cage is nearly at line frequency and tends to be in the outer parts of the rotor cage. As the motor accelerates, the slip frequency becomes lower, and more current is in the interior of the winding. By shaping the bars to change the resistance of the winding portions in the interior and outer parts of the cage, effectively a variable resistance is inserted in the rotor circuit. However, the majority of such motors have uniform bars.

In a wound-rotor motor, the rotor winding is made of many turns of insulated wire and is connected to slip rings on the motor shaft. An external resistor or other control devices can be connected in the rotor circuit. Resistors allow control of the motor speed, although significant power is dissipated in the external resistance. A converter can be fed from the rotor circuit and return the slip-frequency power that would otherwise be wasted back into the power system through an inverter or separate motor-generator.

The wound-rotor induction motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range. By correctly selecting the resistors used in the secondary resistance or slip ring starter, the motor is able to produce maximum torque at a relatively low supply current from zero speed to full speed. This type of motor also offers controllable speed.

Motor speed can be changed because the torque curve of the motor is effectively modified by the amount of resistance connected to the rotor circuit. Increasing the value of resistance will move the speed of maximum torque down. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs at zero speed, the torque will be further reduced.

When used with a load that has a torque curve that increases with speed, the motor will operate at the speed where the torque developed by the motor is equal to the load torque. Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner, the slip losses are dissipated in the secondary resistors and can be very significant.

The speed regulation and net efficiency is also very poor. Various regulatory authorities in many countries have introduced and implemented legislation to encourage the manufacture and use of higher efficiency electric motors.

Doubly Fed Electric Motor
Doubly fed electric motors have two independent multiphase winding sets, which contribute active (i.e., working) power to the energy conversion process, with at least one of the winding sets electronically controlled for variable speed operation. Two independent multiphase winding sets (i.e., dual armature) are the maximum provided in a single package without topology duplication. Doubly fed electric motors are machines with an effective constant torque speed range that is twice synchronous speed for a given frequency of excitation. This is twice the constant torque speed range as singly fed electric machines, which have only one active winding set.

A doubly fed motor allows for a smaller electronic converter but the cost of the rotor winding and slip rings may offset the saving in the power electronics components. Difficulties with controlling speed near synchronous speed limit applications.

Singly Fed Electric Motor
Most AC motors are singly fed. Singly fed electric motors have a single multiphase winding set that is connected to a power supply. Singly fed electric machines may be either induction or synchronous. The active winding set can be electronically controlled. Singly fed electric machines have an effective constant torque speed range up to synchronous speed for a given excitation frequency.

Torque Motors
A torque motor (also known as a limited torque motor) is a specialized form of induction motor which is capable of operating indefinitely while stalled, that is, with the rotor blocked from turning, without incurring damage. In this mode of operation, the motor will apply a steady torque to the load (hence the name).

A common application of a torque motor would be the supply- and take-up reel motors in a tape drive. In this application, driven from a low voltage, the characteristics of these motors allow a relatively constant light tension to be applied to the tape whether or not the capstan is feeding tape past the tape heads. Driven from a higher voltage, (and so delivering a higher torque), the torque motors can also achieve fast-forward and rewind operation without requiring any additional mechanics such as gears or clutches. In the computer gaming world, torque motors are used in force feedback steering wheels.

Another common application is the control of the throttle of an internal combustion engine in conjunction with an electronic governor. In this usage, the motor works against a return spring to move the throttle in accordance with the output of the governor. The latter monitors engine speed by counting electrical pulses from the ignition system or from a magnetic pickup and, depending on the speed, makes small adjustments to the amount of current applied to the motor.

If the engine starts to slow down relative to the desired speed, the current will be increased, the motor will develop more torque, pulling against the return spring and opening the throttle. Should the engine run too fast, the governor will reduce the current being applied to the motor, causing the return spring to pull back and close the throttle.
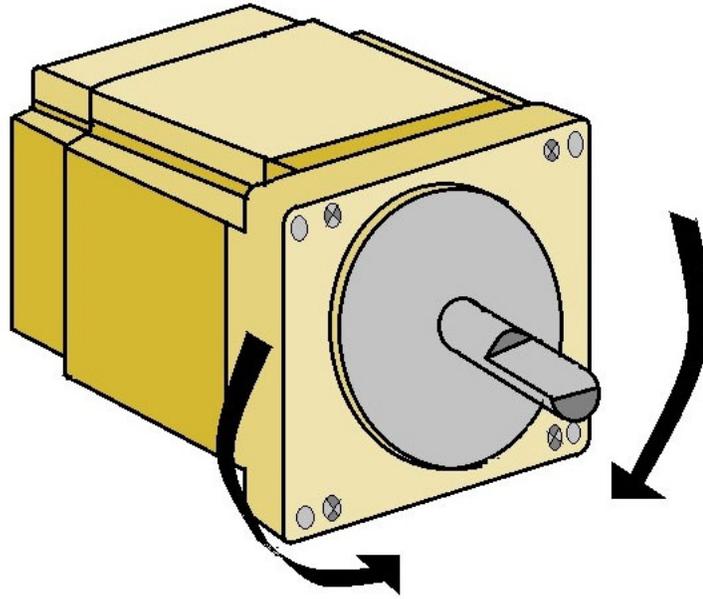
STEPPER MOTOR

Brushless, Synchronous Electric Motor that coverts digital pulses into shaft rotations

MAGNET CHANNEL ASSEMBLY

HALL EFFECTS

COIL ASSEMBLY

FIXED MAGNETS
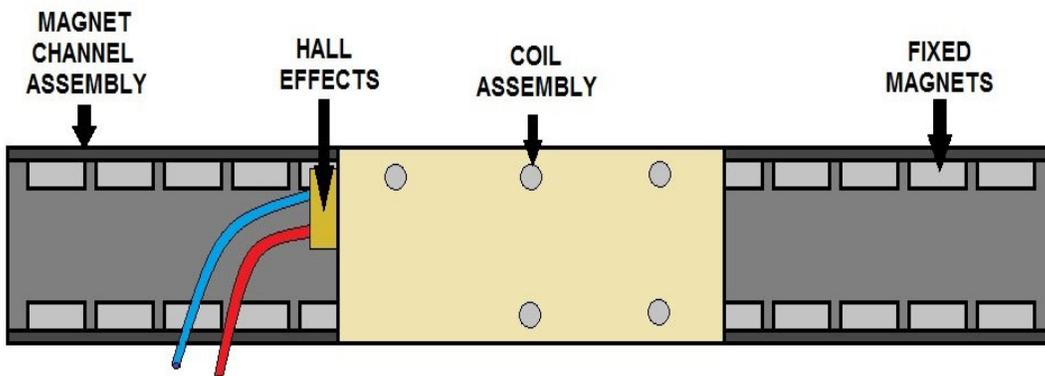
LINEAR MOTOR

Electric Induction Motor that produces Straight-Line motion by means of a Linear Stator and Rotor placed in Parallel

Stepper Motors

Closely related in design to three-phase AC synchronous motors are stepper motors, where an internal rotor containing permanent magnets or a magnetically soft rotor with salient poles is controlled by a set of external magnets that are switched electronically. A stepper motor may also be thought of as a cross between a DC electric motor and a rotary solenoid. As each coil is energized in turn, the rotor aligns itself with the magnetic field produced by the energized field winding. Unlike a synchronous motor, in its application, the stepper motor may not rotate continuously; instead, it "steps"—starts and then quickly stops again—from one position to the next as field windings are energized and de-energized in sequence. Depending on the sequence, the rotor may turn forwards or backwards, and it may change direction, stop, speed up or slow down arbitrarily at any time.

Simple stepper motor drivers entirely energize or entirely de-energize the field windings, leading the rotor to "cog" to a limited number of positions; more sophisticated drivers can proportionally control the power to the field windings, allowing the rotors to position between the cog points and thereby rotate extremely smoothly. This mode of operation is often called microstepping. Computer controlled stepper motors are one of the most versatile forms of positioning systems, particularly when part of a digital servo-controlled system.

Stepper motors can be rotated to a specific angle in discrete steps with ease, and hence stepper motors are used for read/write head positioning in computer floppy diskette drives. They were used for the same purpose in pre-gigabyte era computer disk drives, where the precision and speed they offered was adequate for the correct positioning of the read/write head of a hard disk drive.

As drive density increased, the precision and speed limitations of stepper motors made them obsolete for hard drives—the precision limitation made them unusable, and the speed limitation made them uncompetitive—thus newer hard disk drives use voice coil-based head actuator systems. (The term "voice coil" in this connection is historic; it refers to the structure in a typical (cone type) loudspeaker.

This structure was used for a while to position the heads. Modern drives have a pivoted coil mount; the coil swings back and forth, something like a blade of a rotating fan. Nevertheless, like a voice coil, modern actuator coil conductors (the magnet wire) move perpendicular to the magnetic lines of force.)

Stepper motors were and still are often used in computer printers, optical scanners, and digital photocopiers to move the optical scanning element, the print head carriage (of dot matrix and inkjet printers), and the platen or feed rollers. Likewise, many computer plotters (which since the early 1990s have been replaced with large-format inkjet and laser printers) used rotary stepper motors for pen and platen movement; the typical alternatives here were either linear stepper motors or servomotors with closed-loop analog control systems.

So-called quartz analog wristwatches contain the smallest commonplace stepping motors; they have one coil, draw very little power, and have a permanent-magnet rotor. The same kind of motor drives battery-powered quartz clocks. Some of these watches, such as chronographs, contain more than one stepping motor.

Rotary

Uses include rotating machines such as fans, turbines, drills, the wheels on electric cars, locomotives and conveyor belts. Also, in many vibrating or oscillating machines, an electric motor spins an unbalanced mass, causing the motor (and its mounting structure) to vibrate. A familiar application is cell phone vibrating alerts used when the acoustic "ringer" is disabled by the user.

Electric motors are also popular in robotics. They turn the wheels of vehicular robots, and servo motors operate arms in industrial robots; they also move arms and legs in humanoid robots. In flying robots, along with helicopters, a motor rotates a propeller, or aerodynamic rotor blades to create controllable amounts of lift. Electric motors are replacing hydraulic cylinders in airplanes and military equipment.

In industrial and manufacturing businesses, electric motors rotate saws and blades in cutting and slicing processes; they rotate parts being turned in lathes and other machine tools, and spin grinding wheels. Fast, precise servo motors position tools and work in modern CNC machine tools. Motor-driven mixers are very common in food manufacturing. Linear motors are often used to push products into containers horizontally.

Many kitchen appliances also use electric motors. Food processors and grinders spin blades to chop and break up foods. Blenders use electric motors to mix liquids, and microwave ovens use motors to turn the tray that food sits on. Toaster ovens also use electric motors to turn a conveyor to move food over heating elements.

Servo Motor
A servomotor is a motor, very often sold as a complete module, which is used within a position-control or speed-control feedback control system mainly control valves, such as motor operated control valves. Servomotors are used in applications such as machine tools, pen plotters, and other process systems. Motors intended for use in a servomechanism must have well-documented characteristics for speed, torque, and power.

The speed vs. torque curve is quite important and is high ratio for a servo motor. Dynamic response characteristics such as winding inductance and rotor inertia are also important; these factors limit the overall performance of the servomechanism loop. Large, powerful, but slow-responding servo loops may use conventional AC or DC motors and drive systems with position or speed feedback on the motor. As dynamic response requirements increase, more specialized motor designs such as coreless motors are used.

A servo system differs from some stepper motor applications in that the position feedback is continuous while the motor is running; a stepper system relies on the motor not to "miss steps" for short term accuracy, although a stepper system may include a "home" switch or other element to provide long-term stability of control.

For instance, when a typical dot matrix computer printer starts up, its controller makes the print head stepper motor drive to its left-hand limit, where a position sensor defines home position and stops stepping. As long as power is on, a bidirectional counter in the printer's microprocessor keeps track of print-head position.

Linear Motor

A linear motor is essentially any electric motor that has been "unrolled" so that, instead of producing a torque (rotation), it produces a straight-line force along its length. Linear motors are most commonly induction motors or stepper motors. Linear motors are commonly found in many roller-coasters where the rapid motion of the motorless railcar is controlled by the rail. They are also used in maglev trains, where the train "flies" over the ground. On a smaller scale, the HP 7225A pen plotter, released in 1978, used two linear stepper motors to move the pen along the X and Y axes.

Torque Capability of Motor Types
When optimally designed within a given core saturation constraint and for a given active current (i.e., torque current), voltage, pole-pair number, excitation frequency (i.e., synchronous speed), and air-gap flux density, all categories of electric motors or generators will exhibit virtually the same maximum continuous shaft torque (i.e., operating torque) within a given air-gap area with winding slots and back-iron depth, which determines the physical size of electromagnetic core. Some applications require bursts of torque beyond the maximum operating torque, such as short bursts of torque to accelerate an electric vehicle from standstill. Always limited by magnetic core saturation or safe operating temperature rise and voltage, the capacity for torque bursts beyond the maximum operating torque differs significantly between categories of electric motors or generators.

Capacity for bursts of torque should not be confused with field weakening capability inherent in fully electromagnetic electric machines (Permanent Magnet (PM) electric machine are excluded). Field weakening, which is not available with PM electric machines, allows an electric machine to operate beyond the designed frequency of excitation.

Electric machines without a transformer circuit topology, such as Field-Wound (i.e., electromagnet) or Permanent Magnet (PM) Synchronous electric machines cannot realize bursts of torque higher than the maximum designed torque without saturating the magnetic core and rendering any increase in current as useless. Furthermore, the permanent magnet assembly of PM synchronous electric machines can be irreparably damaged, if bursts of torque exceeding the maximum operating torque rating are attempted.

Electric machines with a transformer circuit topology, such as Induction (i.e., asynchronous) electric machines, Induction Doubly Fed electric machines, and Induction or Synchronous Wound-Rotor Doubly Fed (WRDF) electric machines, exhibit very high bursts of torque because the active current (i.e., Magneto-Motive-Force or the product of current and winding-turns) induced on either side of the transformer oppose each other and as a result, the active current contributes nothing to the transformer coupled magnetic core flux density, which would otherwise lead to core saturation.

Electric machines that rely on Induction or Asynchronous principles short-circuit one port of the transformer circuit and as a result, the reactive impedance of the transformer circuit becomes dominant as slip increases, which limits the magnitude of active (i.e., real) current. Still, bursts of torque that are two to three times higher than the maximum design torque are realizable.

The Synchronous WRDF electric machine is the only electric machine with a truly dual ported transformer circuit topology (i.e., both ports independently excited with no short-circuited port). The dual ported transformer circuit topology is known to be unstable and requires a multiphase slip-ring-brush assembly to propagate limited power to the rotor winding set.

If a precision means were available to instantaneously control torque angle and slip for synchronous operation during motoring or generating while simultaneously providing brushless power to the rotor winding set (see Brushless wound-rotor doubly fed electric machine), the active current of the Synchronous WRDF electric machine would be independent of the reactive impedance of the transformer circuit and bursts of torque significantly higher than the maximum operating torque and far beyond the practical capability of any other type of electric machine would be realizable. Torque bursts greater than eight times operating torque have been calculated.

Continuous Torque Density
The continuous torque density of conventional electric machines is determined by the size of the air-gap area and the back-iron depth, which are determined by the power rating of the armature winding set, the speed of the machine, and the achievable air-gap flux density before core saturation.

Despite the high coercivity of neodymium or samarium-cobalt permanent magnets, continuous torque density is virtually the same amongst electric machines with optimally designed armature winding sets. Continuous torque density should never be confused with peak torque density, which comes with the manufacturer's chosen method of cooling, which is available to all, or period of operation before destruction by overheating of windings or even permanent magnet damage.

Motor Review Section

Reviewing D-C Motors

DC motors have been available for nearly 100 years. In fact the first electric motors were designed and built for operation from direct current power. AC motors are the basic prime movers for the fixed speed requirements of industry. Their basic simplicity, dependability and ruggedness make AC motors the natural choice for the vast majority of industrial drive applications.

An electric motor can be configured as a solenoid, a stepper motor or a rotational machine. This article covers the DC rotational machine. In all DC rotational machines, there are six components that comprise the electric motor: axle, rotor or armature, stator, commutator, field magnets and brushes.

In order to understand how a direct current (DC) electric motor operates, a few basic principles must be understood. Just as in Faraday's experiment, the DC motor works with magnetic fields and electrical current. Centuries ago it was discovered that a stone found in Asia, referred to as a lodestone, and had an unusual property that would transfer an invisible force to an iron object when the stone was rubbed against it. These lodestones were found to align with the earth's north-south axis when freely hanging on a string or floated on water, and this property aided early explorers in navigating around the earth.

It was understood later that this stone was a permanent magnet with a field that had two poles of opposite effect, referred to as north and south. The magnetic fields, just like electric charges, have forces that are opposite in their effects.

Electric charges are either positive or negative, whereas magnetic fields have a north-south orientation. When magnetic fields are aligned at opposite or dissimilar poles, they'll exert considerable forces of attraction with one another, and when aligned at like or similar poles, they'll strongly repel one another.

The magnetic field will pull or put a force upon a ferrous (magnetic) material. If iron particles are sprinkled on a paper sheet over a permanent magnet, the alignment of the iron particles maps the magnetic field, which shows that this field leaves one pole and enters the other pole with the force field being unbroken. As with any kind of field (electric, magnetic or gravitational), the total quantity, or effect, of the field is referred to as the flux, while the push causing the flux to form in space is called a force. This magnetic force field is comprised of many lines of flux, all starting at one pole and returning to the other pole.

Modern Theory of Magnetism

The modern theory of magnetism states that a magnetic field is produced by an electric charge in motion. When an electric charge is in motion, the electrons orbiting the atom are forced to align and uniformly spin in the same direction. The more atoms uniformly spinning in the same direction, the stronger the force of the magnetic field. When billions of atoms have orbits spinning in the same direction and the material is capable of holding the atoms' orbits, a permanent magnet is created.

When two powerful permanent magnets are moved in close proximity to one another, it's evident that a very real force is exerted that can provide the potential for work to be done. For work to be accomplished, the relationship between the magnetic fields must be controlled properly.

The trick here is to control the magnetic fields by a means other than just using the permanent magnet. This can be accomplished by producing a magnetic field with an electrical conductor that has current flowing through it.

Nearly all electric motors exploit the use of a current-carrying conductor to create mechanical work. When current is flowing through a conductor and the electric charge is in motion, the electrons orbiting the atoms are forced to align and uniformly spin in the same direction. This creates a magnetic field that forms around the conductor. The larger the current flowing through the conductor, the more atoms are forced to align and rotate in a uniform direction.

This rotational alignment of the atoms increases the strength of the magnetic field. However, if one were to place a conductor with current flowing through it near a permanent magnet, he would be disappointed by how feeble this force is. What's needed is a way to amplify the magnetic force field. This is accomplished by taking the conductor wire and making many turns or wraps to produce a winding. Converting the conductor from a single, isolated straight wire to one that contains many turns forming a winding amplifies the magnetic force many times. The amount of magnetic field amplification is based on the number of turns in the winding and the amount of current flowing through the conductor.

In this configuration, the magnetic flux is moving through air, which is a poor conductor of magnetic energy, thus allowing the magnetic flux to spread out over a very wide area. Therefore, the reluctance from the magnetic field when moving through air is quite high. Reluctance is a measure of how difficult it is for the magnetic flux to complete its circuit—that is, to leave one pole and enter the opposite pole. If the magnetic flux is kept close to the magnet, it has less resistance or opposition to flow.

Magnetic Principles and Motor Theory
All machine designs involving rotating equipment ultimately rely on theory to guide the engineer's application choices. Hence, a very brief review of magnetic principles and motor theory is always a convenient starting point for any discussion of DC motor applications. The laws of physics have blessed the world of machine design with the existence of magnetism, which is the foundation of motor theory. In essence, magnets, permanent or electromagnetic, produce fields of magnetic flux. These magnetic fields can produce an induced EMF through a coil of wire when relative movement between the field and a current carrying conductor occurs; and if this movement is reversed, so is the direction of the magnetic field, according to Faraday's Law. Thus, in theory, motor action or torque is produced when electrical energy is applied to conductor in a changing magnetic field, causing current flow in the conductor, generating both an induced EMF and a CEMF (Lenz's Law) resulting in rotational or mechanical energy..

DC Motors: Physical and Functional Descriptions
DC motors are commonly used in industrial machinery because of their inherent advantages— good speed control, high starting torque, reliable control methodology—which generally outweigh the increased maintenance costs associated with them.

Construction
The generic DC motor is constructed 13 with armature and field windings, interpoles, a frame or stator, a segmented commutator, a brush assembly and end bells. The rotating armature winding is wound on a laminated core, mounted on a steel shaft, supported by shaft bearings, and is connected to the segmented commutator that receives external DC power through the brush assembly.

Brushes conduct the current from external DC power circuit to the commutator and finally to the armature windings. The frame or stator supports the field windings and interpoles. The end bells encase all the parts of the motor into one unit.

Operation
DC motors produce torque and mechanical motion due to the interaction of the magnetic fields of the rotating armature coil and the stationary field coil mounted on the frame. The changing magnetic field of the armature is possible through the use of electrically conductive carbon brushes, which ride on the segmented, commutator ring; external DC power is applied to the brushes through the commutator to the armature windings. As current flows through the armature coil, a magnetic field results. The field windings mounted on the frame, also set up a magnetic field. After the rotating armature passes through half of a complete rotation, the commutator switches the direction of the current flow, thereby changing the direction of the magnetic field in the armature winding. This change produces opposing magnetic fields and sustains torque and rotation through the next half cycle of rotation until the commutator changes the direction of current flow and the magnetic field again.

Types
The field and armature windings of DC motors can be connected in series, shunt (parallel) or series-shunt to achieve different kinds of speed-torque characteristics. Hence, the three general categories of wound field DC motors are shunt-wound, series-wound and compound-wound. In series-wound motors, the armature is connected in series with the field to provide high starting torque; however, they do not operate at no-load: when speed decreases, torque increases, which can create a possibly unsafe runaway condition. In shunt wound motors, the armature and field are connected in parallel. This wiring arrangement produces an inverse speed-torque relationship: as speed increases, torque decreases. The compound-wound is a combination of a series- and shunt-wound motor by placing the field winding in series with the armature in addition to a shunt field. This type offers a combination of good starting torque and speed control.

Brushless motors are a hybrid type of DC motor that does not use a commutator. Rather, it is constructed with a permanent magnet rotor, optical shaft encoder that gives positional feedback information, a DC controller that excites the phase of stator windings required to develop torque based upon the encoder's feedback. Brushless motors characteristically have high maximum operating speeds, high torque to weight ratios and are compact in design (fractional horsepower). They are typically used in robotic arm applications.

Associated Solid State Controls
In order to supply the answer, it is necessary to examine some of the basic characteristics obtainable from DC motors and their associated solid state controls.
1. Wide speed range.
2. Good speed regulation.
3. Compact size and light weight (relative to mechanical variable speed).
4. Ease of control.
5. Low maintenance.
6. Low cost.

In order to realize how a DC drive has the capability to provide the above characteristics, the DC drive has to be analyzed as two elements that make up the package. These two elements are of course the motor and the control. (The "control" is more accurately called the "regulator"). Basic DC motors as used on nearly all packaged drives have a very simple performance characteristic the shaft turns at a speed almost directly proportional to the voltage applied to the armature.
External Adjustment

In addition to the normal external adjustment such as the speed potentiometer. there are a number of common internal adjustments that are used on simple small analog type SCR Drives (Silicon Controlled Rectifier Drive). Some of these adjustments are as follows:

- ✓ Minimum Speed

- ✓ Maximum Speed

- ✓ Current Limit (Torque Limit). IR Compensation

- ✓ Acceleration Time. Deceleration Time

The following is a description of the function that these individual adjustments serve and their typical use.

Minimum Speed
In most cases when the control is initially installed the speed potentiometer can be turned down to its lowest point and the output voltage from the control will go to zero causing the motor to stop. There are many situations where this is not desirable. For example there are some machines that want to be kept running at a minimum speed and accelerated up to operating speed as necessary. There is also a possibility that an operator may use the speed potentiometer to stop the motor to work on the machine. This can be a dangerous situation since the motor has only been brought to a stop by zeroing the input signal voltage. A more desirable situation is when the motor is stopped by opening the circuit to the motor or power to the control using the on/off switch. By adjusting the minimum speed up to some point where the motor continues to run even with the speed potentiometer set to its lowest point, the operator must shut the control off to stop the motor. This adds a little safety into the system. The typical minimum speed adjustment is from 0 to 30% of motor base speed.

Maximum Speed
The maximum speed adjustment sets the maximum speed attainable either by raising the input signal to its maximum point or turning the potentiometer to the maximum point. For example on a typical DC motor the rated speed of the motor might 1750 RPM but the control might be capable of running it up to 1850 or 1900 RPM. In some cases it's desirable to limit the motor (and machine speed) to something less than would be available at this maximum setting. The maximum adjustment allows this to be done. By turning the internal potentiometer to a lower point the maximum output voltage from the control is limited. This limits the maximum speed available from the motor. In typical controls such as our BC140 the range of adjustment on the maximum speed is from 50 to 110% of motor base speed.

Current Limit
One very nice feature of electronic speed controls is that the current going to the motor is constantly monitored by the control. As mentioned previously, the current drawn by the armature of the DC motor is related to the torque that is required by the load. Since this monitoring and control is available an adjustment is provided in the control that limits the output current to a maximum value.

This function can be used to set a threshold point that will cause the motor to stall rather than putting out an excessive amount of torque. This capability gives the motor/control combination the ability to prevent damage that might otherwise occur if higher values of torque were available. This is handy on machines that might become jammed or otherwise stalled. It can also be used where the control is operating a device such as the center winder where the important thing becomes torque rather than the speed. In this case the current limit is set and the speed goes up

or down to hold the tension 0 the material being wound. The current limit is normally factory set at 150% of the motor's rated current. This allows the motor to produce enough torque to start and accelerate the load and yet will not let the current (and torque) exceed 150% of its rated value when running. The range of adjustment is typically from 0 to 200% of the motor rated current.

IR Compensation

IR compensation is a method used to adjust for the droop in a motor's speed due to armature resistance. As mentioned previously, IR compensation is positive feedback that causes the control output voltage to rise slightly with increasing output current. This will help stabilize the motor's speed from a no load to full load condition. If the motor happens to be driving a load where the torque is constant or nearly so, then this adjustment is usually unnecessary. However, if the motor is driving a load with a widely fluctuating torque requirement, and speed regulation is critical, then IR compensation can be adjusted to stabilize the speed from the light load to full load condition. One caution is that when IR compensation is adjusted too high it results in an increasing speed characteristic. This means that as the load is applied the motor is actually going to be forced to run faster. When this happens it increases the voltage and current to the motor which in turn increases the motor speed further. If this adjustment is set too high an unstable "hunting" or oscillating condition occurs that is undesirable.

Acceleration Time Adjustment

The Acceleration Time adjustment performs the function that is indicated by its name. It will extend or shorten the amount of time for the motor to go from zero speed up to the set speed. It also regulates the time it takes to change speeds from one setting (say 50%) to another setting (perhaps 100%). So this setting has the ability to moderate the acceleration rate on the drive.

A couple notes are important: if an acceleration time that is too rapid is called for "acceleration time" will be overridden by the current limit. Acceleration will only occur at a rate that is allowed by the amount of current the control passes through to the motor. Also important to note is that on most small controls the acceleration time is not linear. What this means is that a change of 50 RPM may occur more rapidly when the motor is at low speed than it does when the motor is approaching the set point speed. This is important to know but usually not critical on simple applications where these drives are used.

Deceleration Time

This is an adjustment that allows loads to be slowed over an extended period of time. For example, if power is removed from the motor and the load stops in 3 seconds, then the decel time adjustment would allow you" to increase that time and "power down" the load over a period of 4, 5, 6 or more seconds. Note: On a conventional simple DC drive it will not allow for the shortening of the time below the "coast to rest" time.

Adjustment Summary

The ability to adjust these six adjustments gives great flexibility to the typical inexpensive DC drive. In most cases the factory preset settings are adequate and need not be changed, but on other applications it may be desirable to tailor the characteristics of the control to the specific application. Many of these adjustments are available in other types of controls, such as variable frequency drives.

1 POWER PLANT

2 TOWER

3 TRANSMISSION SUBSTATION

4 DISTRIBUTION SUBSTATION

5 TRANSFORMERS

6 HOUSE
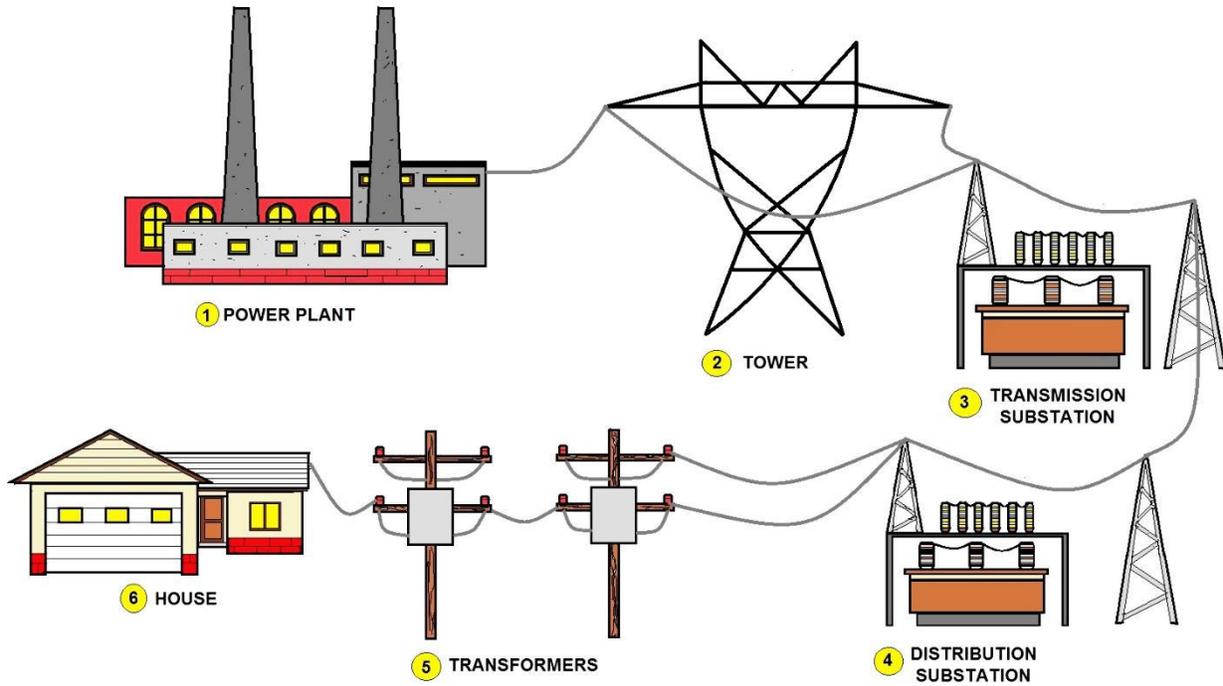
POWER - TO - HOME

Understanding Single Phase

In electrical engineering, single-phase electric power refers to the distribution of alternating current electric power using a system in which all the voltages of the supply vary in unison. Single-phase distribution is used when loads are mostly lighting and heating, with few large electric motors. A single-phase supply connected to an alternating current electric motor does not produce a revolving magnetic field; single-phase motors need additional circuits for starting, and such motors are uncommon above 10 or 20 kW in rating.

In contrast, in a three-phase system, the currents in each conductor reach their peak instantaneous values sequentially, not simultaneously; in each cycle of the power frequency, first one, then the second, then the third current reaches its maximum value. The waveforms of the three supply conductors are offset from one another in time (delayed in phase) by one-third of their period. When the three phases are connected to windings around the interior of a motor stator, they produce a revolving magnetic field; such motors are self-starting.

Standard Frequencies of Single-Phase Power
Standard frequencies of single-phase power systems are either 50 or 60 Hz. Special single-phase traction power networks may operate at 16.67 Hz or other frequencies to power electric railways. In some countries such as the United States, single phase is commonly divided in half to create split-phase electric power for household appliances and lighting.

Single-phase power distribution is widely used especially in rural areas, where the cost of a three-phase distribution network is high and motor loads are small and uncommon.

High power systems, say, hundreds of kVA or larger, are nearly always three phase. The largest supply normally available as single phase varies according to the standards of the electrical utility. In the UK a single-phase household supply may be rated 100 A or even 125 A, meaning that there is little need for 3 phase in a domestic or small commercial environment.

Much of the rest of Europe has traditionally had much smaller limits on the size of single phase supplies resulting in even houses being supplied with 3 phase (in urban areas with three-phase supply networks).

In North America, individual residences and small commercial buildings with services up to about 100 kV·A (417 amperes at 240 volts) will usually have three-wire single-phase distribution, often with only one customer per distribution transformer.

In exceptional cases larger single-phase three-wire services can be provided, usually only in remote areas where poly-phase distribution is not available. In rural areas farmers who wish to use three-phase motors may install a phase converter if only a single-phase supply is available.

Larger consumers such as large buildings, shopping centers, factories, office blocks, and multiple-unit apartment blocks will have three-phase service. In densely populated areas of cities, network power distribution is used with many customers and many supply transformers connected to provide hundreds or thousands of kV·A, a load concentrated over a few hundred square meters.

STATOR

S

N

BUSHES

SLIP RINGS

ARMATURE

GALVOMETER
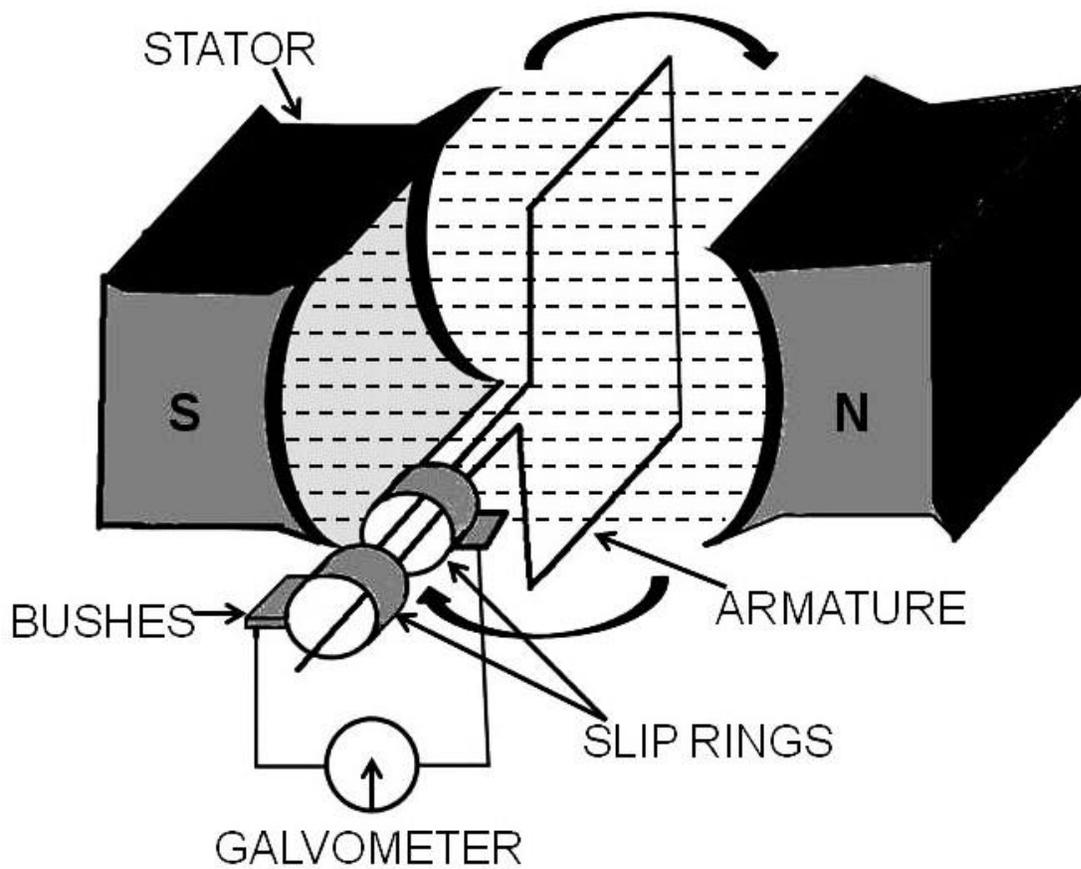
PRODUCTION OF AC CURRENT

Understanding Three Phase

Three-phase electric power is a common method of alternating-current electric power generation, transmission, and distribution. It is a type of polyphase system and is the most common method used by electrical grids worldwide to transfer power. It is also used to power large motors and other heavy loads. A three-phase system is generally more economical than others because it uses less conductor material to transmit electric power than equivalent single-phase or two-phase systems at the same voltage. The three-phase system was introduced and patented by Nikola Tesla in 1887 and 1888.

In a three-phase system, three circuit conductors carry three alternating currents (of the same frequency) which reach their instantaneous peak values at different times. Taking one conductor as the reference, the other two currents are delayed in time by one-third and two-thirds of one cycle of the electric current. This delay between phases has the effect of giving constant power transfer over each cycle of the current and also makes it possible to produce a rotating magnetic field in an electric motor.

Three-phase systems may have a neutral wire. A neutral wire allows the three-phase system to use a higher voltage while still supporting lower-voltage single-phase appliances. In high-voltage distribution situations, it is common not to have a neutral wire as the loads can simply be connected between phases (phase-phase connection).

Three-phase has properties that make it very desirable in electric power systems:
- ✓ The phase currents tend to cancel out one another, summing to zero in the case of a linear balanced load. This makes it possible to eliminate or reduce the size of the neutral conductor; all the phase conductors carry the same current and so can be the same size, for a balanced load.

- ✓ Power transfer into a linear balanced load is constant, which helps to reduce generator and motor vibrations.

- ✓ Three-phase systems can produce a magnetic field that rotates in a specified direction, which simplifies the design of electric motors.

- ✓ Three is the lowest phase order to exhibit all of these properties.

Most household loads are single-phase. In North America and a few other places, three-phase power generally does not enter homes. Even in areas where it does, it is typically split out at the main distribution board and the individual loads are fed from a single phase. Sometimes it is used to power electric stoves and electric clothes dryers.

3 Or 4 Wire
Three-phase circuits occur in two varieties: three-wire and four-wire. Both types have three energized ("hot" or "live") wires, but the 4-wire circuit also has neutral wire. The three-wire system is used when the loads on the 3 live wires will be balanced, for example in motors or heating elements with 3 identical coils. The neutral wire is used when there is a chance that the loads are not balanced. A common example of this is local distribution in Europe, where each house will be connected to just one of the live wires, but all connected to the same neutral.

The neutral carries the "imbalance" between the power carried on the 3 live wires. Hence electrical engineers work hard to make sure that the power is shared around equally, so the neutral wire carries as little power as possible and can therefore be made much smaller than the other 3.

The '3-wire' and '4-wire' designations do not count the ground wire used on many transmission lines, as this is solely for fault and lightning protection and does not serve to deliver electrical power.

The most important class of three-phase load is the electric motor. A three-phase induction motor has a simple design, inherently high starting torque and high efficiency. Such motors are applied in industry for pumps, fans, blowers, compressors, conveyor drives, electric vehicles and many other kinds of motor-driven equipment. A three-phase motor is more compact and less costly than a single-phase motor of the same voltage class and rating and single-phase AC motors above 10 HP (7.5 kW) are uncommon. Three-phase motors also vibrate less and hence last longer than single-phase motors of the same power used under the same conditions.

Resistance heating loads such as electric boilers or space heating may be connected to three-phase systems. Electric lighting may also be similarly connected. These types of loads do not require the revolving magnetic field characteristic of three-phase motors but take advantage of the higher voltage and power level usually associated with three-phase distribution. Legacy single-phase fluorescent lighting systems also benefit from reduced flicker in a room if adjacent fixtures are powered from different phases.

Large rectifier systems may have three-phase inputs; the resulting DC is easier to filter (smooth) than the output of a single-phase rectifier. Such rectifiers may be used for battery charging, electrolysis processes such as aluminum production or for operation of DC motors.

Phase Converters
Occasionally the advantages of three-phase motors make it worthwhile to convert single-phase power to three-phase. Small customers, such as residential or farm properties, may not have access to a three-phase supply or may not want to pay for the extra cost of a three-phase service but may still wish to use three-phase equipment. Such converters may also allow the frequency to be varied (resynthesis) allowing speed control. Some railway locomotives are moving to multi-phase motors driven by such systems even though the incoming supply to a locomotive is nearly always either DC or single-phase AC.

Because single-phase power goes to zero at each moment that the voltage crosses zero but three-phase delivers power continuously, any such converter must have a way to store the necessary energy for a fraction of a second.

One method for using three-phase equipment on a single-phase supply is with a rotary phase converter, essentially a three-phase motor with special starting arrangements and power factor correction that produces balanced three-phase voltages.

When properly designed, these rotary converters can allow satisfactory operation of three-phase equipment such as machine tools on a single-phase supply. In such a device, the energy storage is performed by the mechanical inertia (flywheel effect) of the rotating components. An external flywheel is sometimes found on one or both ends of the shaft.

A second method that was popular in the 1940s and 1950s was the transformer method. At that time, capacitors were more expensive than transformers, so an autotransformer was used to apply more power through fewer capacitors. This method performs well and does have supporters, even today. The usage of the name transformer method separated it from another common method, the static converter, as both methods have no moving parts, which separates them from the rotary converters.

Another method often attempted is with a device referred to as a static phase converter. This method of running three-phase equipment is commonly attempted with motor loads though it only supplies power and can cause the motor loads to run hot and in some cases overheat. This method does not work when sensitive circuitry is involved such as CNC devices or in induction and rectifier-type loads.

A three-phase generator can be driven by a single-phase motor. This motor-generator combination can provide a frequency changer function as well as phase conversion, but requires two machines with all their expense and losses. The motor-generator method can also form an uninterruptable power supply when used in conjunction with a large flywheel and a standby generator set.

Some devices are made which create an imitation three-phase from three-wire single-phase supplies. This is done by creating a third "subphase" between the two live conductors, resulting in a phase separation of 180° - 90° = 90°. Many three-phase devices can run on this configuration but at lower efficiency.

Variable-frequency drives (also known as solid-state inverters) are used to provide precise speed and torque control of three-phase motors. Some models can be powered by a single-phase supply. VFDs work by converting the supply voltage to DC and then converting the DC to a suitable three-phase source for the motor.

Digital phase converters are designed for fixed-frequency operation from a single-phase source. Similar to a variable-frequency drive, they use a microprocessor to control solid-state power switching components to maintain balanced three-phase voltages.

Alternatives to Three-Phase
✓ Split-phase electric power is used when three-phase power is not available and allows double the normal utilization voltage to be supplied for high-power loads.

✓ Two-phase electric power, like three-phase, gives constant power transfer to a linear load. For loads that connect each phase to neutral, assuming the load is the same power draw, the two-wire system has a neutral current which is greater than neutral current in a three-phase system. Also motors are not entirely linear, which means that despite the theory, motors running on three-phase tend to run smoother than those on two-phase. The generators in the Adams Power Plant at Niagara Falls which were installed in 1895 were the largest generators in the world at the time and were two-phase machines. True two-phase power distribution is basically obsolete. Special-purpose systems may use a two-phase system for control. Two-phase power may be obtained from a three-phase system (or vice versa) using an arrangement of transformers called a Scott-T transformer.

- ✓ Monocyclic power was a name for an asymmetrical modified two-phase power system used by General Electric around 1897, championed by Charles Proteus Steinmetz and Elihu Thomson. This system was devised to avoid patent infringement. In this system, a generator was wound with a full-voltage single-phase winding intended for lighting loads and with a small fraction (usually ¼ of the line voltage) winding which produced a voltage in quadrature with the main windings. The intention was to use this "power wire" additional winding to provide starting torque for induction motors, with the main winding providing power for lighting loads. After the expiration of the Westinghouse patents on symmetrical two-phase and three-phase power distribution systems, the monocyclic system fell out of use; it was difficult to analyze and did not last long enough for satisfactory energy metering to be developed.

- ✓ High-phase-order systems for power transmission have been built and tested. Such transmission lines use six (two-pole, three-phase) or twelve (two-pole, six-phase) lines and employ design practices characteristic of extra-high-voltage transmission lines. High-phase-order transmission lines may allow transfer of more power through a given transmission line right-of-way without the expense of a high-voltage direct current (HVDC) converter at each end of the line.

Reviewing Slip Ring Motors

A slip ring (in electrical engineering terms) is a method of making an electrical connection through a rotating assembly. Slip rings, also called rotary electrical interfaces, rotating electrical connectors, collectors, swivels, or electrical rotary joints, are commonly found in slip ring motors, electrical generators for alternating current (AC) systems and alternators and in packaging machinery, cable reels, and wind turbines. They can be used on any rotating object to transfer power, control circuits, or analog or digital signals including data such as those found on aerodrome beacons, rotating tanks, power shovels, radio telescopes or heliostats.

A slip ring is a rotary coupling used to transfer electric current from a stationary unit to a rotating unit. Either the brushes or the rings are stationary and the other component rotates. This system is similar to the brushes and commutator, found in many types of DC motors. While commutators are segmented, slip rings are continuous, and the terms are not interchangeable. Rotary transformers are often used instead of slip rings in high speed or low friction environments.

The slip ring induction motors usually have "Phase-Wound" rotor. This type of rotor is provided with a 3-phase, double-layer, distributed winding consisting of coils used in alternators. The rotor core is made up of steel laminations which has slots to accommodate formed 3-single phase windings. These windings are placed 120 degrees electrically apart.

The rotor is wound for as many poles as the number of poles in the stator and is always 3-phase, even though the stator is wound for 2-phase. These three windings are "starred" internally and other end of these three windings are brought out and connected to three insulated slip-rings mounted on the rotor shaft itself. The three terminal ends touch these three slip rings with the help of carbon brushes which are held against the rings with the help of spring assembly.

These three carbon brushes are further connected externally to a 3-phase start connected rheostat. Thus these slip ring and external rheostat makes the slip ring induction motors possible to add external resistance to the rotor circuit, thus enabling them to have a higher resistance during starting and thus higher starting torque.

When running during normal condition, the slip rings are automatically short-circuited by means of a metal collar, which is pushed along the shaft, thus making the three rings touching each other. Also, the brushes are automatically lifted from the slip-rings to avoid frictional losses, wear and tear. Hence, under normal running conditions, the wound rotor is acting as same as the squirrel cage rotor.

Mercury-wetted slip rings, noted for their low resistance and stable connection use a different principle which replaces the sliding brush contact with a pool of liquid metal molecularly bonded to the contacts. During rotation the liquid metal maintains the electrical connection between the stationary and rotating contacts.

However, the use of mercury poses safety concerns, as it is a toxic substance. If a slip ring application involves food manufacturing or processing, pharmaceutical equipment, or any other use where contamination could be a serious threat, the choice should be precious metal contacts. Leakage of the mercury and the resultant contamination could be extremely serious.

The slip ring device is also limited by temperature, as mercury solidifies at approximately -40 C.

A pancake slip ring has the conductors arranged on a flat disk as concentric rings centered on the rotating shaft. This configuration has greater weight and volume for the same circuits, greater capacitance and crosstalk, greater brush wear and more readily collects wear debris on its vertical axis. However, a pancake offers reduced axial length for the number of circuits, and so may be appropriate in some applications. Slip rings are made in various sizes; one device made for theatrical stage lighting had 100 conductors. The slip ring allows for unlimited rotations of the connected object, whereas a slack cable can only be twisted a few times before it will fail.

Stator
The stator construction is same for both squirrel cage and slip ring induction motor. The main difference in slip ring induction motor is on the rotor construction and usage. Some changes in the stator may be encountered when a slip ring motor is used in a cascaded system, as the supply for the slave motor is controlled by the supply from rotor of other slip ring motor with external resistance mounted on its rotor.

A wound-rotor motor is a type of induction motor where the rotor windings are connected through slip rings to external resistances. Adjusting the resistance allows control of the speed/torque characteristic of the motor. Wound-rotor motors can be started with low inrush current, by inserting high resistance into the rotor circuit; as the motor accelerates, the resistance can be decreased.

Compared to a squirrel-cage rotor, the rotor of the slip ring motor has more winding turns; the induced voltage is then higher, and the current lower, than for a squirrel-cage rotor. During the start-up a typical rotor has 3 poles connected to the slip ring. Each pole is wired in series with a variable power resistor. When the motor reaches full speed the rotor poles are switched to short circuit. During start-up the resistors reduce the field strength in the stator. As a result the inrush current is reduced. Another important advantage over squirrel-cage motors is higher start-up torque.

A wound-rotor motor can be used in several forms of adjustable-speed drive. Certain types of variable-speed drives recover slip-frequency power from the rotor circuit and feed it back to the supply, allowing wide speed range with high energy efficiency. Doubly fed electric machines use the slip rings to supply external power to the rotor circuit, allowing wide-range speed control. Today speed control by use of slip ring motor is mostly superseded by induction motors with variable-frequency drives.

Pump Repairs
Examining pump repair records and MTBF (mean time between failures) is of great importance to responsible and conscientious pump users. In view of that fact, the preface to the 2006 Pump User's Handbook alludes to "pump failure" statistics. For the sake of convenience, these failure statistics often are translated into MTBF (in this case, installed life before failure).

Unscheduled maintenance is often one of the most significant costs of ownership, and failures of mechanical seals and bearings are among the major causes. Keep in mind the potential value of selecting pumps that cost more initially, but last much longer between repairs. The MTBF of a better pump may be one to four years longer than that of its non-upgraded counterpart. Consider that published average values of avoided pump failures range from $2600 to $12,000. This does not include lost opportunity costs. One pump fire occurs per 1000 failures. Having fewer pump failures means having fewer destructive pump fires.

Electrical Motor Glossary

ALTERNATING CURRENT (AC) - A current which reverses in regularly recurring intervals of time and which has alternative positive and negative values, and occurring a specified number of times per second. The number is expressed in cycles per second or Hertz (Hz).

ALARM LIGHT - A light which is used to attract attention when a problem occurs in the system.

ALTERNATOR - A relay device designed for alternating the run cycle or duplexing action of two or more motors automatically. There are two basic types; one mechanically changes its contacts each time the operating coil is de-energized, and the second is a solid state unit with an output relay. The alternator is used in the automatic control circuit to the motor starters to rotate the duty cycle of each motor.

AMBIENT TEMPERATURE - Temperature of the surroundings in which the equipment is used or operated.

AMMETER - Meter for measuring the current in an electrical circuit, measured in amperes.

AMPERE - The unit of electric current flow. One ampere will flow when one volt is applied across a resistance of one ohm.

AUDIBLE ALARM - Horn, siren, bell, or buzzer which is used to attract the attention of the operator when a problem occurs in the system.

AUXILIARY CONTACTS - Contacts of a switching device in addition to the main current contacts that operate with the movement of the latter. They can be normally open (NO) or normally closed (NC) and change state when operated.

CAPACITOR - A device which introduces capacitance into an electrical circuit. The capacitor, when connected in an alternating current circuit, causes the current to lead the voltage in time phase. The peak of the current wave is reached ahead of the peak of the voltage wave. This is the result of the successive storage and discharge of electric energy.

CIRCUIT BREAKER - A mechanical switching device capable of making, carrying, and breaking currents under normal conditions. Also making, carrying for a specific time, and automatically breaking currents under specified abnormal circuit conditions, such as those of short circuit. Circuit breakers have an ampere trip rating for normal overload protection and a maximum magnetic ampere interrupting capacity (AIC) for short circuit protection.

COMMERCIAL POWER - The power furnished by an electric power utility.

CONDENSATION HEATER - A device that warms the air within an enclosure and prevents condensation of moisture during shut-down periods. Also known as a space heater.

CONDUCTOR - A wire, cable or bus bar designed for the passage of electrical current.

CONTACTOR - An electro-mechanical device that is operated by an electric coil and allows automatic or remote operation to repeatedly establish or interrupt an electrical power circuit. A contactor provides no overload protection as required for motor loads. Sometimes called a power relay.

CONTACTS - Devices for making and breaking electrical circuits, which are a part of all electrical switching devices.

CURRENT - The amount of electricity measured in amperes which is flowing in a circuit.

CYCLE - A given length of time (See Alternating Current). In the U.S., most electric current is 60 cycle (60 Hz).

CYCLE TIMER - A timer that repeatedly opens and closes contacts according to pre-set time cycles.

DELTA CONNECTION - A common three phase connection shaped schematically like the Greek Delta. The end of one phase is connected to the beginning of the next phase, or vice versa.

DESIGN LETTER - A letter that is shown on the motor nameplate indicating NEMA's classification of that motor. Classification encompasses characteristics such as full-voltage starting, locked rotor torque, breakdown torque, and others that determine electrical type.

DISCONNECTING MEANS (DISCONNECT) - A device or group of devices, or other means whereby all the ungrounded conductors of a circuit can be disconnected simultaneously from their source of supply.

ELAPSED TIME METER - An instrument used to record the amount of time each pump runs. One elapsed time meter is used per pump.

ELECTRIC UTILITIES - All enterprises engaged in the production and/or distribution of electricity for use by the public.

EMERGENCY POWER (ALTERNATE SOURCE OF POWER) - An independent reserve source of electric power which, upon failure or outage of the normal power source, provides stand-by electric power.

ENCLOSURE - The cabinet or specially designed box in which electrical controls and apparatus are housed. It is required by the National Electrical Code (NEC) to protect persons from live electrical parts and limit access to authorized personnel. It also provides mechanical and environmental protection. An enclosure should be designed to provide the required protection and sized to provide good, safe wire access and replacement of components. It can be manufactured of steel, galvanized or stainless steel, aluminum, or suitable non-metallic materials including fiberglass.

EXPLOSION-PROOF MOTOR - A motor in a special enclosure. The purpose of the enclosure is twofold:

  1) If an explosive vapor (gas) should explode inside the motor, the frame of the motor will not be affected.

  2) The enclosure is so constructed that no such explosion will ignite vapors outside the motor.

FACTORY MUTUAL (FM) - Independent U.S. agency associated with the insurance industry which tests for safety.

FREQUENCY - The number of complete cycles of an alternating voltage or current per unit of time and usually expressed in cycles per second or Hertz (Hz).

FULL LOAD CURRENT - The greatest current that a motor or other device is designed to carry under specific conditions; any additional is an overload.

FULL LOAD AMPS (FULL LOAD CURRENT) - The current flowing through a line terminal of a winding when rated voltage is applied at rated frequency with rated horsepower.

FUSE - An over-current protective device which consists of a conductor that melts and breaks when current exceeds rated value beyond a predetermined time.

GENERAL PURPOSE RELAY - A relay that is adaptable to a wide variety of applications as opposed to a relay designed for a specific purpose or specific application.

GENERATOR - A machine for converting mechanical energy into electrical energy or power.

GENERATOR RECEPTACLE - A contact device installed for the connection of a plug and flexible cord to supply emergency power from a portable generator or other alternate source of power. Receptacles are rated in voltage, amps, number of wires, and by enclosure type.

GROUND - A connection, either intentional or accidental, between an electric circuit and the earth or some conducting body serving in place of the earth.

GROUND FAULT INTERRUPTION (GFI) - A unit or combination of units which provides protection against ground fault currents below the trip levels of the breakers of a circuit. The system must be carefully designed and installed to sense low magnitude insulation breakdowns and other faults that cause a fault ground current path. The GFI system must be capable of sensing the ground fault current and disconnecting the faulted circuit from the source voltage.

GROUNDED NEUTRAL - The common neutral conductor of an electrical system which is intentionally connected to ground to provide a current carrying path for the line to neutral load devices.

GROUNDING CONDUCTOR - The conductor that is used to establish a ground and that connects equipment, a device, a wiring system, or another conductor (usually the neutral conductor) with the grounding electrode.

HAND-OFF-AUTOMATIC (HOA) - Selector switch determining the mode of system operation. H is the hand mode only. 0 is system Off. A is automatic operation, normally with pump alternation.

HAZARDOUS LOCATIONS - Those areas as defined in the NEC where a potential for explosion and fire exist because of flammable gasses, vapors, or finely pulverized dusts in the atmosphere, or because of the presence of easily ignitable fibers or flyings.

HERTZ (Hz) - A unit of frequency equal to one cycle per second.

HIGH POTENTIAL TEST - A test which consists of the application of a voltage higher than the rated voltage between windings and frame, or between two or more windings, for the purpose of determining the adequacy of insulating materials and spacing against breakdown under normal conditions. It is not the test of the conductor insulation of any one winding.

HORSEPOWER - A method of rating motors whereby values are determined by factors including rotational speed and torque producing capability as well as other factors.

IN-RUSH CURRENT - See Locked Rotor Current.

INTERLOCK - Interrelates with other controllers. An auxiliary contact. A device connected in such a way that the motion of one part is held back by another part.

INTRINSICALLY SAFE - A term used to define a level of safety associated with the electrical controls used in some lift stations. Intrinsically safe equipment and wiring is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a hazardous atmospheric mixture - without the need for explosion-proof enclosures in the hazardous area. Any associated devices must be outside the hazardous area with an approved seal-off fitting used as an isolating barrier.

KILOWATT (KW) - A unit of measure of electrical power. One kilowatt equals 1000 watts. Used where larger units of electrical power are measured.

LOCKED ROTOR CURRENT - (See Starting Amps).

LOCKOUT - A mechanical device which may be set to prevent the operation of a push-button or other device.

MANUAL TRANSFER SWITCH - A switch designed so that it will disconnect the load from one power source and reconnect it to another source while at no time allowing both sources to be connected to the load simultaneously.

MEGGER OR MEGOHMETER - A high resistance range ohmmeter utilizing a power source for measuring insulation resistance.

MEGOHM - A unit of resistance equal to one million ohms.

MOTOR CIRCUIT PROTECTOR - A molded case disconnect switch specifically designed for motor circuits. It has a trip unit that operates on the magnetic principle only, sensing current in each of the three poles with an adjustable trip point. It provides short circuit protection, required by the National Electrical Code (NEC). It differs from a standard breaker in that it does not have a thermal overload unit.

MOTOR EFFICIENCY - A measure of how effectively a motor converts electrical energy into mechanical energy. Motor efficiency is never 100 percent. It is a variable that depends on a given motor's performance. Tabulated at 100, 75 and 50 percent load, it is the ratio of power output to power input.

MOTOR, ELECTRIC - A rotating device which converts electrical power into mechanical power.

MOTOR HORSEPOWER RATING - The motor horsepower nameplate rating fully-loaded at the ambient temperature.

NEC - The National Electrical Code (NEC) is the standard of the National Board of Fire Underwriters for electric wiring and apparatus, as recommended by the National Fire Protection Association.

NEC CODE LETTER - Motors with 60 and 50 Hertz ratings shall be marked with a code letter designating the locked-rotor KVA per horsepower on 60 Hertz.

NEMA - National Electrical Manufacturers Association, a non-profit trade association supported by the manufacturers of electrical apparatus and supplies. NEMA promulgates standards to facilitate understanding between the manufacturers and users of electrical products.

NFPA - National Fire Protection Association. Sponsors and publishes the National Electrical Code (NEC).

NEUTRAL - The point common to all phases of a polyphase circuit, a conductor to that point, or the return conductor in a single phase circuit. The neutral in most systems is grounded at or near the point of service entrance only and becomes the grounded neutral.

NORMALLY OPEN and NORMALLY CLOSED - The terms "Normally Open" and "Normally Closed" when applied to a magnetically operated switching device - such as a contactor or relay, or to the contacts thereof - signify the position taken when the operating magnet is de-energized. These terms pertain to all switches.

OHM - Unit of electrical resistance. One volt will cause a current of one ampere to flow through a resistance of one ohm.

OHMMETER - A device for measuring electrical resistance expressed in ohms.

OVERLOAD PROTECTION - The effect of a device operative on excessive current, but not necessarily on short circuit, to cause and maintain the interruption of current flow to the device being governed. Re-set may be manual or automatic.

OVERLOAD RELAY - A relay that responds to electric load and operates at a pre-set value of overload. The unit senses the current in each line to the motor and is either bimetallic, melting alloy or solid state actuated. It may be of the non-compensated or ambient-compensated type, and of a standard or fast-trip design.

PHASE (THREE PHASE CIRCUIT) - A combination of circuits energized by alternating electromotive forces which differ in phase by one-third of a cycle (120 degrees). In practice, the phases may vary several degrees from the specified angle.

PHASE MONITOR - A device in the control circuit of motors which monitors the three phase voltage and protects against a phase loss (single phasing), under voltage (brown outs) and phase reversal (improper phase sequence). Most are adjustable to set the nominal voltage and some have a LED indicator to indicate acceptable voltage and phase conditions. The output contacts are used to control the motor starters and provide signaling for telemetering.

PILOT LIGHT - A lamp available with various colored lenses designed to operate on a control voltage. They are each turned On and Off to provide the required indication for specific functions or alarm conditions. They are available in various sizes and voltage ratings. They are each designed for a specific bulb style and base configuration and some have an integral transformer to allow the use of low voltage bulbs. Full voltage incandescent bulbs are most common, but neon bulbs are also used.

POWER FACTOR - The ratio of the true power to the volt-amperes in an alternating current circuit. Power factor is expressed in a percent of unity either lagging for inductive loads or leading for capacitive loads. Resistive loads produce a unity power factor.

PUSHBUTTON - Part of an electrical device, consisting of a button that must be pressed to effect an operation.

RATED VOLTAGE - The voltage of electrical apparatus at which it is designed to operate.

REDUCED VOLTAGE AUTO-TRANSFORMER STARTER - A starter that includes an auto-transformer to furnish reduced voltage for starting an alternating current motor. It includes the necessary switching mechanism. This is the most widely used reduced voltage starter because of its efficiency and flexibility.

RELAY - An electric device that is designed to interpret input conditions in a prescribed manner and, after specified conditions are met, to respond and cause contact operation or similar abrupt changes in associated electric control circuits.

RELAY, ELECTROMAGNETIC - A relay controlled by electromagnetic means, to open and close electric contacts.

RELAY, SOLID STATE - A completely electronic switching device with no moving parts or contacts.

RPM - Revolutions per minute of the motor/pump rotating assembly.

REMOTE CONTROL - Control function initiation or change of electrical device from a remote point.

RESISTANCE - The non-reactive opposition which a device or material offers to the flow of direct or alternating current. Usually measured in ohms.

SAFETY SWITCH - An enclosed, manually-operated disconnecting switch, which is horsepower and current rated. Disconnects all power lines simultaneously.

SEAL FAILURE ALARM - The sensing and indication of the intrusion of water into the oil-filled seal chamber between the inner and outer shaft seal of a submersible pump.

SELECTOR SWITCH - A multi-position switch which can be set to the desired mode of operation.

SERVICE FACTOR - A safety factor designed and built into some motors which allows the motor, when necessary, to deliver greater than its rated horsepower.

SINGLE PHASE - A circuit that differs in phase by 180 degrees. Single phase circuits have two conductors, one of which may be a neutral, or three conductors, one of which is neutral.

STANDBY POWER SUPPLY - The power supply that is available to furnish electric power when the normal power supply is not available.

STAR CONNECTION - Same as a "Y" or "Wye" connection. This three-phase connection is so called because, schematically, the joint of the "Y" points looks like a star.

STARTER - A device used to control the electrical power to motors and provide overload protection as required by the NEC. The starter can be operated manually, electrically, or by automatic pilot devices. A starter has two basic parts - a contactor for power switching and an overload relay for protection.

STARTING AMPS (LOCKED ROTOR) - The maximum current drawn by the motor during the starting period.

STARTING RELAY - A relay - actuated by current, voltage or the combined effect of current and voltage - which is used to perform a circuit-changing function in the primary winding of single phase induction motor within a pre-determined range of speed as the motor accelerates; and to perform the reverse circuit-changing operation when the motor is disconnected from the supply line. One of the circuit changes that is usually performed is to open or disconnect the auxiliary winding (starting) circuit.

SUBMERSIBLE MOTOR - A motor whose housing and terminal box is so designed that the motor can run underwater - completely submerged at an allowable temperature.

SURGE ARRESTER - A protective device for limiting surge voltages on equipment by discharging or bypassing surge current; it prevents continued flow of follow current to ground, and is capable of repeating these functions as specified.

SWITCH - A device for making, breaking, or changing connections in a circuit.

TELEMETERING - The transmitting of alarm and control signals to and from remote lift station controls and a central monitoring location.

TERMINAL BLOCK - An insulating base equipped with terminals for connecting wires.

THERMAL OVERLOAD PROTECTOR - Device, either a bimetal element or electric circuit, which protects motor windings from excessive temperature by opening a set of contacts. This device may reach its' pre-set trip point as a result of ambient temperature, current, or both. May be automatic or manually set.

THREE PHASE CIRCUIT - A combination of circuits energized by alternating electromotive sources which differ in phase by one third of a cycle - that is, 120 degrees. A three phase circuit may be three wires or four wires with the fourth wire being connected to the neutral point of the circuit which may be grounded.

TIME CLOCK - A device used to schedule electrical On/Off cycling operations. The device may be solid state or mechanical designed using a synchronous motor. The cycling operation must be programmed manually. The time clocks may operate in any increments of days, weeks, minutes, or hours.

TIME DELAY RELAY (TDR) - A device with either mechanical or solid state output contacts that performs a timing function upon energization or control signal.

TRANSDUCER - A device to condition and transform an analog signal to a specific variable output electrical signal proportional to the input signal. Typical inputs include variable pressure, level, voltage or current. Some common outputs are O to 1ma, 4 to 20 ma, and various MVDC signals. A transducer must be specifically designed to be compatible with the input/output requirements of the total system.

TRANSFORMER - A static electric device consisting of a single winding, or two or more coupled windings, used to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current.

UNDERWRITERS LABORATORIES, INC. (UL) - An independent, non-profit U.S. organization that tests products for safety.

VFD - Variable frequency drive.

VOLTAGE (NOMINAL A) - A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 120/240, 480/240, 600, etc.). The actual voltage at which a circuit operates can vary from the nominal within a range that permits satisfactory operation of equipment.

VOLTMETER - An instrument for measuring voltage.

WATT - A unit of measure of electrical power.

WYE CONNECTION - See Star Connection.

Hydraulic Principles Section

Definition **Hydraulics** is a branch of engineering concerned mainly with moving liquids. The term is applied commonly to the study of the mechanical properties of water, other liquids, and even gases when the effects of compressibility are small. Hydraulics can be divided into two areas, hydrostatics and hydrokinetics.

Hydraulics *The Engineering science pertaining to liquid pressure and flow.*
The word ***hydraulics*** is based on the Greek word for water, and originally covered the study of the physical behavior of water at rest and in motion. Use has broadened its meaning to include the behavior of all liquids, although it is primarily concerned with the motion of liquids.

Hydraulics includes the manner in which liquids act in tanks and pipes, deals with their properties, and explores ways to take advantage of these properties.

Hydrostatics, the consideration of liquids at rest, involves problems of buoyancy and flotation, pressure on dams and submerged devices, and hydraulic presses. The relative incompressibility of liquids is one of its basic principles.

Hydrodynamics, the study of liquids in motion, is concerned with such matters as friction and turbulence generated in pipes by flowing liquids, the flow of water over weirs and through nozzles, and the use of hydraulic pressure in machinery.

Hydrostatics
Hydrostatics is about the pressures exerted by a fluid at rest. Any fluid is meant, not just water. Research and careful study on water yields many useful results of its own, however, such as forces on dams, buoyancy and hydraulic actuation, and is well worth studying for such practical reasons.

Hydrostatics is an excellent example of deductive mathematical physics, one that can be understood easily and completely from a very few fundamentals, and in which the predictions agree closely with experiment.

There are few better illustrations of the use of the integral calculus, as well as the principles of ordinary statics, available to the student. A great deal can be done with only elementary mathematics. Properly adapted, the material can be used from the earliest introduction of school science, giving an excellent example of a quantitative science with many possibilities for hands-on experiences.

The definition of a fluid deserves careful consideration. Although time is not a factor in hydrostatics, it enters in the approach to hydrostatic equilibrium. It is usually stated that a fluid is a substance that cannot resist a shearing stress, so that pressures are normal to confining surfaces.

Geology has now shown us clearly that there are substances which can resist shearing forces over short time intervals, and appear to be typical solids, but which flow like liquids over long time intervals. Such materials include wax and pitch, ice, and even rock.

A ball of pitch, which can be shattered by a hammer, will spread out and flow in months. Ice, a typical solid, will flow in a period of years, as shown in glaciers, and rock will flow over hundreds of years, as in convection in the mantle of the earth.

Shear earthquake waves, with periods of seconds, propagate deep in the earth, though the rock there can flow like a liquid when considered over centuries. The rate of shearing may not be strictly proportional to the stress, but exists even with low stress.

Viscosity may be the physical property that varies over the largest numerical range, competing with electrical resistivity. There are several familiar topics in hydrostatics which often appears in expositions of introductory science, and which are also of historical interest and can enliven their presentation. Let's start our study with the principles of our atmosphere.
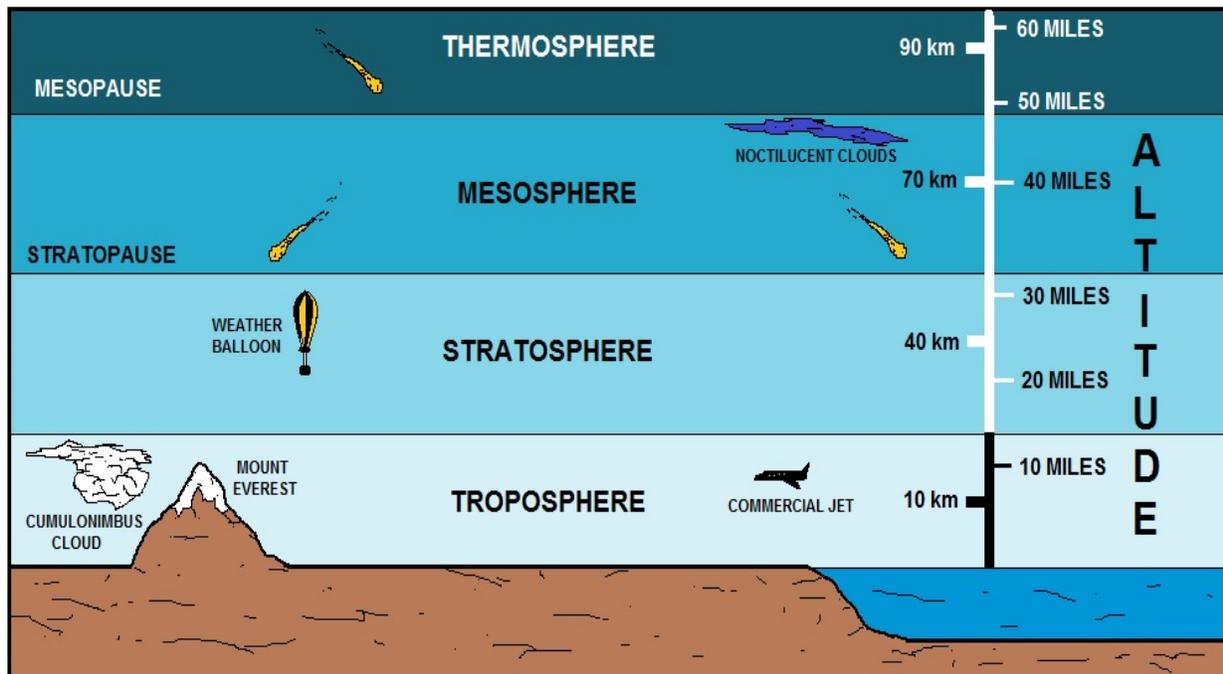
ATMOSPHERE DIAGRAM

Atmospheric Pressure

The atmosphere is the entire mass of air that surrounds the earth. While it extends upward for about 500 miles, the section of primary interest is the portion that rests on the earth's surface and extends upward for about 7 1/2 miles. This layer is called the troposphere.

If a column of air 1-inch square extending all the way to the "*top*" of the atmosphere could be weighed, this column of air would weigh approximately 14.7 pounds at sea level. Thus, atmospheric pressure at sea level is approximately 14.7 psi.

As one ascends, the atmospheric pressure decreases by approximately 1.0 psi for every 2,343 feet. However, below sea level, in excavations and depressions, atmospheric pressure increases. Pressures under water differ from those under air only because the weight of the water must be added to the pressure of the air.

Atmospheric pressure can be measured by any of several methods. The common laboratory method uses the mercury column barometer. The height of the mercury column serves as an indicator of atmospheric pressure. At sea level and at a temperature of 0° Celsius (**C**), the height of the mercury column is approximately 30 inches, or 76 centimeters. This represents a pressure of approximately 14.7 psi. The 30-inch column is used as a reference standard.

Another device used to measure atmospheric pressure is the aneroid barometer. The aneroid barometer uses the change in shape of an evacuated metal cell to measure variations in atmospheric pressure. The thin metal of the aneroid cell moves in or out with the variation of pressure on its external surface. This movement is transmitted through a system of levers to a pointer, which indicates the pressure.

The atmospheric pressure does not vary uniformly with altitude. It changes very rapidly. Atmospheric pressure is defined as the force per unit area exerted against a surface by the weight of the air above that surface.

In the diagram, the pressure at point "**X**" increases as the weight of the air above it increases. The same can be said about decreasing pressure, where the pressure at point "**X**" decreases if the weight of the air above it also decreases.

Top of the Atmosphere

Weight of the air in the column applies a pressure to point "X"

Surface

Unit Area
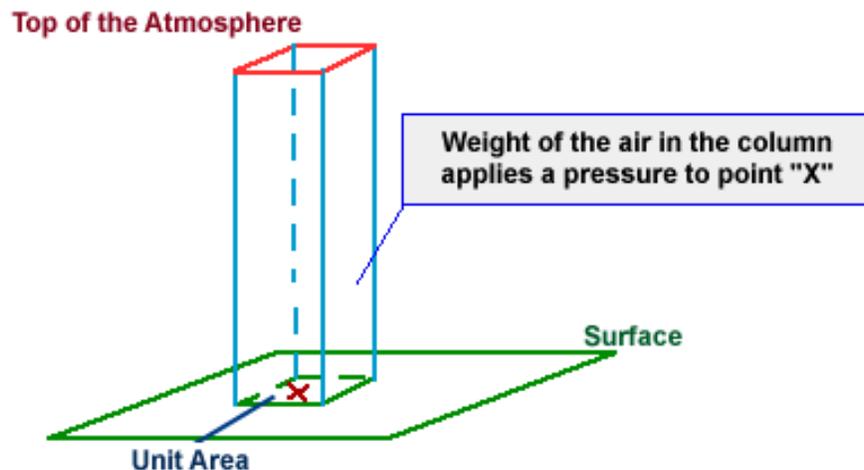
Barometric Loop

The barometric loop consists of a continuous section of supply piping that abruptly rises to a height of approximately 35 feet and then returns back down to the originating level. It is a loop in the piping system that effectively protects against backsiphonage. It may not be used to protect against back-pressure.

Its operation, in the protection against backsiphonage, is based upon the principle that a water column, at sea level pressure, will not rise above 33.9 feet.

In general, barometric loops are locally fabricated, and are 35 feet high.

Pressure may be referred to using an absolute scale, pounds per square inch absolute (**psia**), or gauge scale, (**psiag**). Absolute pressure and gauge pressure are related.

Absolute pressure is equal to gauge pressure plus the atmospheric pressure. At sea level, the atmospheric pressure is 14.7 psai.

Absolute pressure is the total pressure.

Gauge pressure is simply the pressure read on the gauge. If there is no pressure on the gauge other than atmospheric, the gauge will read zero. Then the absolute pressure would be equal to 14.7 psi, which is the atmospheric pressure.
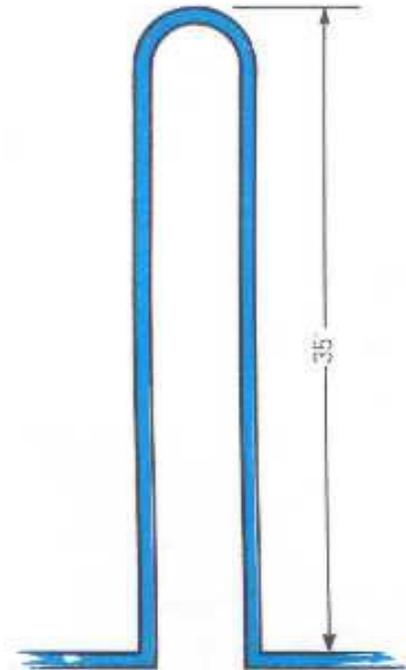
UNIT	ABBREVIATION	EQUIVALENT NUMBER OF PASCALS
ATMOSPHERE	atm	1 atm = 101,325 Pa
BAR	bar	1 bar = 100,025 Pa
MILLIMETER OF MERCURY	mmHg	1 mmHg = 133.322 Pa
INCHES OF MERCURY	inHg	1 inHg = 3386 Pa
PASCAL	Pa	1
KILOPASCAL	kPa	1 kPa = 1000 Pa
POUNDS PER SQUARE INCH	psi	1 psi = 6,893 Pa
TORR	torr	1 torr = 133.322 Pa

DIFFERENT UNITS OF PRESSURE

Pressure

By a fluid, we have a material in mind like water or air, two very common and important fluids. Water is incompressible, while air is very compressible, but both are fluids. Water has a definite volume; air does not. Water and air have low viscosity; that is, layers of them slide very easily on one another, and they quickly assume their permanent shapes when disturbed by rapid flows. Other fluids, such as molasses, may have high viscosity and take a long time to come to equilibrium, but they are no less fluids. The coefficient of viscosity is the ratio of the shearing force to the velocity gradient. Hydrostatics deals with permanent, time-independent states of fluids, so viscosity does not appear, except as discussed in the Introduction.
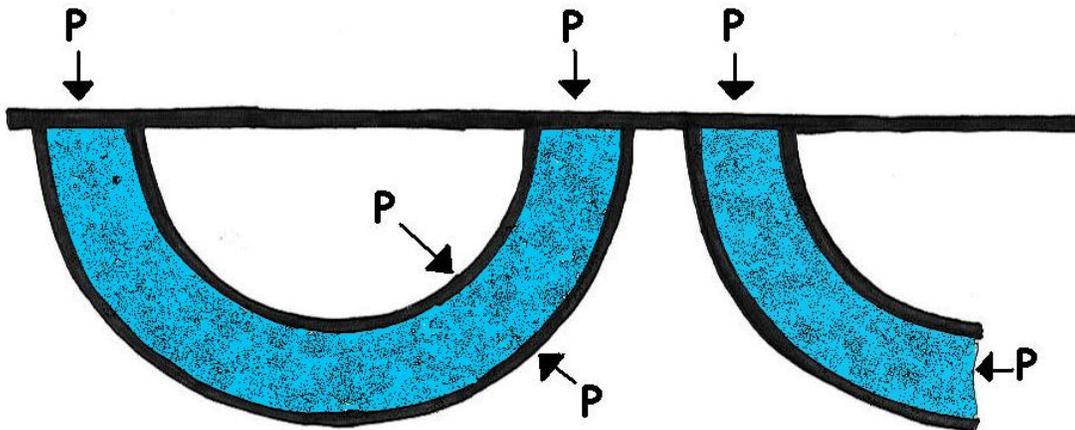
EQUALITY OF PRESSURE

A fluid, therefore, is a substance that cannot exert any permanent forces tangential to a boundary. Any force that it exerts on a boundary must be normal to the boundary. Such a force is proportional to the area on which it is exerted, and is called a pressure. We can imagine any surface in a fluid as dividing the fluid into parts pressing on each other, as if it were a thin material membrane, and so think of the pressure at any point in the fluid, not just at the boundaries. In order for any small element of the fluid to be in equilibrium, the pressure must be the same in all directions (or the element would move in the direction of least pressure), and if no other forces are acting on the body of the fluid, the pressure must be the same at all neighboring points.

Therefore, in this case the pressure will be the same throughout the fluid, and the same in any direction at a point (Pascal's Principle). Pressure is expressed in units of force per unit area such as $dyne/cm^2$, N/cm^2 (pascal), $pounds/in^2$ (psi) or $pounds/ft^2$ (psf). The axiom that if a certain volume of fluid were somehow made solid, the equilibrium of forces would not be disturbed, is useful in reasoning about forces in fluids.

On earth, fluids are also subject to the force of gravity, which acts vertically downward, and has a magnitude $\gamma = \rho g$ per unit volume, where g is the acceleration of gravity, approximately 981 cm/s^2 or 32.15 ft/s^2, ρ is the density, the mass per unit volume, expressed in g/cm^3, kg/m^3, or $slug/ft^3$, and γ is the specific weight, measured in lb/in^3, or lb/ft^3 (pcf).

Gravitation is an example of a body force that disturbs the equality of pressure in a fluid. The presence of the gravitational body force causes the pressure to increase with depth, according to the equation dp = ρg dh, in order to support the water above. We call this relation the barometric equation, for when this equation is integrated, we find the variation of pressure with height or depth. If the fluid is incompressible, the equation can be integrated at once, and the pressure as a function of depth h is p = ρgh + p0.

Free Surface

The density of water is about 1 g/cm^3, or its specific weight is 62.4 pcf. We may ask what depth of water gives the normal sea-level atmospheric pressure of 14.7 psi, or 2117 psf.

This is simply 2117 / 62.4 = 33.9 ft of water. This is the maximum height to which water can be raised by a suction pump, or, more correctly, can be supported by atmospheric pressure. Professor James Thomson (brother of William Thomson, Lord Kelvin) illustrated the equality of pressure by a "curtain-ring" analogy shown in the diagram.

A section of the toroid was identified, imagined to be solidified, and its equilibrium was analyzed.

The forces exerted on the curved surfaces have no component along the normal to a plane section, so the pressures at any two points of a plane must be equal, since the fluid represented by the curtain ring was in equilibrium.

P_1

pgh

h

P_2
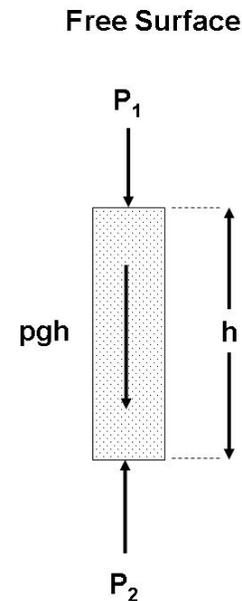
Increase of Pressure with Depth

The diagram illustrates the equality of pressures in orthogonal directions. This can be extended to any direction whatever, so Pascal's Principle is established. This demonstration is similar to the usual one using a triangular prism and considering the forces on the end and lateral faces separately.
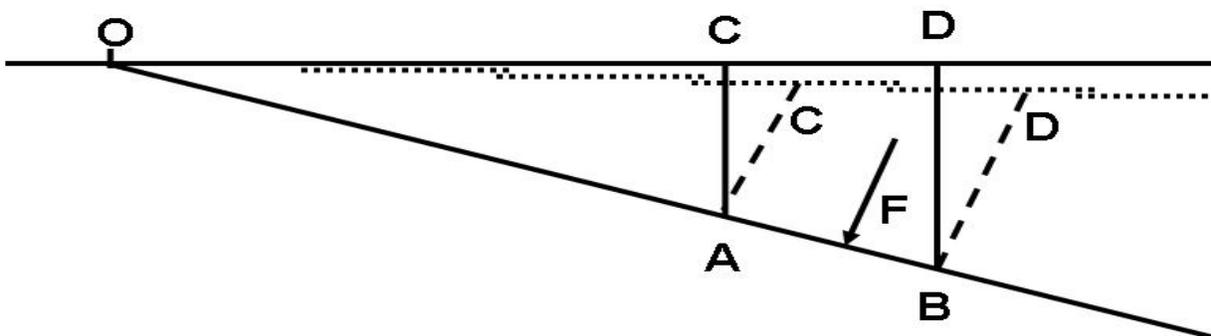
Thrust on a Plane

Free Surface Perpendicular to Gravity

When gravity acts, the liquid assumes a free surface perpendicular to gravity, which can be proved by Thomson's method. A straight cylinder of unit cross-sectional area (assumed only for ease in the arithmetic) can be used to find the increase of pressure with depth. Indeed, we see that $p2 = p1 + \rho gh$. The upper surface of the cylinder can be placed at the free surface if desired. The pressure is now the same in any direction at a point, but is greater at points that lie deeper. From this same figure, it is easy to prove Archimedes' Principle that the buoyant force is equal to the weight of the displaced fluid, and passes through the center of mass of this displaced fluid.

Geometric Arguments

Ingenious geometric arguments can be used to substitute for easier, but less transparent arguments using calculus. For example, the force acting on one side of an inclined plane surface whose projection is AB can be found as in the diagram on the previous page. O is the point at which the prolonged projection intersects the free surface. The line AC' perpendicular to the plane is made equal to the depth AC of point A, and line BD' is similarly drawn equal to BD. The line OD' also passes through C', by proportionality of triangles OAC' and OAD'. Therefore, the thrust F on the plane is the weight of a prism of fluid of cross-section AC'D'B, passing through its centroid normal to plane AB. Note that the thrust is equal to the density times the area times the depth of the center of the area; its line of action does not pass through the center, but below it, at the center of thrust. The same result can be obtained with calculus by summing the pressures and the moments.


Barometer
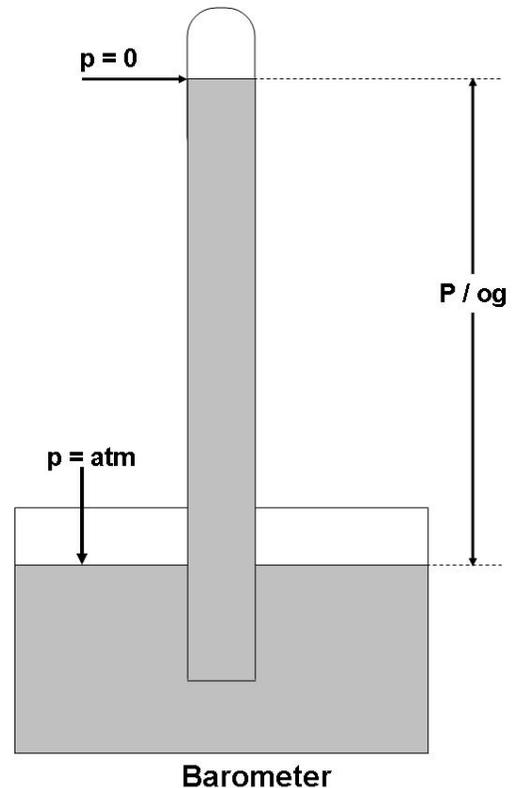
Atmospheric Pressure and its Effects

Suppose a vertical pipe is stood in a pool of water, and a vacuum pump applied to the upper end. Before we start the pump, the water levels outside and inside the pipe are equal, and the pressures on the surfaces are also equal and are equal to the atmospheric pressure.

Now start the pump. When it has sucked all the air out above the water, the pressure on the surface of the water inside the pipe is zero, and the pressure at the level of the water on the outside of the pipe is still the atmospheric pressure.

Of course, there is the vapor pressure of the water to worry about if you want to be precise, but we neglect this complication in making our point. We require a column of water 33.9 ft high inside the pipe, with a vacuum above it, to balance the atmospheric pressure. Now do the same thing with liquid mercury, whose density at 0 °C is 13.5951 times that of water. The height of the column is 2.494 ft, 29.92 in, or 760.0 mm.

Standard Atmospheric Pressure

This definition of the standard atmospheric pressure was established by Regnault in the mid-19th century. In Britain, 30 in. Hg (inches of mercury) had been used previously. As a practical matter, it is convenient to measure pressure differences by measuring the height of liquid columns, a practice known as manometry. The barometer is a familiar example of this, and atmospheric pressures are traditionally given in terms of the length of a mercury column. To make a barometer, the barometric tube, closed at one end, is filled with mercury and then inverted and placed in a mercury reservoir. Corrections must be made for temperature, because the density of mercury depends on the temperature, and the brass scale expands for capillarity if the tube is less than about 1 cm in diameter, and even slightly for altitude, since the value of g changes with altitude.

The vapor pressure of mercury is only 0.001201 mmHg at 20°C, so a correction from this source is negligible. For the usual case of a mercury column (α = 0.000181792 per °C) and a brass scale (&alpha = 0.0000184 per °C) the temperature correction is -2.74 mm at 760 mm and 20°C. Before reading the barometer scale, the mercury reservoir is raised or lowered until the surface of the mercury just touches a reference point, which is mirrored in the surface so it is easy to determine the proper position.
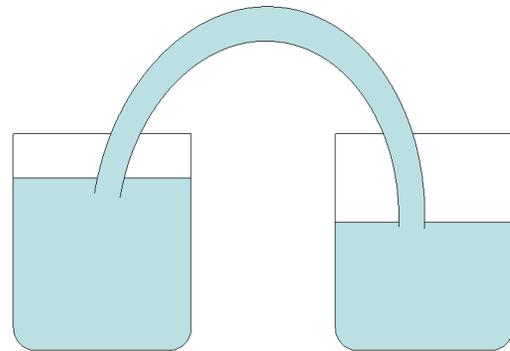
Siphon

An aneroid barometer uses a partially evacuated chamber of thin metal that expands and contracts according to the external pressure. This movement is communicated to a needle that revolves in a dial. The materials and construction are arranged to give a low temperature coefficient. The instrument must be calibrated before use, and is usually arranged to read directly in elevations. An aneroid barometer is much easier to use in field observations, such as in reconnaissance surveys. In a particular case, it would be read at the start of the day at the base camp, at various points in the vicinity, and then finally at the starting point, to determine the change in pressure with time. The height differences can be calculated from h = 60,360 log (P/p) [1 + (T + t - 64)/986) feet, where P and p are in the same units, and T, t are in °F.

An absolute pressure is referring to a vacuum, while a gauge pressure is referring to the atmospheric pressure at the moment. A negative gauge pressure is a (partial) vacuum. When a vacuum is stated to be so many inches, this means the pressure below the atmospheric pressure of about 30 in. A vacuum of 25 inches is the same thing as an absolute pressure of 5 inches (of mercury).

Vacuum

The term *vacuum* indicates that the absolute pressure is less than the atmospheric pressure and that the gauge pressure is negative. A complete or total vacuum would mean a pressure of 0 psia or –14.7 psig. Since it is impossible to produce a total vacuum, the term vacuum, as used in this document, will mean all degrees of partial vacuum. In a partial vacuum, the pressure would range from slightly less than 14.7 psia (0 psig) to slightly greater than 0 psia (-14.7 psig). Backsiphonage results from atmospheric pressure exerted on a liquid, forcing it toward a supply system that is under a vacuum.

Water Pressure

The weight of a cubic foot of water is 62.4 pounds per square foot. The base can be subdivided into 144-square inches with each subdivision being subjected to a pressure of 0.433 psig. Suppose you placed another cubic foot of water on top of the first cubic foot. The pressure on the top surface of the first cube which was originally atmospheric, or 0 psig, would now be 0.4333 psig as a result of the additional cubic foot of water. The pressure of the base of the first cubic foot would be increased by the same amount of 0.866 psig or two times the original pressure.

Pressures are very frequently stated in terms of the height of a fluid. If it is the same fluid whose pressure is being given, it is usually called "head," and the factor connecting the head and the pressure is the weight density ρg. In the English engineer's system, weight density is in pounds per cubic inch or cubic foot. A head of 10 ft is equivalent to a pressure of 624 psf, or 4.33 psi. It can also be considered an energy availability of ft-lb per lb. Water with a pressure head of 10 ft can furnish the same energy as an equal amount of water raised by 10 ft. Water flowing in a pipe is subject to head loss because of friction.

Take a jar and a basin of water. Fill the jar with water and invert it under the water in the basin. Now raise the jar as far as you can without allowing its mouth to come above the water surface. It is always a little surprising to see that the jar does not empty itself, but the water remains with no visible means of support. By blowing through a straw, one can put air into the jar, and as much water leaves as air enters. In fact, this is a famous method of collecting insoluble gases in the chemical laboratory, or for supplying hummingbird feeders. It is good to remind oneself of exactly the balance of forces involved.

Another application of pressure is the siphon. The name is Greek for the tube that was used for drawing wine from a cask. This is a tube filled with fluid connecting two containers of fluid, normally rising higher than the water levels in the two containers, at least to pass over their rims.

In the diagram, the two water levels are the same, so there will be no flow. When a siphon goes below the free water levels, it is called an inverted siphon. If the levels in the two basins are not equal, fluid flows from the basin with the higher level into the one with the lower level, until the levels are equal.
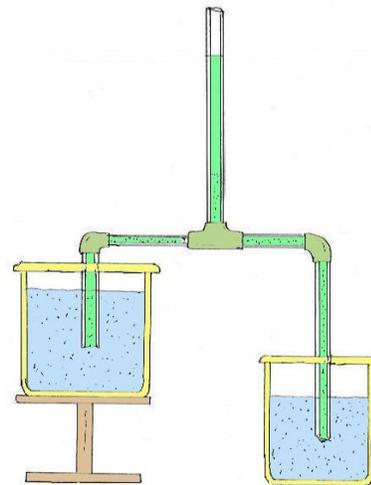
PASCAL'S SIPHON

A siphon can be made by filling the tube, closing the ends, and then putting the ends under the surface on both sides. Alternatively, the tube can be placed in one fluid and filled by sucking on it. When it is full, the other end is put in place. The analysis of the siphon is easy, and should be obvious. The pressure rises or falls as described by the barometric equation through the siphon tube.

There is obviously a maximum height for the siphon which is the same as the limit of the suction pump, about 34 feet. Inverted siphons are sometimes used in pipelines to cross valleys. Differences in elevation are usually too great to use regular siphons to cross hills, so the fluids must be pressurized by pumps so the pressure does not fall to zero at the crests.

Liquids at Rest

In studying fluids at rest, we are concerned with the transmission of force and the factors which affect the forces in liquids. Additionally, pressure in and on liquids and factors affecting pressure are of great importance.

Pressure and Force

Pressure is the force that pushes water through pipes. Water pressure determines the flow of water from the tap. If pressure is not sufficient then the flow can reduce to a trickle and it will take a long time to fill a kettle or a cistern.

The terms *force* and *pressure* are used extensively in the study of fluid power. It is essential that we distinguish between the terms.

Force means a total push or pull. It is the push or pull exerted against the total area of a particular surface and is expressed in pounds or grams. Pressure means the amount of push or pull (force) applied to each unit area of the surface and is expressed in pounds per square inch (lb/in^2) or grams per square centimeter (gm/cm^2). Pressure maybe exerted in one direction, in several directions, or in all directions.

Computing Force, Pressure, and Area

A formula is used in computing force, pressure, and area in fluid power systems. In this formula, P refers to pressure, F indicates force, and A represents area. Force equals pressure times area. Thus, the formula is written:

$$A = \frac{F}{P}$$

$$F = A \cdot P$$

Development of Hydraulics

Although the modern development of hydraulics is comparatively recent, the ancients were familiar with many hydraulic principles and their applications. The Egyptians and the ancient people of Persia, India, and China conveyed water along channels for irrigation and domestic purposes, using dams and sluice gates to control the flow. The ancient Cretans had an elaborate plumbing system. Archimedes studied the laws of floating and submerged bodies. The Romans constructed aqueducts to carry water to their cities.

After the breakup of the ancient world, there were few new developments for many centuries. Then, over a comparatively short period, beginning near the end of the seventeenth century, Italian physicist, Evangelista Torricelle, French physicist, Edme Mariotte, and later, Daniel Bernoulli conducted experiments to study the elements of force in the discharge of water through small openings in the sides of tanks and through short pipes. During the same period, Blaise Pascal, a French scientist, discovered the fundamental law for the science of hydraulics. Pascal's law states that increase in pressure on the surface of a confined fluid is transmitted undiminished throughout the confining vessel or system.

For Pascal's law to be made effective for practical applications, it was necessary to have a piston that "fit exactly." It was not until the latter part of the eighteenth century that methods were found to make these snugly fitted parts required in hydraulic systems.

This was accomplished by the invention of machines that were used to cut and shape the necessary closely fitted parts and, particularly, by the development of gaskets and packings. Since that time, components such as valves, pumps, actuating cylinders, and motors have been developed and refined to make hydraulics one of the leading methods of transmitting power.

Liquids are almost incompressible. For example, if a pressure of 100 pounds per square inch (**psi**) is applied to a given volume of water that is at atmospheric pressure, the volume will decrease by only 0.03 percent. It would take a force of approximately 32 tons to reduce its volume by 10 percent; however, when this force is removed, the water immediately returns to its original volume. Other liquids behave in about the same manner as water.

Another characteristic of a liquid is the tendency to keep its free surface level. If the surface is not level, liquids will flow in the direction which will tend to *make* the surface level.

Evangelista Torricelli

Evangelista Torricelli (1608-1647), Galileo's student and secretary and a member of the Florentine Academy of Experiments, invented the mercury barometer in 1643, and brought the weight of the atmosphere to light. The mercury column was held up by the pressure of the atmosphere, not by horror vacui as Aristotle had supposed. Torricelli's early death was a blow to science, but his ideas were furthered by Blaise Pascal (1623-1662).

Pascal had a barometer carried up the 1465 m high Puy de Dôme, an extinct volcano in the Auvergne just west of his home of Clermont-Ferrand in 1648 by Périer, his brother-in-law. Pascal's experimentum crucis is one of the triumphs of early modern science. The Puy de Dôme is not the highest peak in the Massif Central--the Puy de Sancy, at 1866 m is, but it was the closest. Clermont is now the center of the French pneumatics industry.

Burgomeister of Magdeburg

The remarkable Otto von Guericke (1602-1686), Burgomeister of Magdeburg, Saxony, took up the cause, making the first vacuum pump, which he used in vivid demonstrations of the pressure of the atmosphere to the Imperial Diet at Regensburg in 1654. Famously, he evacuated a sphere consisting of two well-fitting hemispheres about a foot in diameter, and showed that 16 horses, 8 on each side, could not pull them apart. An original vacuum pump and hemispheres from 1663 are shown at the right (photo edited from the Deutsches Museum; see on right). He also showed that air had weight, and how much force it did require to separate evacuated hemispheres. Then, in England, Robert Hooke (1635-1703) made a vacuum pump for Robert Boyle (1627-1691). Christian Huygens (1629-1695) became interested in a visit to London in 1661 and had a vacuum pump built for him. By this time, Torricelli's doctrine had triumphed over the Church's support for horror vacui. This was one of the first victories for rational physics over the illusions of experience, and is well worth consideration.

Pascal demonstrated that the siphon worked by atmospheric pressure, not by horror vacui. The two beakers of mercury are connected by a three-way tube as shown, with the upper branch open to the atmosphere. As the large container is filled with water, pressure on the free surfaces of the mercury in the beakers pushes mercury into the tubes. When the state shown is reached, the beakers are connected by a mercury column, and the siphon starts, emptying the upper beaker and filling the lower. The mercury has been open to the atmosphere all this time, so if there were any horror vacui, it could have flowed in at will to soothe itself.

Torr

The mm of mercury is sometimes called a torr after Torricelli, and Pascal also has been honored by a unit of pressure, a newton per square meter or 10 dyne/cm2. A cubic centimeter of air weighs 1.293 mg under standard conditions, and a cubic meter 1.293 kg, so air is by no means even approximately weightless, though it seems so. The weight of a sphere of air as small as 10 cm in diameter is 0.68 g, easily measurable with a chemical balance. The pressure of the atmosphere is also considerable, like being 34 ft under water, but we do not notice it. A bar is 106 dyne/cm2, very close to a standard atmosphere, which is 1.01325 bar. In meteorology, the millibar, mb, is used. 1 mb = 1.333 mmHg = 100 Pa = 1000 dyne/cm2.

A kilogram-force per square centimeter is 981,000 dyne/cm2, also close to one atmosphere. In Europe, it has been considered approximately 1 atm, as in tire pressures and other engineering applications. As we have seen, in English units the atmosphere is about 14.7 psi, and this figure can be used to find other approximate equivalents.

For example, 1 psi = 51.7 mmHg. In Britain, tons per square inch has been used for large pressures. The ton in this case is 2240 lb, not the American short ton. 1 tsi = 2240 psi, 1 tsf = 15.5 psi (about an atmosphere!).The fluid in question here is air, which is by no means incompressible. As we rise in the atmosphere and the pressure decreases, the air also expands.

To see what happens in this case, we can make use of the ideal gas equation of state, $p = \rho RT/M$,

and assume that the temperature T is constant. Then the change of pressure in a change of altitude dh is $dp = -\rho g\, dh = -(pM/RT)\, gdh$, or $dp/p = -(Mg/RT)\, dh$.

This is a little harder to integrate than before, but the result is $\ln p = -Mgh/RT + C$, or $\ln (p/p_0) = -Mgh/RT$, or finally $p = p_0 \exp(-Mgh/RT)$.

In an isothermal atmosphere, the pressure decreases exponentially. The quantity $H = RT/Mg$ is called the "height of the homogeneous atmosphere" or the scale height, and is about 8 km at T = 273K.

This quantity gives the rough scale of the decrease of pressure with height. Of course, the real atmosphere is by no means isothermal close to the ground, but cools with height nearly linearly at about 6.5°C/km up to an altitude of about 11 km at middle latitudes, called the tropopause.

Above this is a region of nearly constant temperature, the stratosphere, and then at some higher level the atmosphere warms again to near its value at the surface. Of course, there are variations from the average values. When the temperature profile with height is known, we can find the pressure by numerical integration quite easily.

Meteorology

The atmospheric pressure is of great importance in meteorology, since it determines the winds, which generally move at right angles to the direction of the most rapid change of pressure, that is, along the isobars, which are contours of constant pressure. Certain typical weather patterns are associated with relatively high and relatively low pressures, and how they vary with time. The barometric pressure may be given in popular weather forecasts, though few people know what to do with it. If you live at a high altitude, your local weather reporter may report the pressure to be, say, 29.2 inches, but if you have a real barometer, you may well find that it is closer to 25 inches. At an elevation of 1500 m (near Denver, or the top of the Puy de Dôme), the atmospheric pressure is about 635 mm, and water boils at 95 °C.

In fact, altitude is quite a problem in meteorology, since pressures must be measured at a common level to be meaningful.

The barometric pressures quoted in the news are reduced to sea level by standard formulas that amount to assuming that there is a column of air from your feet to sea level with a certain temperature distribution, and adding the weight of this column to the actual barometric pressure. This is only an arbitrary 'fix' and leads to some strange conclusions, such as the permanent winter highs above high plateaus that are really imaginary.
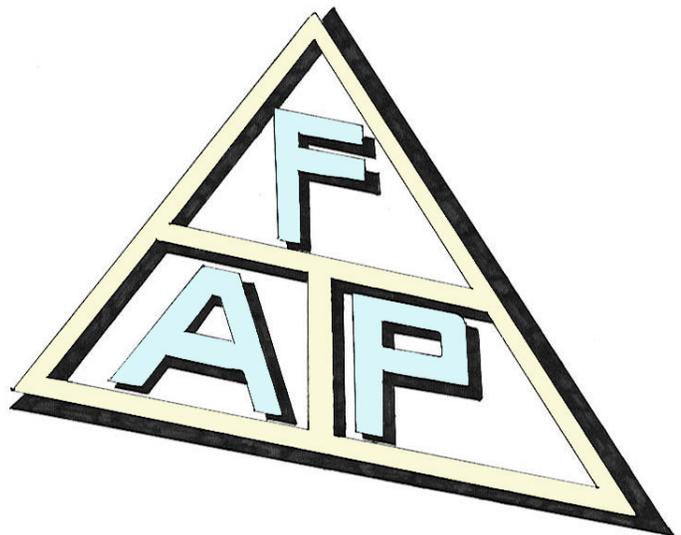
The Hydraulic Lever

A cylinder and piston is a chamber of variable volume, a mechanism for transforming pressure to force.

If A is the area of the cylinder, and p the pressure of the fluid in it, then F = pA is the force on the piston. If the piston moves outwards a distance dx, then the change in volume is dV = A dx.
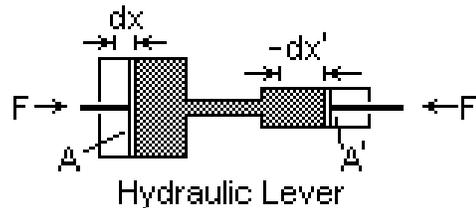
The work done by the fluid in this displacement is dW = F dx = pA dx = p dV. If the movement is slow enough that inertia and viscosity forces are negligible, then hydrostatics will still be valid. A process for which this is true is called quasi-static. Now consider two cylinders, possibly of different areas A and A', connected with each other and filled with fluid. For simplicity, suppose that there are no gravitational forces.

Then the pressure is the same, p, in both cylinders. If the fluid is incompressible, then dV + dV' = 0, so that dW = p dV + p dV' = F dx + F' dx' = 0. This says the work done on one piston is equal to the work done by the other piston: the conservation of energy. The ratio of the forces on the pistons is F' / F = A' / A, the same as the ratio of the areas, and the ratios of the displacements dx' / dx = F / F' = A / A' is in the inverse ratio of the areas. This mechanism is the hydrostatic analogue of the lever, and is the basis of hydraulic activation.

Bramah Hydraulic Press

The most famous application of this principle is the Bramah hydraulic press, invented by Joseph Bramah (1748-1814), who also invented many other useful machines, including a lock and a toilet. Now, it was not very remarkable to see the possibility of a hydraulic press; what was remarkable was to find a way to seal the large cylinder properly.

This was the crucial problem that Bramah solved by his leather seal that was held against the cylinder and the piston by the hydraulic pressure itself. In the presence of gravity, p' = p + ρgh, where h is the difference in elevation of the two cylinders. Now, p' dV' = -dV (p + ρgh) =-p dV - (ρ dV) gh, or the net work done in the process is p' dV' + p dV = -dM gh, where dM is the mass of fluid displaced from the lower cylinder to the upper cylinder.

Again, energy is conserved if we take into account the potential energy of the fluid. Pumps are seen to fall within the province of hydrostatics if their operation is quasi-static, which means that dynamic or inertia forces are negligible.

Pumps

Pumps are used to move or raise fluids. They are not only very useful, but are excellent examples of hydrostatics. Pumps are of two general types, hydrostatic or positive displacement pumps, and pumps depending on dynamic forces, such as centrifugal pumps. Here we will only consider positive displacement pumps, which can be understood purely by hydrostatic considerations. They have a piston (or equivalent) moving in a closely-fitting cylinder and forces are exerted on the fluid by motion of the piston. We have already seen an important example of this in the hydraulic lever or hydraulic press, which we have called quasi-static.
The simplest pump is the syringe, filled by withdrawing the piston and emptied by pressing it back in, as its port is immersed in the fluid or removed from it. More complicated pumps have valves

allowing them to work repetitively. These are usually check valves that open to allow passage in one direction, and close automatically to prevent reverse flow. There are many kinds of valves, and they are usually the most trouble-prone and complicated part of a pump. The force pump has two check valves in the cylinder, one for supply and the other for delivery. The supply valve opens when the cylinder volume increases, the delivery valve when the cylinder volume decreases.

The lift pump has a supply valve and a valve in the piston that allows the liquid to pass around it when the volume of the cylinder is reduced. The delivery in this case is from the upper part of the cylinder which the piston does not enter. Diaphragm pumps are force pumps in which the oscillating diaphragm takes the place of the piston. The diaphragm may be moved mechanically, or by the pressure of the fluid on one side of the diaphragm.

Some positive displacement pumps are shown below. The force and lift pumps are typically used for water. The force pump has two valves in the cylinder, while the lift pump has a one valve in the cylinder and one in the piston.

The maximum lift, or "suction," is determined by the atmospheric pressure, and either cylinder must be within this height of the free surface. The force pump, however, can give an arbitrarily large pressure to the discharged fluid, as in the case of a diesel engine injector.

POSITIVE DISPLACEMENT PUMPS

ROOTS BLOWER

BICYCLE PUMP

BELLOWS PUMP

LIFT PUMP

A nozzle can be used to convert the pressure to velocity, to produce a jet, as for firefighting.

Fire fighting force pumps usually have two cylinders feeding one receiver alternately. The air space in the receiver helps to make the water pressure uniform.

The three pumps on the right are typically used for air, but would be equally applicable to liquids. The Roots blower has no valves, their place taken by the sliding contact between the rotors and the housing.

The Roots blower can either exhaust a receiver or provide air under moderate pressure, in large volumes. The bellows is a very old device, requiring no accurate machining. The single valve is in one or both sides of the expandable chamber.
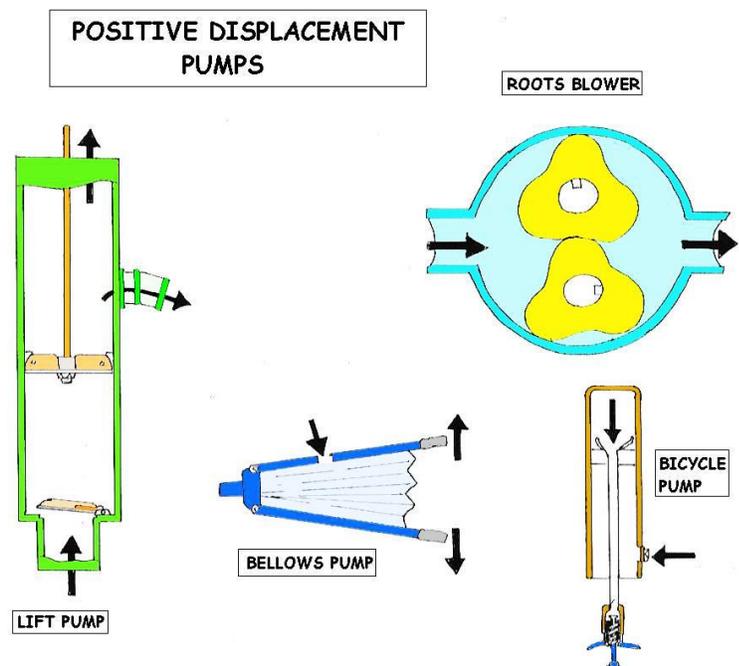
Dudley Castle Engine

The first engine may have been erected in Cornwall in 1710, but the Dudley Castle engine of 1712 is much better known and thoroughly documented. The first pumps used in Cornwall were called bucket pumps, which we recognize as lift pumps, with the pistons somewhat miscalled buckets. They pumped on the up-stroke, when a clack in the bottom of the pipe opened and allowed water to enter beneath the piston. At the same time, the piston lifted the column of water above it, which could be of any length. The piston could only "suck" water 33 ft, or 28 ft more practically, of course, but this occurred at the bottom of the shaft, so this was only a limit on the piston stroke. On the down stroke, a clack in the bucket opened, allowing it to sink through the water to the bottom, where it would be ready to make another lift. More satisfactory were the plunger pumps, also placed at the bottom of the shaft. A plunger displaced volume in a chamber, forcing the water in it through a check valve up the shaft, when it descended. When it rose, water entered the pump chamber through a clack, as in the bucket pump.

Only the top of the plunger had to be packed; it was not necessary that it fit the cylinder accurately. In this case, the engine at the surface lifted the heavy pump rods on the up-stroke. When the atmospheric engine piston returned, the heavy timber pump rods did the actual pumping, borne down by their weight. A special application for pumps is to produce a vacuum by exhausting a container, called the receiver.

VACUUM PUMPS

HAWKSBEE'S AIR PUMP

TATE'S AIR PUMP

SPRENGEL'S PUMP

Hawksbee's Dual Cylinder Pump

Hawksbee's dual cylinder pump, designed in the 18th century, is the final form of the air pump invented by Guericke by 1654. A good pump could probably reach about 5-10 mmHg, the limit set by the valves. The cooperation of the cylinders made the pump much easier to work when the pressure was low. In the diagram, piston A is descending, helped by the partial vacuum remaining below it, while piston B is rising, filling with the low-pressure air from the receiver.
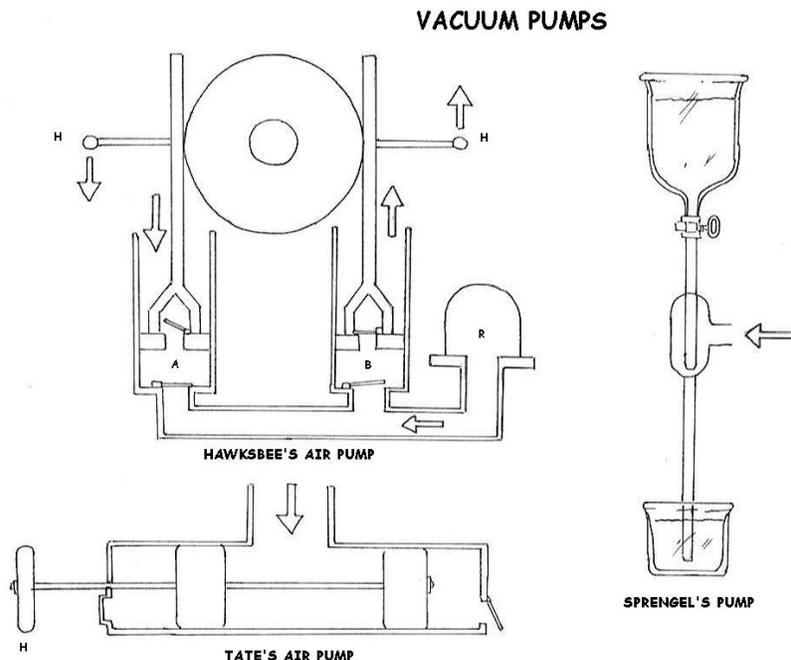
Bell-jar Receiver

The bell-jar receiver, invented by Huygens, is shown; previously, a cumbersome globe was the usual receiver. Tate's air pump is a 19th century pump that would be used for simple vacuum demonstrations and for utility purposes in the lab. It has no valves on the low-pressure side, just exhaust valves V, V', so it could probably reach about 1 mmHg. It is operated by pushing and pulling the handle H. At the present day, motor-driven rotary-seal pumps sealed by running in oil are used for the same purpose. At the right is Sprengel's pump, with the valves replaced by drops of mercury.

Small amounts of gas are trapped at the top of the fall tube as the mercury drops, and moves slowly down the fall tube as mercury is steadily added, coming out at the bottom carrying the air with it. The length of the fall tube must be greater than the barometric height, of course. Theoretically, a vacuum of about 1 μm can be obtained with a Sprengel pump, but it is very slow and can only evacuate small volumes. Later, Langmuir's mercury diffusion pump, which was much faster, replaced Sprengel pumps, and led to oil diffusion pumps that can reach very high vacua. The column of water or hydrostatic engine is the inverse of the force pump, used to turn a large head (pressure) of water into rotary motion. It looks like a steam engine, with valves operated by valve gear, but of course is not a heat engine and can be of high efficiency.

However, it is not of as high efficiency as a turbine, and is much more complicated, but has the advantage that it can be operated at variable speeds, as for lifting. A few very impressive column of water engines were made in the 19th century, but they were never popular and remained rare. Richard Trevithick, famous for high pressure steam engines, also built hydrostatic engines in Cornwall. The photograph at the right shows a column-of-water engine built by Georg von Reichenbach, and placed in service in 1917. This engine was exhibited in the Deutsches Museum in München as late as 1977.

It was used to pump brine for the Bavarian state salt industry. A search of the museum website did not reveal any evidence of it, but a good drawing of another brine pump with four cylinders and driven by a water wheel, also built by von Reichenbach, was found.

Solehebemaschine

This machine, a Solehebemaschine ("brine-lifting machine"), entered service in 1821. It had two pressure-operated poppet valves for each cylinder. These engines are brass to resist corrosion by the salt water. Water pressure engines must be designed taking into account the incompressibility of water, so both valves must not close at the same time, and abrupt changes of rate of flow must not be made. Air chambers can be used to eliminate shocks. Georg von Reichenbach (1771-1826) is much better known as an optical designer than as a mechanical engineer. He was associated with Joseph Fraunhofer, and they died within days of each other in 1826. He was of an aristocratic family, and was Salinenrat, or manager of the state salt works, in southeastern Bavaria, which was centered on the town of Reichenhall, now Bad Reichenhall, near Salzburg.

The name derives from "rich in salt." This famous salt region had salt springs flowing nearly saturated brine, at 24% to 26% (saturated is 27%) salt, that from ancient times had been evaporated over wood fires. A brine pipeline to Traunstein was constructed in 1617-1619, since wood fuel for evaporating the brine was exhausted in Reichenhall. The pipeline was further extended to Rosenheim, where there was turf as well as wood, in 1818-10.

Von Reichenbach is said to have built this pipeline, for which he designed a water-wheel-driven, four-barrel pump. Maximilian I, King of Bavaria, commissioned von Reichenbach to bring brine from Berchtesgaden, elevation 530 m, to Reichenhall, elevation 470 m, over a summit 943 m high. Fresh water was also allowed to flow down to the salt beds, and the brine was then pumped to the surface. This was a much easier way to mine salt than underground mining.

Forces on Submerged Surfaces

Suppose we want to know the force exerted on a vertical surface of any shape with water on one side, assuming gravity to act, and the pressure on the surface of the water zero. We have already solved this problem by a geometrical argument, but now we apply calculus, which is easier but not as illuminating.

The force on a small area dA a distance x below the surface of the water is dF = p dA = ρgx dA, and the moment of this force about a point on the surface is dM = px dA = ρgx2 dA.

$$F = \rho g \frac{h}{2} \cdot hw$$

Force on a Surface

By integration, we can find the total force F, and the depth at which it acts, c = M / F. If the surface is not symmetrical, the position of the total force in the transverse direction can be obtained from the integral of dM' = ρgxy dA, the moment about some vertical line in the plane of the surface. If there happens to be a pressure on the free surface of the water, then the forces due to this pressure can be evaluated separately and added to this result.
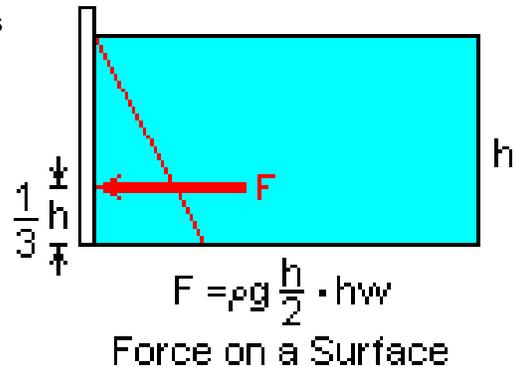
We must add a force equal to the area of the surface times the additional pressure, and a moment equal to the product of this force and the distance to the centroid of the surface.

The simplest case is a rectangular gate of width w, and height h, whose top is a distance H below the surface of the water.

In this case, the integrations are very easy, and F = ρgw [(h + H) 2 - h2]/2 = ρgH (H + 2h)/2 = ρg (h + H/2) Hw.

The total force on the gate is equal to its area times the pressure at its center. M = ρgw [(h + H) 3 - h3]/3 = ρg (H2/3 + Hh + h2) Hw, so that c = (H2/3 + Hh + h2)/ (h + H/2).

In the simple case of h = 0, c = 2H/3, or two-thirds of the way from the top to the bottom of the gate. If we take the atmospheric pressure to act not only on the surface of the water, but also the dry side of the gate, there is no change to this result.

This is the reason atmospheric pressure often seems to have been neglected in solving sub h problems.

Consider a curious rectangular tank, with one side vertical but the opposite side inclined inwards or outwards.

The horizontal forces exerted by the water on the two sides must be equal and opposite, or the tank would scoot off. If the side is inclined outward, then there must be a downward vertical force equal to the weight of the water above it, and passing through the centroid of this water. If the side is inclined inward, there must be an upward vertical force equal to the weight of the 'missing' water above it. In both cases, the result is demanded by ordinary statics.

Hydrostatic Paradox

What we have here has been called the 'hydrostatic paradox.' It was conceived by the celebrated Flemish engineer Simon Stevin (1548-1620) of Brugge, the first modern scientist to investigate the statics of fluids and solids. Consider three tanks with bottoms of equal sizes and equal heights, filled with water. The pressures at the bottoms are equal, so the vertical force on the bottom of each tank is the same. But suppose that one tank has vertical sides, one has sides inclined inward, and third sides inclined outwards. The tanks do not contain the same weight of water, yet the forces on their bottoms are equal! I am sure that you can spot the resolution of this paradox.

Sometimes the forces are required on curved surfaces. The vertical and horizontal components can be found by considering the equilibrium of volumes with a plane surface equal to the projected area of the curved surface in that direction. The general result is usually a force plus a couple, since the horizontal and vertical forces are not necessarily in the same plane. Simple surfaces, such as cylinders, spheres and cones, may often be easy to solve. In general, however, it is necessary to sum the forces and moments numerically on each element of area, and only in simple cases can this be done analytically.

Hydrostatic Paradox
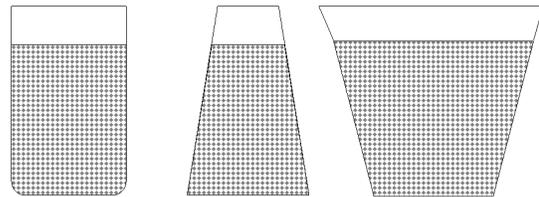
If a volume of fluid is accelerated uniformly, the acceleration can be added to the acceleration of gravity. A free surface now becomes perpendicular to the total acceleration, and the pressure is proportional to the distance from this surface. The same can be done for a rotating fluid, where the centrifugal acceleration is the important quantity. The earth's atmosphere is an example. When air moves relative to the rotating system, the Coriolis force must also be taken into account. However, these are dynamic effects and are not strictly a part of hydrostatics.

Buoyancy

Archimedes, so the legend runs, was asked to determine if the goldsmith who made a golden crown for Hieron, Tyrant of Syracuse, had substituted cheaper metals for gold. The story is told by Vitruvius. A substitution could not be detected by simply weighing the crown, since it was craftily made to the same weight as the gold supplied for its construction. Archimedes realized that finding the density of the crown, that is, the weight per unit volume, would give the answer.

The weight was known, of course, and Archimedes cunningly measured its volume by the amount of water that ran off when it was immersed in a vessel filled to the brim. By comparing the results for the crown, and for pure gold, it was found that the crown displaced more water than an equal weight of gold, and had, therefore, been adulterated.

This story, typical of the charming way science was made more interesting in classical times, may or may not actually have taken place, but whether it did or not, Archimedes taught that a body immersed in a fluid lost apparent weight equal to the weight of the fluid displaced, called Archimedes' Principle. Specific gravity, the ratio of the density of a substance to the density of water, can be determined by weighing the body in air, and then in water. The specific gravity is the weight in air divided by the loss in weight when immersed. This avoids the difficult determination of the exact volume of the sample.

How Buoyancy Works

To see how buoyancy works, consider a submerged brick, of height h, width w and length l. The difference in pressure on top and bottom of the brick is ρgh, so the difference in total force on top and bottom of the brick is simply (ρgh) (wl) = ρgV, where V is the volume of the brick.

Change of Ship Stability

The forces on the sides have no vertical components, so they do not matter. The net upward force is the weight of a volume V of the fluid of density ρ. Anybody can be considered made up of brick shapes, as small as desired, so the result applies in general. This is just the integral calculus in action, or the application of Professor Thomson's analogy.

Consider a man in a rowboat on a lake, with a large rock in the boat. He throws the rock into the water. What is the effect on the water level of the lake? Suppose you make a drink of ice water with ice cubes floating in it. What happens to the water level in the glass when the ice has melted?

The force exerted by the water on the bottom of a boat acts through the center of gravity B of the displaced volume, while the force exerted by gravity on the boat acts through its own center of gravity A. This looks bad for the boat, since the boat's c.g. will naturally be higher than the c.g. of the displaced water, so the boat will tend to capsize. Well, a board floats, and can tell us why. Should the board start to rotate to one side, the displaced volume immediately moves to that side, and the buoyant force tends to correct the rotation. A floating body will be stable provided the line of action of the buoyant force passes through a point M above the c.g. of the body, called the metacenter, so that there is a restoring couple when the boat heels. A ship with an improperly designed hull will not float. It is not as easy to make boats as it might appear.

Montgolfier Brothers' Hot Air Balloon

Archimedes' Principle can also be applied to balloons. The Montgolfier brothers' hot air balloon with a paper envelope ascended first in 1783 (the brothers got Pilâtre de Rozier and Chevalier d'Arlandes to go up in it). Such "fire balloons" were then replaced with hydrogen-filled balloons, and then with balloons filled with coal gas, which was easier to obtain and did not diffuse through the envelope quite as rapidly. Methane would be a good filler, with a density 0.55 that of air. Slack balloons, like most large ones, can be contrasted with taut balloons with an elastic envelope, such as weather balloons.

Slack balloons will not be filled full on the ground, and will plump up at altitude. Balloons are naturally stable, since the center of buoyancy is above the center of gravity in all practical balloons. Submarines are yet another application of buoyancy, with their own characteristic problems. Small neoprene or natural rubber balloons have been used for meteorological observations, with hydrogen filling. A 10g ceiling balloon was about 17" in diameter when inflated to have a free lift of 40g. It ascended 480ft the first minute, 670ft in a minute and a half, and 360ft per minute afterwards, to find cloud ceilings by timing, up to 2500ft, when it subtended about 2' of arc, easily seen in binoculars.

Large sounding balloons were used to lift a radiosonde and a parachute for its recovery. An AN/AMT-2 radiosonde of the 1950's weighed 1500g, the paper parachute 100g, and the balloon 350g. The balloon was inflated to give 800g free lift, so it would rise 700-800 ft/min to an altitude of about 50,000 ft (15 km) before it burst. This balloon was about 6 ft in diameter when inflated at the surface, 3 ft in diameter before inflation. The information was returned by radio telemetry, so the balloon did not have to be followed optically. Of intermediate size was the pilot balloon, which was followed with a theodolite to determine wind directions and speeds. At night, a pilot balloon could carry a light for ceiling determinations.

Weather Balloons

The greatest problem with using hydrogen for lift is that it diffuses rapidly through many substances. Weather balloons had to be launched promptly after filling, or the desired free lift would not be obtained. Helium is a little better in this respect, but it also diffuses rapidly. The lift obtained with helium is almost the same as with hydrogen (density 4 compared to 2, where air is 28.97). However, helium is exceedingly rare, and only its unusual occurrence in natural gas from Kansas makes it available. Great care must be taken when filling balloons with hydrogen to avoid sparks and the accumulation of hydrogen in air, since hydrogen is exceedingly flammable and explosive over a wide range of concentrations. Helium has the great advantage that it is not inflammable.

The hydrogen for filling weather balloons came from compressed gas in cylinders, from the reaction of granulated aluminum with sodium hydroxide and water, or from the reaction of calcium hydroxide with water. The chemical reactions are $2Al + 2NaOH + 2H2O \rightarrow 2NaAlO2 + 3H2$, or $CaH2 + 2H2O \rightarrow Ca (OH) 2 + 2H2$. In the first, silicon or zinc could be used instead of aluminum, and in the second, any similar metal hydride. Both are rather expensive sources of hydrogen, but very convenient when only small amounts are required. Most hydrogen is made from the catalytic decomposition of hydrocarbons, or the reaction of hot coke with steam.

Electrolysis of water is an expensive source, since more energy is used than is recovered with the hydrogen. Any enthusiasm for a "hydrogen economy" should be tempered by the fact that there are no hydrogen wells, and all the hydrogen must be made with an input of energy usually greater than that available from the hydrogen, and often with the appearance of carbon.

Although about 60,000 Btu/lb is available from hydrogen, compared to 20,000 Btu/lb from gasoline, hydrogen compressed to 1000 psi requires 140 times as much volume for the same weight as gasoline. For the energy content of a 13-gallon gasoline tank, a 600-gallon hydrogen tank would be required. The critical temperature of hydrogen is 32K, so liquid storage is out of the question for general use.

Measurement of Specific Gravity

The specific gravity of a material is the ratio of the mass (or weight) of a certain sample of it to the mass (or weight) of an equal volume of water, the conventional reference material. In the metric system, the density of water is 1 g/cc, which makes the specific gravity numerically equal to the density. Strictly speaking, density has the dimensions g/cc, while specific gravity is a dimensionless ratio. However, in casual speech the two are often confounded. In English units, however, density, perhaps in lb/cu.ft or pcf, is numerically different from the specific gravity, since the weight of water is 62.5 lb/cu.ft.

Variations

Things are complicated by the variation of the density of water with temperature, and also by the confusion that gave us the distinction between cc and ml. The milliliter is the volume of 1.0 g of water at 4°C, by definition. The actual volume of 1.0 g of water at 4°C is 0.999973 cm3 by measurement. Since most densities are not known, or needed, to more than three significant figures, it is clear that this difference is of no practical importance, and the ml can be taken equal to the cc. The density of water at 0°C is 0.99987 g/ml, at 20° 0.99823, and at 100°C 0.95838. The temperature dependence of the density may have to be taken into consideration in accurate work. Mercury, while we are at it, has a density 13.5955 at 0°C, and 13.5461 at 20°C.

The basic idea in finding specific gravity is to weigh a sample in air, and then immersed in water. Then the specific gravity is W/ (W - W'), if W is the weight in air, and W' the weight immersed. The denominator is just the buoyant force, the weight of a volume of water equal to the volume of the sample. This can be carried out with an ordinary balance, but special balances, such as the Jolly balance, have been created specifically for this application. Adding an extra weight to the sample allows measurement of specific gravities less than 1.

Pycnometer

A pycnometer is a flask with a close-fitting ground glass stopper with a fine hole through it, so a given volume can be accurately obtained. The name comes from the Greek word meaning "density." If the flask is weighed empty, full of water, and full of a liquid whose specific gravity is desired, the specific gravity of the liquid can easily be calculated. A sample in the form of a powder, to which the usual method of weighing cannot be used, can be put into the pycnometer. The weight of the powder and the weight of the displaced water can be determined, and from them the specific gravity of the powder.

The specific gravity of a liquid can be found with a collection of small weighted, hollow spheres that will just float in certain specific gravities. The closest spheres that will just float and just sink put limits on the specific gravity of the liquid. This method was once used in Scotland to determine the amount of alcohol in distilled liquors. Since the density of a liquid decreases as the temperature increases, the spheres that float are an indication of the temperature of the liquid. Galileo's thermometer worked this way.

Hydrometer

A better instrument is the hydrometer, which consists of a weighted float and a calibrated stem that protrudes from the liquid when the float is entirely immersed. A higher specific gravity will result in a greater length of the stem above the surface, while a lower specific gravity will cause the hydrometer to float lower.

The small cross-sectional area of the stem makes the instrument very sensitive. Of course, it must be calibrated against standards. In most cases, the graduations ("degrees") are arbitrary and reference is made to a table to determine the specific gravities. Hydrometers are used to determine the specific gravity of lead-acid battery electrolyte, and the concentration of antifreeze compounds in engine coolants, as well as the alcohol content of whiskey.

Pascal's Law Assignment

The foundation of modern hydraulics was established when Pascal discovered that pressure in a fluid acts equally in all directions. This pressure acts at right angles to the containing surfaces. If some type of pressure gauge, with an exposed face, is placed beneath the surface of a liquid at a specific depth and pointed in different directions, the pressure will read the same. Thus, we can say that pressure in a liquid is independent of direction.

Pressure due to the weight of a liquid, at any level, depends on the depth of the fluid from the surface. If the exposed face of the pressure gauges are moved closer to the surface of the liquid, the indicated pressure will be less. When the depth is doubled, the indicated pressure is doubled. Thus the pressure in a liquid is directly proportional to the depth. Consider a container with vertical sides that is 1 foot long and 1 foot wide. Let it be filled with water 1 foot deep, providing 1 cubic foot of water. 1 cubic foot of water weighs 62.4 pounds. Using this information and equation, **P = F/A**, we can calculate the pressure on the bottom of the container.

Since there are 144 square inches in 1 square foot, this can be stated as follows: the weight of a column of water 1 foot high, having a cross-sectional area of 1 square inch, is 0.433 pound. If the depth of the column is tripled, the weight of the column will be 3 x 0.433, or 1.299 pounds, and the pressure at the bottom will be 1.299 lb/in^2 (psi), since pressure equals the force divided by the area.

Thus, the pressure at any depth in a liquid is equal to the weight of the column of liquid at that depth divided by the cross-sectional area of the column at that depth. The volume of a liquid that produces the pressure is referred to as the fluid head of the liquid. The pressure of a liquid due to its fluid head is also dependent on the density of the liquid.

Gravity

Gravity is one of the four forces of nature. The strength of the gravitational force between two objects depends on their masses. The more massive the objects are, the stronger the gravitational attraction.

When you pour water out of a container, the earth's gravity pulls the water towards the ground. The same thing happens when you put two buckets of water, with a tube between them, at two different heights. You must work to start the flow of water from one bucket to the other, but then gravity takes over and the process will continue on its own.

Gravity, applied forces, and atmospheric pressure are static factors that apply equally to fluids at rest or in motion, while inertia and friction are dynamic factors that apply only to fluids in motion. The mathematical sum of gravity, applied force, and atmospheric pressure is the static pressure obtained at any one point in a fluid at any given time.

Static Pressure

Static pressure exists in addition to any dynamic factors that may also be present at the same time. Pascal's law states that a pressure set up in a fluid acts equally in all directions and at right angles to the containing surfaces. This covers the situation only for fluids at rest or practically at rest. It is true only for the factors making up static head.

Obviously, when velocity becomes a factor it must have a direction, and as previously explained, the force related to the velocity must also have a direction, so that Pascal's law alone does not apply to the dynamic factors of fluid power.

The dynamic factors of inertia and friction are related to the static factors. Velocity head and friction head are obtained at the expense of static head. However, a portion of the velocity head can always be reconverted to static head. Force, which can be produced by pressure or head when dealing with fluids, is necessary to start a body moving if it is at rest, and is present in some form when the motion of the body is arrested; therefore, whenever a fluid is given velocity, some part of its original static head is used to impart this velocity, which then exists as velocity head.

Volume and Velocity of Flow

The volume of a liquid passing a point in a given time is known as its *volume of flow* or flow rate. The volume of flow is usually expressed in gallons per minute (gpm) and is associated with relative pressures of the liquid, such as 5 gpm at 40 psi. The *velocity of flow* or velocity of the fluid is defined as the average speed at which the fluid moves past a given point. It is usually expressed in feet per second (fps) or feet per minute (fpm). Velocity of flow is an important consideration in sizing the hydraulic lines.

Volume and velocity of flow are often considered together. With other conditions unaltered—that is, with volume of input unchanged—the velocity of flow increases as the cross section or size of the pipe decreases, and the velocity of flow decreases as the cross section increases. For example, the velocity of flow is slow at wide parts of a stream and rapid at narrow parts, yet the volume of water passing each part of the stream is the same.

Bernoulli's Principle

Bernoulli's principle thus says that a rise (fall) in pressure in a flowing fluid must always be accompanied by a decrease (increase) in the speed, and conversely, if an increase (decrease) in, the speed of the fluid results in a decrease (increase) in the pressure.

This is at the heart of a number of everyday phenomena. As a very trivial example, Bernoulli's principle is responsible for the fact that a shower curtain gets "***sucked inwards***" when the water is first turned on. What happens is that the increased water/air velocity inside the curtain (relative to the still air on the other side) causes a pressure drop.

The pressure difference between the outside and inside causes a net force on the shower curtain which sucks it inward. A more useful example is provided by the functioning of a perfume bottle: squeezing the bulb over the fluid creates a low pressure area due to the higher speed of the air, which subsequently draws the fluid up. This is illustrated in the following figure.

Action of a spray atomizer
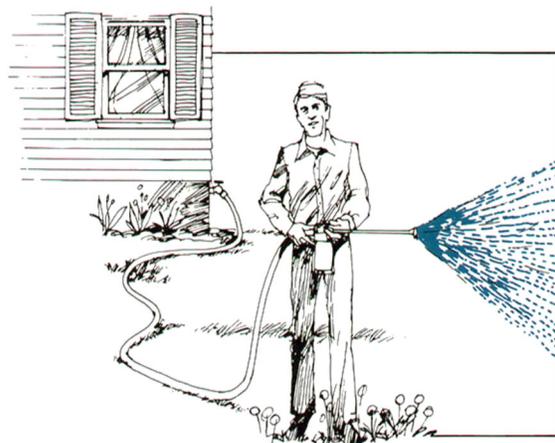
Bernoulli's principle also tells us why windows tend to explode, rather than implode in hurricanes:

the very high speed of the air just outside the window causes the pressure just outside to be much less than the pressure inside, where the air is still. The difference in force pushes the windows outward, and hence they explode. If you know that a hurricane is coming it is therefore better to open as many windows as possible, to equalize the pressure inside and out.

Another example of Bernoulli's principle at work is in the lift of aircraft wings and the motion of "***curve balls***" in baseball. In both cases the design is such as to create a speed differential of the flowing air past the object on the top and the bottom - for aircraft wings this comes from the movement of the flaps, and for the baseball it is the presence of ridges. Such a speed differential leads to a pressure difference between the top and bottom of the object, resulting in a net force being exerted, either upwards or downwards.

Bernoulli's Equation

Glenn Research Center

V = Velocity
p = Pressure
r = Density

Restrictions :
Inviscid
Steady
Incompressible   (low velocity)
No heat addition.
Negligible change in height.
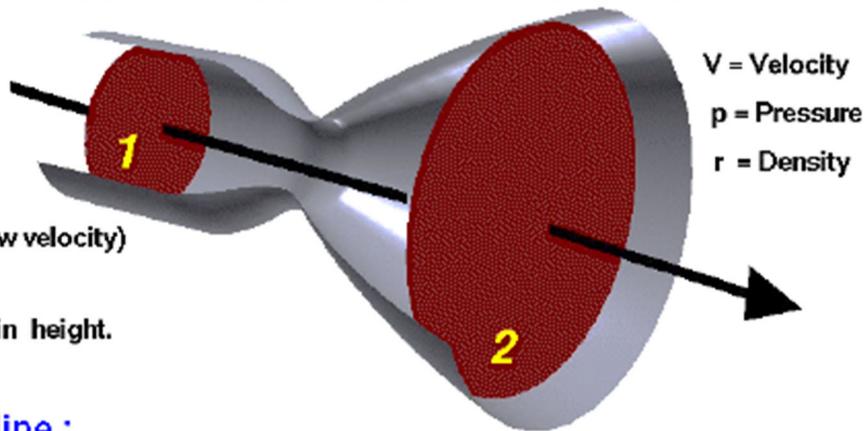
Along a streamline :

static pressure **+** dynamic pressure **=** total pressure

$$p_s \quad + \quad \frac{r V^2}{2} \quad = \quad p_t$$

$$\left(p_s + \frac{r V^2}{2} \right)_1 = \left(p_s + \frac{r V^2}{2} \right)_2$$

General Pumping Fundamentals
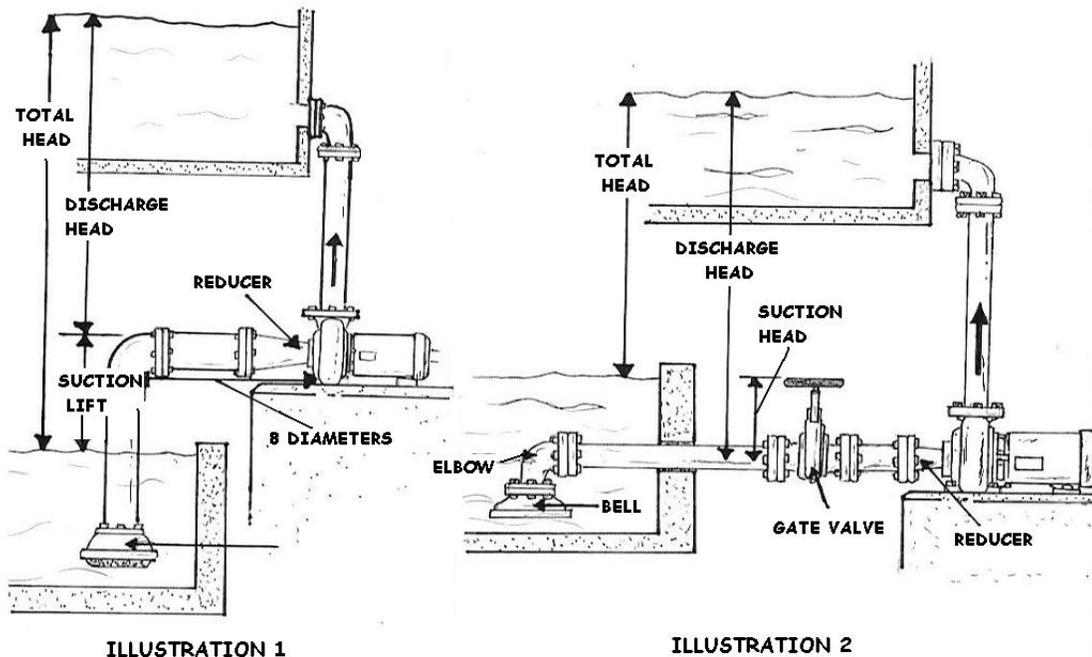
ILLUSTRATION 1   ILLUSTRATION 2

Here are the important points to consider about suction piping when the liquid being pumped is below the level of the pump:

- First, suction lift is when the level of water to be pumped is below the centerline of the pump. Sometimes suction lift is also referred to as 'negative suction head'.
- The ability of the pump to lift water is the result of a partial vacuum created at the center of the pump.
- This works similar to sucking soda from a straw. As you gently suck on a straw, you are creating a vacuum or a pressure differential. Less pressure is exerted on the liquid inside the straw, so that the greater pressure is exerted on the liquid around the outside of the straw, causing the liquid in the straw to move up. By sucking on the straw, this allows atmospheric pressure to move the liquid.
- Look at the diagram illustrated as "1". The foot valve is located at the end of the suction pipe of a pump. It opens to allow water to enter the suction side, but closes to prevent water from passing back out of the bottom end.
- The suction side of pipe should be one diameter larger than the pump inlet. The required eccentric reducer should be turned so that the top is flat and the bottom tapered.

Notice in illustration "2" that the liquid is above the level of the pump. Sometimes this is referred to as *'flooded suction'* or *'suction head'* situations.

Points to Note are:
If an elbow and bell are used, they should be at least one pipe diameter from the tank bottom and side. This type of suction piping must have a gate valve which can be used to prevent the reverse flow when the pump has to be removed. In the illustrations you can see in both cases the discharge head is from the centerline of the pump to the level of the discharge water. The total head is the difference between the two liquid levels.

Understanding the Pump

Pumps are used to move or raise fluids. They are not only very useful, but are excellent examples of hydrostatics. Pumps are of two general types, hydrostatic or positive displacement pumps, and pumps depending on dynamic forces, such as centrifugal pumps. Here we will only consider positive displacement pumps, which can be understood purely by hydrostatic considerations. They have a piston (or equivalent) moving in a closely-fitting cylinder, and forces are exerted on the fluid by motion of the piston.
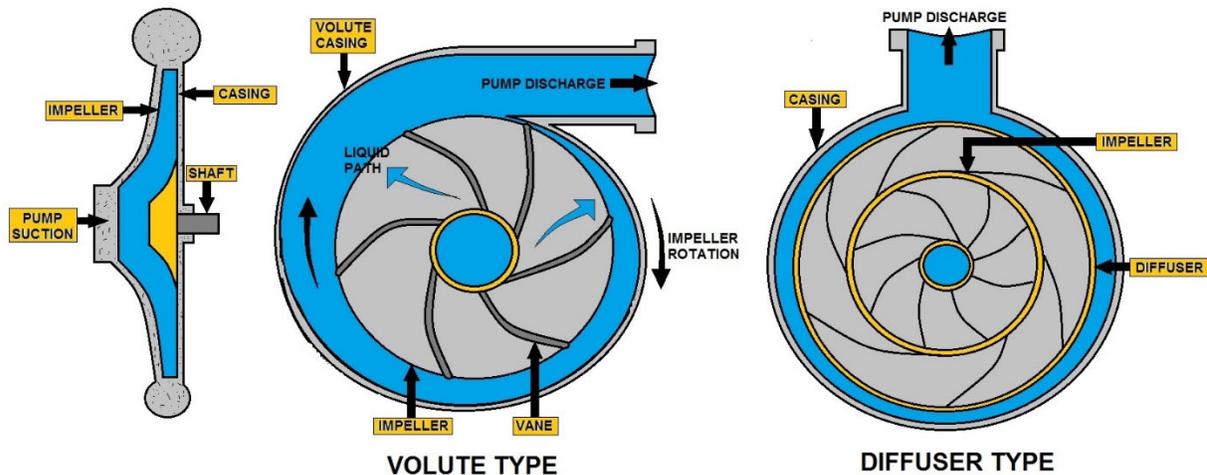
TYPES OF CENTRIFUGAL PUMPS

We have already seen an important example of this in the hydraulic lever or hydraulic press, which we have called quasi-static. The simplest pump is the syringe, filled by withdrawing the piston and emptied by pressing it back in, as its port is immersed in the fluid or removed from it.

More complicated pumps have valves allowing them to work repetitively. These are usually check valves that open to allow passage in one direction, and close automatically to prevent reverse flow. There are many kinds of valves, and they are usually the most trouble-prone and complicated part of a pump. The force pump has two check valves in the cylinder, one for supply and the other for delivery. The supply valve opens when the cylinder volume increases, the delivery valve when the cylinder volume decreases.

The lift pump has a supply valve and a valve in the piston that allows the liquid to pass around it when the volume of the cylinder is reduced. The delivery in this case is from the upper part of the cylinder, which the piston does not enter.

Diaphragm pumps are force pumps in which the oscillating diaphragm takes the place of the piston. The diaphragm may be moved mechanically, or by the pressure of the fluid on one side of the diaphragm.

Some positive displacement pumps are shown below. The force and lift pumps are typically used for water. The force pump has two valves in the cylinder, while the lift pump has one valve in the cylinder and one in the piston. The maximum lift, or "suction," is determined by the atmospheric pressure, and either cylinder must be within this height of the free surface.
The force pump, however, can give an arbitrarily large pressure to the discharged fluid, as in the case of a diesel engine injector. A nozzle can be used to convert the pressure to velocity, to

produce a jet, as for firefighting. Fire fighting force pumps usually have two cylinders feeding one receiver alternately. The air space in the receiver helps to make the water pressure uniform.

The three pumps below are typically used for air, but would be equally applicable to liquids. The Roots blower has no valves, their place taken by the sliding contact between the rotors and the housing. T

he Roots blower can either exhaust a receiver or provide air under moderate pressure, in large volumes.

The Bellows is a very old device, requiring no accurate machining. The single valve is in one or both sides of the expandable chamber.

Another valve can be placed at the nozzle if required. The valve can be a piece of soft leather held close to holes in the chamber.

The Bicycle pump uses the valve on the valve stem of the tire or inner tube to hold pressure in the tire. The piston, which is attached to the discharge tube, has a flexible seal that seals when the cylinder is moved to compress the air, but allows air to pass when the movement is reversed.

Diaphragm and vane pumps are not shown, but they act the same way by varying the volume of a chamber, and directing the flow with check valves.

LIFT PUMP

ROOTS BLOWER

BELLOWS PUMP
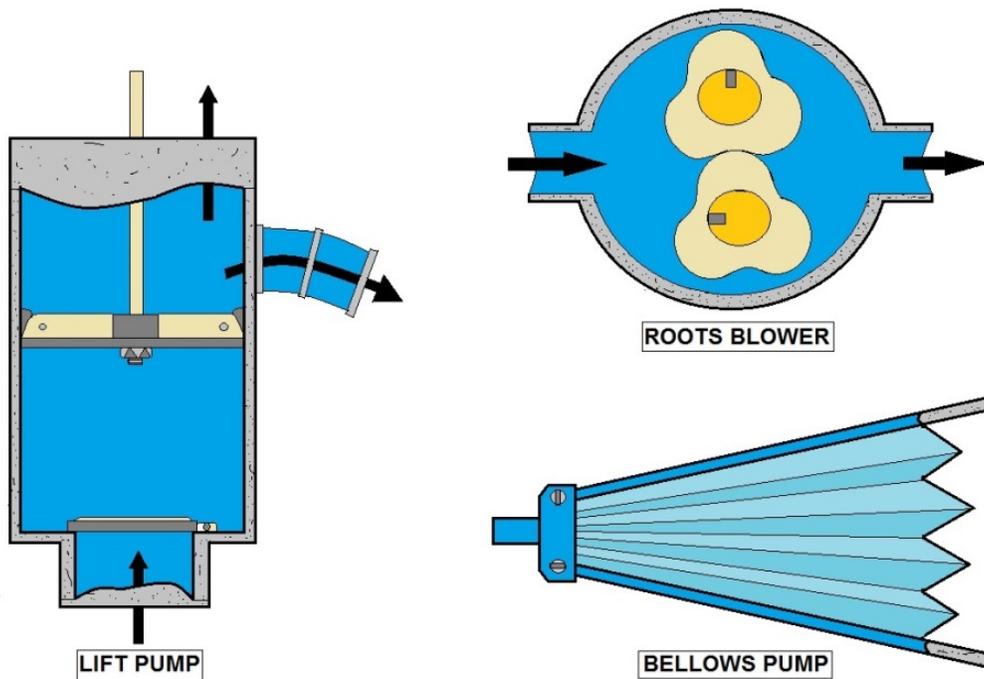
TYPES OF POSITIVE DISPLACEMENT PUMPS

Types of Pumps

The family of pumps comprises a large number of types based on application and capabilities. The two major groups of pumps are dynamic and positive displacement.

Dynamic Pumps (Centrifugal Pump)

Centrifugal pumps are classified into three general categories:
Radial flow—a centrifugal pump in which the pressure is developed wholly by centrifugal force.
Mixed flow—a centrifugal pump in which the pressure is developed partly by centrifugal force and partly by the lift of the vanes of the impeller on the liquid.
Axial flow—a centrifugal pump in which the pressure is developed by the propelling or lifting action of the vanes of the impeller on the liquid.

Positive Displacement Pumps

A Positive Displacement Pump has an expanding cavity on the suction side of the pump and a decreasing cavity on the discharge side. Liquid is allowed to flow into the pump as the cavity on the suction side expands and the liquid is forced out of the discharge as the cavity collapses. This principle applies to all types of Positive Displacement Pumps whether the pump is a rotary lobe, gear within a gear, piston, diaphragm, screw, progressing cavity, etc.

A Positive Displacement Pump, unlike a Centrifugal Pump, will produce the same flow at a given RPM no matter what the discharge pressure is. A Positive Displacement Pump cannot be operated against a closed valve on the discharge side of the pump, i.e. it does not have a shut-off head like a Centrifugal Pump does. If a Positive Displacement Pump is allowed to operate against a closed discharge valve it will continue to produce flow which will increase the pressure in the discharge line until either the line bursts or the pump is severely damaged or both.

Types of Positive Displacement Pumps

Single Rotor	Multiple Rotor
Vane	Gear
Piston	Lobe
Flexible Member	Circumferential Piston
Single Screw	Multiple Screw

There are many types of positive displacement pumps. We will look at:
☛ Plunger pumps
☛ Diaphragm pumps
☛ Progressing cavity pumps, and
☛ Screw pumps
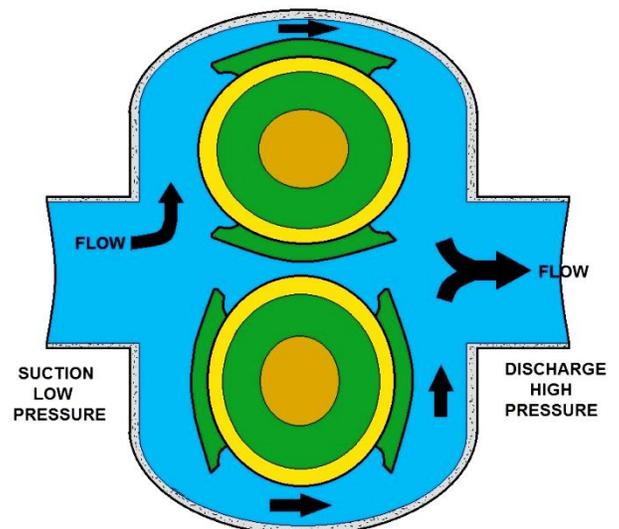
COMMONLY FOUND POSITIVE DISPLACEMENT PUMP

Single Rotator

Component	Description
Vane	The vane(s) may be blades, buckets, rollers, or slippers that cooperate with a dam to draw fluid into and out of the pump chamber.
Piston	Fluid is drawn in and out of the pump chamber by a piston(s) reciprocating within a cylinder(s) and operating port valves.
Flexible Member	Pumping and sealing depends on the elasticity of a flexible member(s) that may be a tube, vane, or a liner.
Single Screw	Fluid is carried between rotor screw threads as they mesh with internal threads on the stator.

Multiple Rotator

Component	Description
Gear	Fluid is carried between gear teeth and is expelled by the meshing of the gears that cooperate to provide continuous sealing between the pump inlet and outlet.
Lobe	Fluid is carried between rotor lobes that cooperate to provide continuous sealing between the pump inlet and outlet.
Circumferential piston	Fluid is carried in spaces between piston surfaces not requiring contacts between rotor surfaces.
Multiple Screw	Fluid is carried between rotor screw threads as they mesh.

In the same way, the progressing cavity and the screw are two other types of mechanical action that can be used to provide movement of the liquid through the pump.

Plunger Pump
The plunger pump is a positive displacement pump that uses a plunger or piston to force liquid from the suction side to the discharge side of the pump. It is used for heavy sludge.

The movement of the plunger or piston inside the pump creates pressure inside the pump, so you have to be careful that this kind of pump is never operated against any closed discharge valve.

All discharge valves must be open before the pump is started, to prevent any fast build-up of pressure that could damage the pump.

Diaphragm Pumps
In this type of pump, a diaphragm provides the mechanical action used to force liquid from the suction to the discharge side of the pump. The advantage the diaphragm has over the plunger is that the diaphragm pump does not come in contact with moving metal. This can be important when pumping abrasive or corrosive materials.

There are three main types of diaphragm pumps available:
1. Diaphragm sludge pump
2. Chemical metering or proportional pump
3. Air-powered double-diaphragm pump

Pump Categories

Let's cover the essentials first. The key to the whole operation is, of course, the *pump.* And regardless of what type it is (reciprocating piston, centrifugal, turbine or jet-ejector, for either shallow or deep well applications), its purpose is to move water and generate the delivery force we call pressure.

Sometimes — with centrifugal pumps in particular — pressure is not referred to in pounds per square inch but rather as the equivalent in elevation, called head. No matter; head in feet divided by 2.31 equals pressure, so it's simple enough to establish a common figure.

Pumps may be classified on the basis of the application they serve. All pumps may be divided into two major categories: (1) dynamic, in which energy is continuously added to increase the fluid velocities within the machine, and (2) displacement, in which the energy is periodically added by application of force.

CASING TYPES

| AXIAL VERTICAL SPLIT | AXIAL HORIZONTAL SPLIT | CENTRAL SPLIT | HORIZONTAL SPLIT | VERTICAL SPLIT | DIAGONAL SPLIT | CIRCULAR SPLIT | SIDE-COVER TYPE | DUAL-COVER TYPE |

STAGES

SINGLE STAGE | MULTISTAGE

SUCTION TYPE

DOUBLE SUCTION | SINGLE SUCTION

DIRECTION OF PRINCIPAL AXIS

DIAGONAL | HORIZONTAL | VERTICAL

PUMP CONFIGURATIONS

ENERGY INPUT TO PRIME MOVER

100 %

| PRIME MOVER EFFICIENCY= 10 - 80 % | MECHANICAL DRIVE EFFICIENCY= 50 - 100 % | PUMP EFFICIENCY= 30 - 80 % | PIPE EFFICIENCY= 50 - 98 % | CONVEYANCE SYSTEM EFFICIENCY 80 - 90 % | FIELD DISTRIBUTION SYSTEM EFFICIENCY= 30 - 70 % |

20-90%   10-90%   3-72%   1.5-71%   1.2-64%   0.4-45%

| THERMAL AND MECHANICAL LOSSES | MECHANICAL LOSSES | HYDRAULIC AND MECHANICAL LOSSES | HYDRAULIC LOSSES | LEAKAGE OR HYDRAULIC LOSSES | LEAKAGE AND/OR HYDRAULIC LOSSES |

PUMPING EFFICIENCY

Basic Water Pump

The water pump commonly found in our systems is centrifugal pumps. These pumps work by spinning water around in a circle inside a cylindrical pump housing. The pump makes the water spin by pushing it with an impeller. The blades of this impeller project outward from an axle like the arms of a turnstile and, as the impeller spins, the water spins with it. As the water spins, the pressure near the outer edge of the pump housing becomes much higher than near the center of the impeller.

There are many ways to understand this rise in pressure, and here are two:

CENTRIFUGAL FORCE ACTS THIS WAY

BUT RELEASED PARTICLE GOES THIS WAY

ROTATING CYLINDER
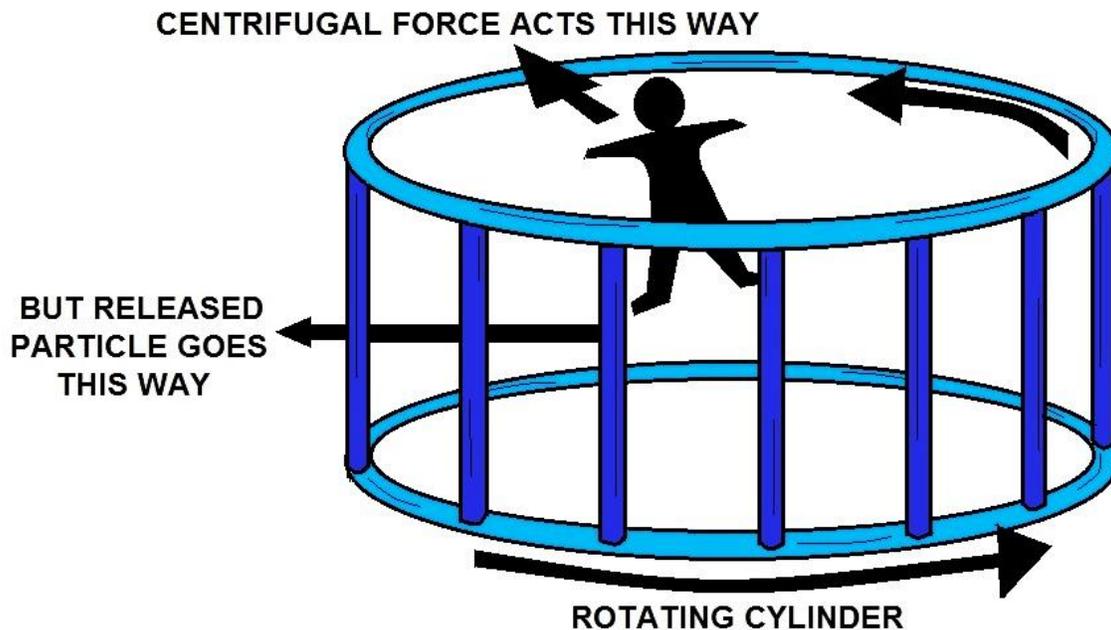
CENTRIFUGAL WATER EFFECTS

First, you can view the water between the impeller blades as an object traveling in a circle. Objects do not naturally travel in a circle--they need an inward force to cause them to accelerate inward as they spin. Without such an inward force, an object will travel in a straight line and will not complete the circle. In a centrifugal pump, that inward force is provided by high-pressure water near the outer edge of the pump housing. The water at the edge of the pump pushes inward on the water between the impeller blades and makes it possible for that water to travel in a circle. The water pressure at the edge of the turning impeller rises until it is able to keep water circling with the impeller blades.

You can also view the water as an incompressible fluid, one that obeys Bernoulli's equation in the appropriate contexts. As water drifts outward between the impeller blades of the pump, it must move faster and faster because its circular path is getting larger and larger. The impeller blades cause the water to move faster and faster. By the time the water has reached the outer edge of the impeller, it is moving quite fast. However, when the water leaves the impeller and arrives at the outer edge of the cylindrical pump housing, it slows down.

Bernoulli's Equation

NASA — Glenn Research Center

Restrictions :
Inviscid
Steady
Incompressible (low velocity)
No heat addition.
Negligible change in height.

V = Velocity
p = Pressure
r = Density
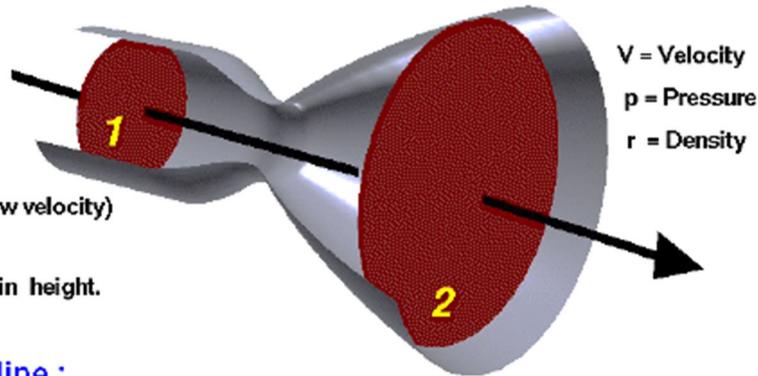
Along a streamline :

static pressure + dynamic pressure = total pressure

$$p_s + \frac{rV^2}{2} = p_t$$

$$\left(p_s + \frac{rV^2}{2}\right)_1 = \left(p_s + \frac{rV^2}{2}\right)_2$$

Here is where Bernoulli's equation figures in. As the water slows down and its kinetic energy decreases, that water's pressure potential energy increases (*to conserve energy*). Thus, the slowing is accompanied by a pressure rise. That is why the water pressure at the outer edge of the pump housing is higher than the water pressure near the center of the impeller. When water is actively flowing through the pump, arriving through a hole near the center of the impeller and leaving through a hole near the outer edge of the pump housing, the pressure rise between center and edge of the pump is not as large.

IMPELLER BLADE

INLET

FLOW TRACES

VANELESS DIFFUSER
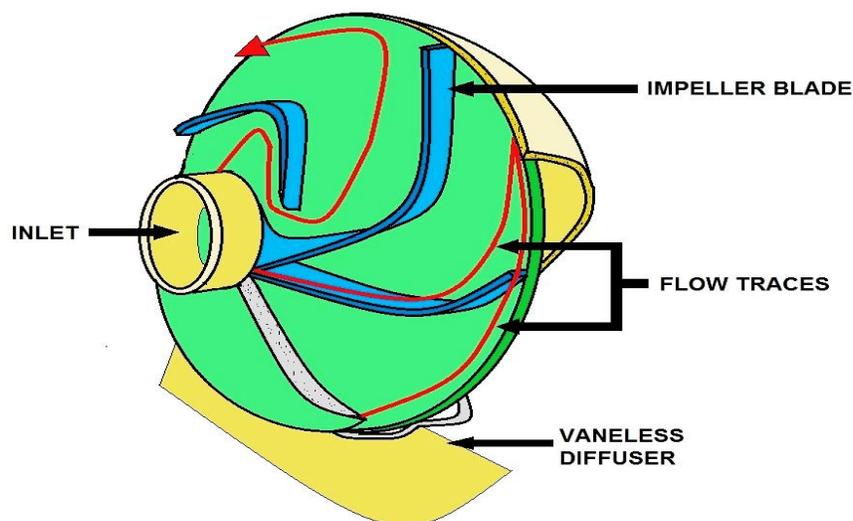
COMMON PUMP IMPELLER

Types of Water Pumps

The most common type of water pumps used for municipal and domestic water supplies are *variable displacement* pumps. A variable displacement pump will produce at different rates relative to the amount of pressure or lift the pump is working against. *Centrifugal* pumps are variable displacement pumps that are by far used the most. The water production well industry almost exclusively uses *Turbine* pumps, which are a type of centrifugal pump.

The turbine pump utilizes *impellers* enclosed in single or multiple *bowls or stages* to lift water by *centrifugal force*. The impellers may be of either a *semi-open or closed type*. Impellers are rotated by the *pump motor*, which provides the horsepower needed to overcome the pumping head. A more thorough discussion of how these and other pumps work is presented later in this section. The size and number of stages, horsepower of the motor and pumping head are the key components relating to the pump's lifting capacity.

Vertical turbine pumps are commonly used in groundwater wells. These pumps are driven by a shaft rotated by a motor on the surface. The shaft turns the impellers within the pump housing while the water moves up the column.

This type of pumping system is also called a *line-shaft turbine*. The rotating shaft in a line shaft turbine is actually housed within the column pipe that delivers the water to the surface. The size of the column, impeller, and bowls are selected based on the desired pumping rate and lift requirements.

Column pipe sections can be threaded or coupled together while the drive shaft is coupled and suspended within the column by *spider bearings*. The spider bearings provide both a seal at the column pipe joints and keep the shaft aligned within the column. The water passing through the column pipe serves as the lubricant for the bearings. Some vertical turbines are lubricated by oil rather than water. These pumps are essentially the same as water lubricated units; only the drive shaft is enclosed within an *oil tube*.

Food grade oil is supplied to the tube through a gravity feed system during operation. The oil tube is suspended within the column by *spider flanges,* while the line shaft is supported within the oil tube by *brass or redwood bearings*. A continuous supply of oil lubricates the drive shaft as it proceeds downward through the oil tube.

A small hole located at the top of the pump bow unit allows excess oil to enter the well. This results in the formation of an oil film on the water surface within oil-lubricated wells. Careful operation of oil lubricated turbines is needed to ensure that the pumping levels do not drop enough to allow oil to enter the pump. Both water and oil lubricated turbine pump units can be driven by electric or fuel powered motors.

Most installations use an electric motor that is connected to the drive shaft by a keyway and nut. However, where electricity is not readily available, fuel powered engines may be connected to the drive shaft by a right angle drive gear. Also, both oil and water lubricated systems will have a strainer attached to the intake to prevent sediment from entering the pump.

When the line shaft turbine is turned off, water will flow back down the column, turning the impellers in a reverse direction. A pump and shaft can easily be broken if the motor were to turn on during this process.

This is why a *time delay* or *ratchet* assembly is often installed on these motors to either prevent the motor from turning on before reverse rotation stops or simply not allow it to reverse at all.

There are three main types of diaphragm pumps:
In the first type, the diaphragm is sealed with one side in the fluid to be pumped, and the other in air or hydraulic fluid. The diaphragm is flexed, causing the volume of the pump chamber to increase and decrease. A pair of non-return check valves prevents reverse flow of the fluid. As described above, the second type of diaphragm pump works with volumetric positive displacement, but differs in that the prime mover of the diaphragm is neither oil nor air; but is electro-mechanical, working through a crank or geared motor drive. This method flexes the diaphragm through simple mechanical action, and one side of the diaphragm is open to air. The third type of diaphragm pump has one or more unsealed diaphragms with the fluid to be pumped on both sides. The diaphragm(s) again are flexed, causing the volume to change.

When the volume of a chamber of either type of pump is increased (the diaphragm moving up), the pressure decreases, and fluid is drawn into the chamber. When the chamber pressure later increases from decreased volume (the diaphragm moving down), the fluid previously drawn in is forced out. Finally, the diaphragm moving up once again draws fluid into the chamber, completing the cycle. This action is similar to that of the cylinder in an internal combustion engine.

Cavitation
Cavitation is defined as the phenomenon of formation of vapor bubbles of a flowing liquid in a region where the pressure of the liquid falls below its vapor pressure. Cavitation is usually divided into two classes of behavior: inertial (or transient) cavitation and non-inertial cavitation. Inertial cavitation is the process where a void or bubble in a liquid rapidly collapses, producing a shock wave. Such cavitation often occurs in pumps, propellers, impellers, and in the vascular tissues of plants. Non-inertial cavitation is the process in which a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field. Such cavitation is often employed in ultrasonic cleaning baths and can also be observed in pumps, propellers etc.

Cavitation is, in many cases, an undesirable occurrence. In devices such as propellers and pumps, cavitation causes a great deal of noise, damage to components, vibrations, and a loss of efficiency. When the cavitation bubbles collapse, they force liquid energy into very small volumes, thereby creating spots of high temperature and emitting shock waves, the latter of which are a source of noise. The noise created by cavitation is a particular problem for military submarines, as it increases the chances of being detected by passive sonar. Although the collapse of a cavity is a relatively low-energy event, highly localized collapses can erode metals, such as steel, over time. The pitting caused by the collapse of cavities produces great wear on components and can dramatically shorten a propeller's or pump's lifetime. After a surface is initially affected by cavitation, it tends to erode at an accelerating pace. The cavitation pits increase the turbulence of the fluid flow and create crevasses that act as nucleation sites for additional cavitation bubbles. The pits also increase the component's surface area and leave behind residual stresses. This makes the surface more prone to stress corrosion.

Impeller
An impeller is a rotating component of a centrifugal pump, usually made of iron, steel, aluminum or plastic, which transfers energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid outwards from the center of rotation.

Submersible Pumps

Submersible pumps are in essence very similar to turbine pumps. They both use impellers rotated by a shaft within the bowls to pump water. However, the pump portion is directly connected to the motor.

The pump shaft has a keyway in which the splined motor end shaft inserts. The motor is bolted to the pump housing. The pump's intake is located between the motor and the pump and is normally screened to prevent sediment from entering the pump and damaging the impellers.

The efficient cooling of submersible motors is very important, so these types of pumps are often installed such that flow through the well screen can occur upwards past the motor and into the intake. If the motor end is inserted below the screened interval or below all productive portions of the aquifer, it will not be cooled, resulting in premature motor failure.

Some pumps may have *pump shrouds* installed on them to force all the water to move past the motor to prevent overheating.

The shroud is a piece of pipe that attaches to the pump housing with an open end below the motor. As with turbine pumps, the size of the bowls and impellers, number of stages, and horsepower of the motor are adjusted to achieve the desired production rate within the limitations of the pumping head.

The velocity achieved by the impeller transfers into pressure when the outward movement of the fluid is confined by the pump casing. Impellers are usually short cylinders with an open inlet (called an eye) to accept incoming fluid, vanes to push the fluid radically, and a splined center to accept a driveshaft.

Insertion of motor spline into the pump keyway.

Cut away of a small submersible pump.

Key Pump Words

NPSH: Net positive suction head - related to how much suction lift a pump can achieve by creating a partial vacuum. Atmospheric pressure then pushes liquid into the pump. A method of calculating if the pump will work or not.

S.G.: Specific gravity. The weight of liquid in comparison to water at approx. 20 degrees C (SG = 1).

Specific Speed: A number which is the function of pump flow, head, efficiency etc. Not used in
day to day pump selection, but very useful, as pumps with similar specific speed will have similar shaped curves, similar efficiency / NPSH / solids handling characteristics.

Vapor Pressure: If the vapor pressure of a liquid is greater than the surrounding air pressure, the liquid will boil.

Viscosity: A measure of a liquid's resistance to flow. i.e.: how thick it is. The viscosity determines the type of pump used, the speed it can run at, and with gear pumps, the internal clearances required.

Friction Loss: The amount of pressure / head required to 'force' liquid through pipe and fittings.

Pump Specifications

Pumps are commonly rated by horsepower, flow rate, outlet pressure in meters (or feet) of head, inlet suction in suction feet (or meters) of head. The head can be simplified as the number of feet or meters the pump can raise or lower a column of water at atmospheric pressure. From an initial design point of view, engineers often use a quantity termed the specific speed to identify the most suitable pump type for a particular combination of flow rate and head.

Pump Construction Material
The pump material can be Stainless steel (SS 316 or SS 304), cast iron etc. It depends on the application of the pump. In the water industry and for pharma applications SS 316 is normally used, as stainless steel gives better results at high temperatures.

Pumping Power
The power imparted into a fluid will increase the energy of the fluid per unit volume. Thus the power relationship is between the conversion of the mechanical energy of the pump mechanism and the fluid elements within the pump. In general, this is governed by a series of simultaneous differential equations, known as the Navier-Stokes equations. However a more simple equation relating only the different energies in the fluid, known as Bernoulli's equation can be used.

Hence the power, P, required by the pump:

$$P = \frac{\Delta P Q}{\eta}$$

where ΔP is the change in total pressure between the inlet and outlet (in Pa), and Q, the fluid flowrate is given in m^3/s. The total pressure may have gravitational, static pressure and kinetic energy components; i.e. energy is distributed between change in the fluid's gravitational potential energy (going up or down hill), change in velocity, or change in static pressure. η is the pump efficiency, and may be given by the manufacturer's information, such as in the form of a pump curve, and is typically derived from either fluid dynamics simulation (i.e. solutions to the Navier-stokes for the particular pump geometry), or by testing. The efficiency of the pump will depend upon the pump's configuration and operating conditions (such as rotational speed, fluid density and viscosity etc.)

$$\Delta P = \frac{(v_2^2 - v_1^2)}{2} + \Delta z g + \frac{\Delta p_{static}}{\rho}$$

For a typical "pumping" configuration, the work is imparted

Suction Lift Chart

The vertical distance that a pump may be placed above the water level (and be able to draw water) is determined by pump design and limits dictated by altitude. The chart below shows the absolute limits. The closer the pump is to the water level, the easier and quicker it will be to prime.

Suction Lift at Various Elevations

Altitude:	Suction Lift In Feet
Sea Level	25.0
2,000 ft.	22.0
4,000 ft.	19.5
6,000 ft.	17.3
8,000 ft.	15.5
10,000 ft.	14.3

Centrifugal pumps are particularly vulnerable especially when pumping heated solution near the vapor pressure, whereas positive displacement pumps are less affected by cavitation, as they are better able to pump two-phase flow (the mixture of gas and liquid), however, the resultant flow rate of the pump will be diminished because of the gas volumetrically displacing a disproportion of liquid. Careful design is required to pump high temperature liquids with a centrifugal pump when the liquid is near its boiling point.

The violent collapse of the cavitation bubble creates a shock wave that can literally carve material from internal pump components (usually the leading edge of the impeller) and creates noise often described as "pumping gravel".

Additionally, the inevitable increase in vibration can cause other mechanical faults in the pump and associated equipment.

For a typical "pumping" configuration, the work is imparted on the fluid, and is thus positive. For the fluid imparting the work on the pump (i.e. a turbine), the work is negative power required to drive the pump is determined by dividing the output power by the pump efficiency. Furthermore, this definition encompasses pumps with no moving parts, such as a siphon.

When asked how a pump operates, most reply that it "sucks." While not a false statement, it's easy to see why so many pump operators still struggle with pump problems. Fluid flows from areas of high pressure to areas of low pressure.

Pumps operate by creating low pressure at the inlet which allows the liquid to be pushed into the pump by atmospheric or head pressure (pressure due to the liquid's surface being above the centerline of the pump).

Consider placing a pump at the top of the mercury barometer above: Even with a perfect vacuum at the pump inlet, atmospheric pressure limits how high the pump can lift the liquid. With liquids lighter than mercury, this lift height can increase, but there's still a physical limit to pump operation based on pressure external to the pump. This limit is the key consideration for Net Positive Suction Head. *Reference Centrifugal/Vertical NPSH Margin (ANSI/HI 9.6.1-1998), www.pumps.org, Hydraulic Institute, 1998.*

Pump Efficiency

Pump efficiency is defined as the ratio of the power imparted on the fluid by the pump in relation to the power supplied to drive the pump. Its value is not fixed for a given pump; efficiency is a function of the discharge and therefore also operating head. For centrifugal pumps, the efficiency tends to increase with flow rate up to a point midway through the operating range (peak efficiency) and then declines as flow rates rise further. Pump performance data such as this is usually supplied by the manufacturer before pump selection. Pump efficiencies tend to decline over time due to wear (e.g. increasing clearances as impellers reduce in size).

When a system design includes a centrifugal pump, an important issue it its design is matching the head loss-flow characteristic with the pump so that it operates at or close to the point of its maximum efficiency. Pump efficiency is an important aspect and pumps should be regularly tested. Thermodynamic pump testing is one method.

Depending on how the measurement is taken suction lift and head may also be referred to as static or dynamic. Static indicates the measurement does not take into account the friction caused by water moving through the hose or pipes. Dynamic indicates that losses due to friction are factored into the performance. The following terms are usually used when referring to lift or head.

Static Suction Lift - The vertical distance from the water line to the centerline of the impeller.

Static Discharge Head - The vertical distance from the discharge outlet to the point of discharge or liquid level when discharging into the bottom of a water tank.

Dynamic Suction Head - The Static Suction Lift plus the friction in the suction line. Also referred to as a Total Suction Head.

Dynamic Discharge Head - The Static Discharge Head plus the friction in the discharge line. Also referred to as Total Discharge Head.

Total Dynamic Head - The Dynamic Suction Head plus the Dynamic Discharge Head. Also referred to as Total Head.

Net Positive Suction Head (NPSH)
NPSH can be defined as two parts:

NPSH Available (NPSHA): The absolute pressure at the suction port of the pump.

AND

NPSH Required (NPSHR): The minimum pressure required at the suction port of the pump to keep the pump from cavitating.

NPSHA is a function of your system and must be calculated, whereas NPSHR is a function of the pump and must be provided by the pump manufacturer. NPSHA MUST be greater than NPSHR for the pump system to operate without cavitating. Put another way, you must have more suction side pressure available than the pump requires.

Specific Gravity
The term specific gravity compares the density of some substance to the density of water. Since specific gravity is the ratio of those densities, the units of measure cancel themselves, and we end up with a dimensionless number that is the same for all systems of measure. Therefore, the specific gravity of water is 1— regardless of the measurement system. Specific gravity is important when sizing a centrifugal pump because it is indicative of the weight of the fluid, and its weight will have a direct effect on the amount of work performed by the pump. One of the beauties of the centrifugal pump is that the head (in feet) and flow it produces has nothing to do with the weight of the liquid. It is all about the velocity that is added by the impeller. The simplest way to prove the validity of this statement is to use the falling body equation:

$$v2 = 2gh$$

Where:
v = Velocity
g = The universal gravitational constant
h = height.

This equation will predict the final velocity some object will attain when falling from some height (ignoring friction of course). When rearranged, it takes the form of h = v2/2g and predicts the maximum height an object can attain based on its initial velocity. The final velocity attained by a falling object is actually the same as the initial velocity required for it to rise to the same height from which it fell. When this equation is applied to a centrifugal pump, h becomes the maximum theoretical head that it can produce. As the equation illustrates, that head depends upon the exit velocity of the liquid from the impeller vanes and the effect of gravity; it has absolutely nothing to do with the weight of the liquid.

The weight of the liquid does affect the amount of work done by a pump and, therefore, the HP required. A good way to understand the impact of liquid weight is to convert flow in GPM and head in feet into units of work. The equation below performs this conversion.

$$(gpm \ X \ 8.34 \ lb/gal \ X \ h) = w$$

Here the flow is multiplied by the weight of a gallon of water and then multiplied by the head in feet. The result is the work performed in ft-lb/minute. The equation shows us that the amount of work done by a centrifugal pump is directly proportional to the weight of the pumped liquid.

If you divide w by 33,000, the result is the HP required at that particular point of flow and head. The downward sloping curve in the upper portion of the graph is the H/Q curve and the red, blue and green curves are the horsepower curves for three different liquids.

The scale of the Y axis is both head and horsepower. The blue curve shows the HP required for water (SG=1). The red and green curves show the HP required to pump sugar syrup (SG=1.29) and gasoline (SG=0.71). If you analyze the three HP curves at each flow point, you will see that the increase or decrease is directly proportional to the SG of that particular liquid.

As long as the viscosity of a liquid is similar to that of water, its specific gravity will have no effect on pump performance. It will, however, directly affect the input power required to pump that particular liquid. The equation below can be used to compute the horsepower required to pump liquids of varying specific gravities (where BHP is brake horsepower, Q is flow in GPM, H is head in feet, SG is specific gravity and Eff is the hydraulic efficiency of the pump). It assumes a viscosity similar to that of water.

$$BHP = (Q \times H \times SG) / (3960 \times Eff)$$

SG can also have an effect on the onset of cavitation in a particular pump. Heavier liquids cause a proportional increase in a pump's suction energy and those with a high suction energy level are more likely to experience cavitation damage. Next month we will review the effect of viscosity on centrifugal pump performance.

Pump Testing
To minimize energy use, and to ensure that pumps are correctly matched to the duty expected pumps, and pumping stations should be regularly tested. In water supply applications, which are usually fitted with centrifugal pumps, individual large pumps should be 70 - 80% efficient. They should be individually tested to ensure they are in the appropriate range, and replaced or prepared as appropriate. Pumping stations should also be tested collectively, because where pumps can run in combination to meet a given demand, it is often possible for very inefficient combination of pumps to occur.

For example: it is perfectly possible to have a large and a small pump operating in parallel, with the smaller pump not delivering any water, but merely consuming energy. Pumps are readily tested by fitting a flow meter, measuring the pressure difference between inlet and outlet, and measuring the power consumed. Another method is thermodynamic pump testing where only the temperature rise and power consumed need be measured.

Depending on how the measurement is taken suction lift and head may also be referred to as static or dynamic. Static indicates the measurement does not take into account the friction caused by water moving through the hose or pipes.

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-POINT "B" IS HIGHER THAN POINT "A"
-NECESSARY TO ADD ENERGY TO LIQUID TO GET FROM "A' TO "B'
-AMOUNT IS EQUAL TO THE DIFFERENCE IN ELEVATION BETWEEN
 POINT "A" AND POINT "B", ASSUMING FRICTION LOSS.

B

A

FLOW

CENTRIFUGAL
PUMP

CENTRIFUGAL PUMP CURVE CHARACTERISITICS

STATIC PRESSURE

DISCHARGE PRESSURE

VAPOR PRESSURE

NO BUBBLE FORMATION

SUCTION   IMPELLER EYE   DISCHARGE

STATIC PRESSURE

DISCHARGE PRESSURE

VAPOR PRESSURE

BUBBLE FORMATION

SUCTION   IMPELLER EYE   DISCHARGE

DISCHARGE

EYE

SUCTION

*NO BUBBLE FORMATION UNDER NORMAL
 OPERATING CONDITIONS

*LOW SUCTION PRESSURE CAN CAUSE
 FLUID TO START BOILING

*BOILING STARTS WHEN PRESSURE IN LIQUID
 IS REDUCED TO VAPOR PRESSURE OF THE
 FLUID AT ACTUAL TEMPERATURE

*CAUSES:
 REDUCED PUMP EFFCIENCY
 CAVITATION IN PUMP
 PUMP DAMAGE

NET POSITIVE SUCTION HEAD

$$WHP = \frac{Q \times H}{3960}$$

TIME
ELAPSED

DISTANCE

Q= FLUID FLOW RATE (gal/min)

H= TOTAL DYNAMIC HEAD (feet)

3960= FACTOR THAT CONVERTS
HORSEPOWER INTO PUMPING TERMS
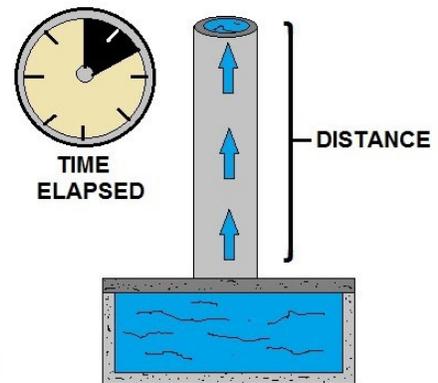
WATER HORSEPOWER

(THE ENERGY ADDED TO THE WATER BY THE PUMP ITSELF)
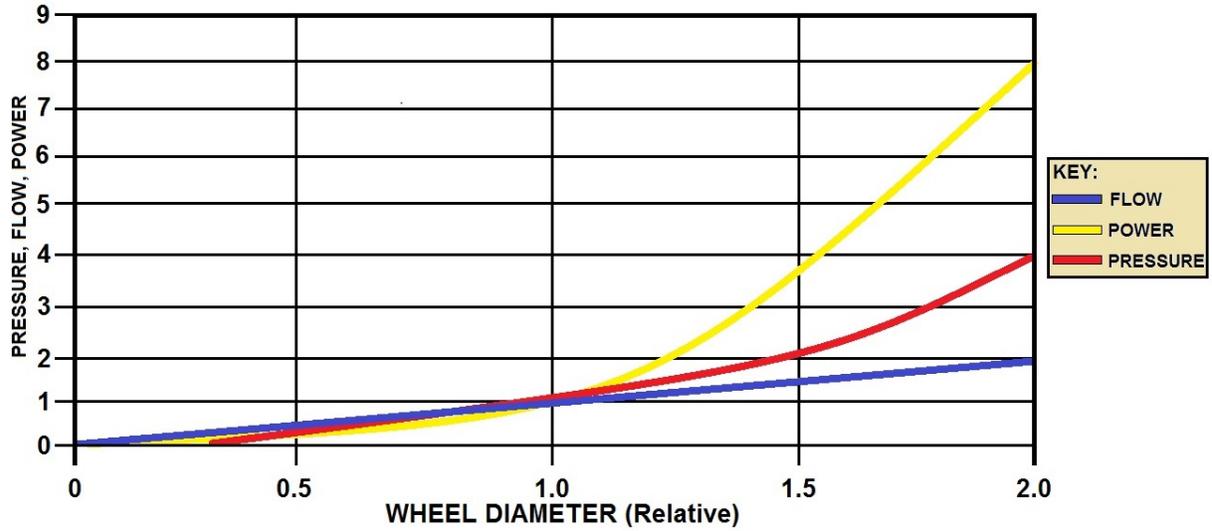
PUMP AFFINITY LAWS

(PUMP AFFINITY INDICATES THE INFLUENCE ON VOLUME CAPACITY, HEAD PRESSURE, AND POWER   CONSUMPTION
OF A PUMP DUE TO CHANGE IN SPEED OF WHEEL (RPM) AND CHANGE IN IMPELLER DIAMETER)
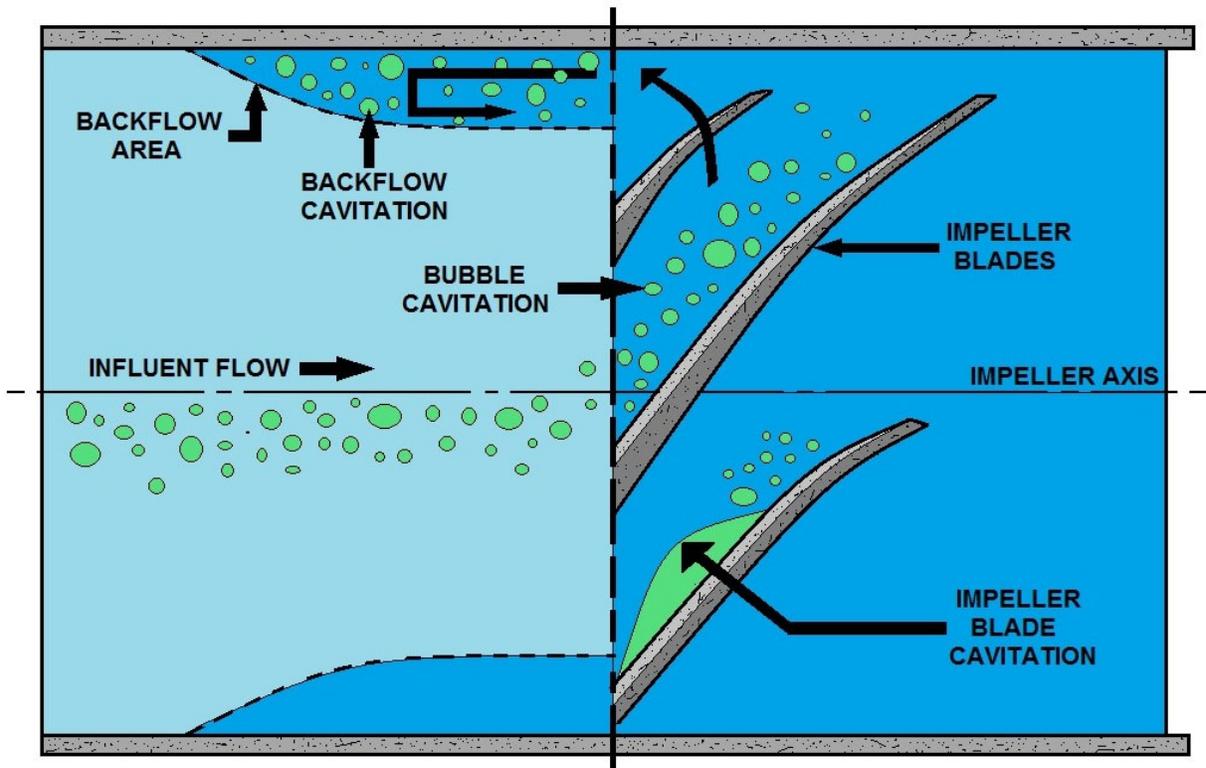
PUMP CAVITATION

Understanding Your Pumping System Requirements

Pumps transfer liquids from one point to another by converting mechanical energy from a rotating impeller into pressure energy (head). The pressure applied to the liquid forces the fluid to flow at the required rate and to overcome friction (or head) losses in piping, valves, fittings, and process equipment. The pumping system designer must consider fluid properties, determine end use requirements, and understand environmental conditions. Pumping applications include constant or variable flow rate requirements, serving single or networked loads, and consisting of open loops (non-return or liquid delivery) or closed loops (return systems).
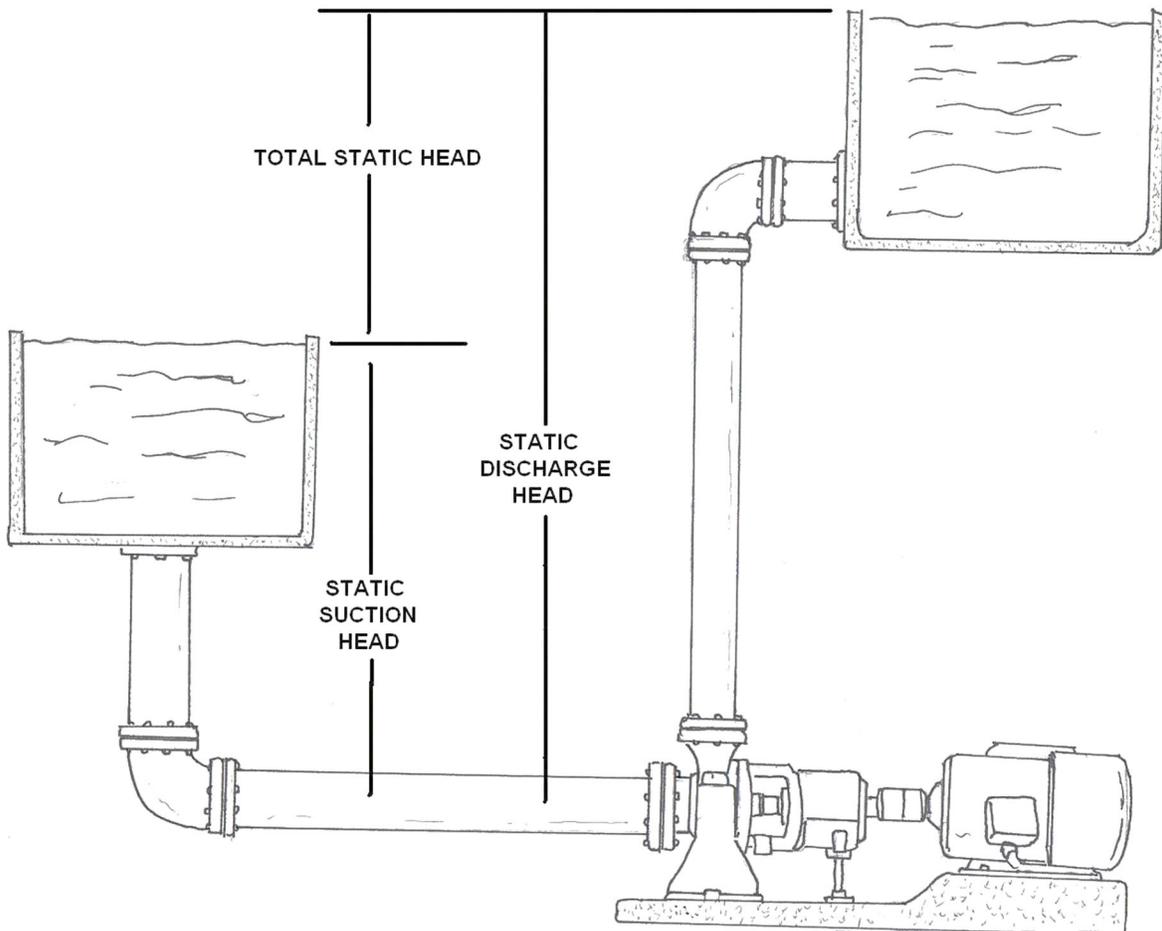
End Use Requirements—System Flow Rate and Head
The design pump capacity, or desired pump discharge in gallons per minute (gpm) is needed to accurately size the piping system, determine friction head losses, construct a system curve, and select a pump and drive motor.

Process requirements may be met by providing a constant flow rate (with on/off control and storage used to satisfy variable flow rate requirements), or by using a throttling valve or variable speed drive to supply continuously variable flow rates.

The total system head has three components: static head, elevation (potential energy), and velocity (or dynamic) head. Static head is the pressure of the fluid in the system, and is the

quantity measured by conventional pressure gauges. The height of the fluid level can have a substantial impact on system head.
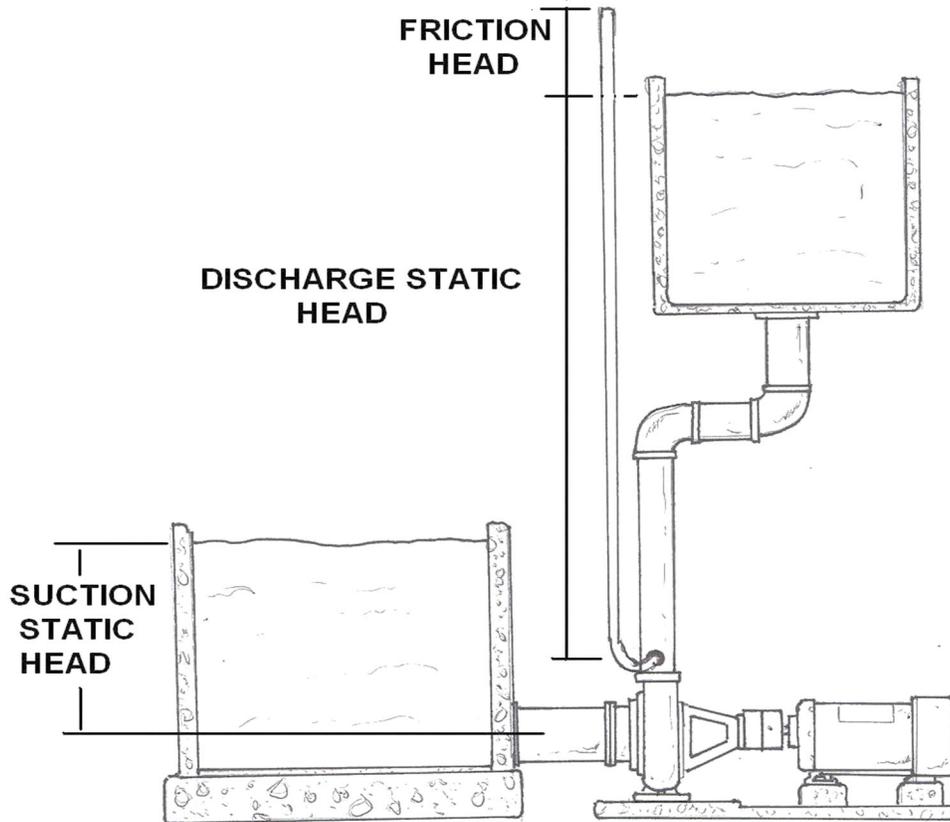
PUMPING FUNDAMENTALS

The dynamic head is the pressure required by the system to overcome head losses caused by flow rate resistance in pipes, valves, fittings, and mechanical equipment. Dynamic head losses are approximately proportional to the square of the fluid flow velocity, or flow rate. If the flow rate doubles, dynamic losses increase fourfold.

For many pumping systems, total system head requirements vary. For example, in wet well or reservoir applications, suction and static lift requirements may vary as the water surface elevations fluctuate. For return systems such as HVAC circulating water pumps, the values for the static and elevation heads equal zero. You also need to be aware of a pump's net positive suction head requirements.

Centrifugal pumps require a certain amount of fluid pressure at the inlet to avoid cavitation. A rule of thumb is to ensure that the suction head available exceeds that required by the pump by at least 25% over the range of expected flow rates.

Understanding Pump Viscosity

When to use a centrifugal or a Positive Displacement pump ("PD Pump") is not always a clear choice. To make a good choice between these pump types it is important to understand that these two types of pumps behave very differently.

First let's examine the density of the substance to be pumped. The density of a substance is defined as its mass per unit volume, but here on the earth's surface, we can substitute weight for mass. At 39-deg F (4-deg C), water has a density of 8.34 pounds per gallon or 62.43 pounds per cubic foot. In the metric system its density is one gram per cubic centimeter, or 1,000-kg per cubic meter.

Specific Gravity
The term specific gravity compares the density of some substance to the density of water. Since specific gravity is the ratio of those densities, the units of measure cancel themselves, and we end up with a dimensionless number that is the same for all systems of measure. Therefore, the specific gravity of water is 1— regardless of the measurement system. Specific gravity is important when sizing a centrifugal pump because it is indicative of the weight of the fluid and its weight will have a direct effect on the amount of work performed by the pump. One of the beauties of the centrifugal pump is that the head (in feet) and flow it produces has nothing to do with the weight of the liquid. It is all about the velocity that is added by the impeller.

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Understanding Pump Friction Loss
To optimize a fluid piping system, it is important to have a clear understanding of how the various system items interact. Regardless of the methods used to gain a thorough picture of piping system operations, a variety of calculations must be performed. Among the formulas are the Bernoulli equation to calculate the pressure in the system, and the Darcy-Weisbach equation, which is commonly used to calculate head loss in a pipe run. The Bernoulli Equation is a way of expressing the total energy of fluid as it flows through a pipe run

The Piping System
A piping system is configured of individual pipe runs connected in series and parallel combinations with pumps, control valves, flowmeters and components. It is essential to recognize how these unique elements interact and work together as a system. There are both graphical and analytical methods that provide an understanding of how the various items interact as a total system. The head loss is calculated using the graphical method for a variety of flow rates for each pipe run. The results can be read off the graph after the information is plotted. Using the analytical method, the results are calculated directly, which eliminates the need for further graphics.

In fluid dynamics, the Darcy–Weisbach equation is a phenomenological equation, which relates the head loss — or pressure loss — due to friction along a given length of pipe to the average velocity of the fluid flow. The equation is named after Henry Darcy and Julius Weisbach.

The Darcy–Weisbach equation contains a dimensionless friction factor, known as the Darcy friction factor. This is also called the Darcy–Weisbach friction factor or Moody friction factor. The Darcy friction factor is four times the Fanning friction factor, with which it should not be confused.
Head Loss Formula

Head loss can be calculated with

$$h_f = f_D \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$$

where

- h_f is the head loss due to friction (SI units: m);

- L is the length of the pipe (m);

- D is the hydraulic diameter of the pipe (for a pipe of circular section, this equals the internal diameter of the pipe) (m);

- *V* is the average velocity of the fluid flow, equal to the volumetric flow rate per unit cross-sectional wetted area (m/s);

- g is the local acceleration due to gravity (m/s^2);

- f_D is a dimensionless coefficient called the Darcy friction factor. It can be found from a Moody diagram or more precisely by solving the Colebrook equation. Do not confuse this with the Fanning Friction factor, f.

  However the establishment of the friction factors was still an unresolved issue which needed further work.

Darcy-Weisbach Formula
Flow of fluid through a pipe
The flow of liquid through a pipe is resisted by viscous shear stresses within the liquid and the turbulence that occurs along the internal walls of the pipe, created by the roughness of the pipe material. This resistance is usually known as pipe friction and is measured is feet or meters head of the fluid, thus the term head loss is also used to express the resistance to flow.

Many factors affect the head loss in pipes, the viscosity of the fluid being handled, the size of the pipes, the roughness of the internal surface of the pipes, the changes in elevations within the system and the length of travel of the fluid. The resistance through various valves and fittings will also contribute to the overall head loss. A method to model the resistances for valves and fittings is described elsewhere.

In a well-designed system the resistance through valves and fittings will be of minor significance to the overall head loss, many designers choose to ignore the head loss for valves and fittings at least in the initial stages of a design. Much research has been carried out over many years and various formulas to calculate head loss have been developed based on experimental data. Among these is the Chézy formula which dealt with water flow in open channels. Using the concept of 'wetted perimeter' and the internal diameter of a pipe the Chézy formula could be adapted to estimate the head loss in a pipe, although the constant 'C' had to be determined experimentally.

The Darcy-Weisbach Equation

Weisbach first proposed the equation we now know as the Darcy-Weisbach formula or Darcy-Weisbach equation:

hf = f (L/D) x (v2/2g)

where:
hf = head loss (m)
f = friction factor
L = length of pipe work (m)
d = inner diameter of pipe work (m)
v = velocity of fluid (m/s)
g = acceleration due to gravity (m/s²)
or:
hf = head loss (ft)
f = friction factor
L = length of pipe work (ft)
d = inner diameter of pipe work (ft)
v = velocity of fluid (ft/s)
g = acceleration due to gravity (ft/s²)

The Moody Chart
In 1944 LF Moody plotted the data from the Colebrook equation and this chart which is now known as 'The Moody Chart' or sometimes the Friction Factor Chart, enables a user to plot the Reynolds number and the Relative Roughness of the pipe and to establish a reasonably accurate value of the friction factor for turbulent flow conditions.

The Moody Chart encouraged the use of the Darcy-Weisbach friction factor and this quickly became the method of choice for hydraulic engineers.

Many forms of head loss calculator were developed to assist with the calculations, amongst these a round slide rule offered calculations for flow in pipes on one side and flow in open channels on the reverse side.

The development of the personnel computer from the 1980's onwards reduced the time needed to perform the friction factor and head loss calculations, which in turn has widened the use of the Darcy-Weisbach formula to the point that all other formula are now largely unused.

Pipe Runs

A piping system is composed primarily of individual pipe runs connecting all system elements together. Because a pipe run is the basic building block of a piping system, examine the losses associated with individual pipe runs when connected in series and parallel configurations. The pipe head loss in a single pipe run can easily be calculated using the Darcy-Weisbach equation. Performing the head loss calculation for a range of expected flow rates helps to develop a curve showing the pipe run head loss for any flow rate within a defined range. The Bernoulli equation allows for calculation of pressure anywhere in the pipe run.

Multiple pipe runs connected end-to-end form a "series" of individual pipe runs. The flow rate through each pipe run in a series configuration is identical. As a result, the head loss for a series of pipe runs is simply the sum of the head losses for each of the individual pipe runs. When multiple pipe runs are placed in parallel, determining the head loss through them becomes more difficult because the flow is distributed through the various pipe runs. The head loss across the parallel paths can be calculated after determining the flow rate in each pipe run and the head loss across each pipe run in a parallel configuration.

A component-including filters, strainers, towers, columns and heat exchangers-is an item placed in a piping system that has a head loss for a given flow rate. The function describing the head loss across the component versus the flow rate is similar to that of the head loss through valves and fittings.

Pump Curves
A pump curve describes the operation of a pump for a range of flows at a defined speed. Many design elements affect the shape of the pump curve, and most of these cannot be changed by the user. As a result, centrifugal pumps are usually selected from the manufacturer's available designs to match the system requirements. An engineered or assembled-to-order pump can be specified, and the manufacturer can often provide a pump performance characteristic well suited to the specific application depending on the type of pump. Characteristics that can be changed by users to change the pump (performance) curve are the impeller diameter and the rotational speed. The pump curve change will cause the pump curve to intersect the system curve at a different rate of flow. When selected properly, the pump will operate near its best efficiency point (BEP). This relationship of speed change or diameter change is often referred to as the pump affinity rules.

Control valves are inserted into a piping system to regulate the rate of flow or pressure in the piping system. Remember, control valves control the flow by providing a variable hydraulic resistance between the upstream and downstream components in the system. In other words, the control valve does not change the basic shape of the system curve; it provides additional resistance to the system to enable the valve to control the flow.

System Curves
Pump and system curves can illustrate the basic interaction in the total system. Pump and system curves consist of a system curve showing the head required to pass a given flow rate through the piping system, and a pump curve superimposed on the system curve. The point where the system curve and the pump curve intersect is the balanced flow rate through the pump. In the absence of control valves, the system will operate at the intersection of the pump and system curves.

- SIMPLE SYSTEM (POINT "A" AND "B" ON SAME LEVEL)
- FRICTION LOSS THROUGH SYSTEM INCREASES AS CAPACITY (VELOCITY) INCREASES
- NO FRICTION LOSS AT ZERO FLOW

FLOW

A

B

CENTRIFUGAL PUMP

CENTRIFUGAL PUMP CURVE CHARACTERISITICS

-POINT "B" IS HIGHER THAN POINT "A"
-NECESSARY TO ADD ENERGY TO LIQUID TO GET FROM "A' TO "B'
-AMOUNT IS EQUAL TO THE DIFFERENCE IN ELEVATION BETWEEN
 POINT "A" AND POINT "B", ASSUMING FRICTION LOSS.

B

A

FLOW
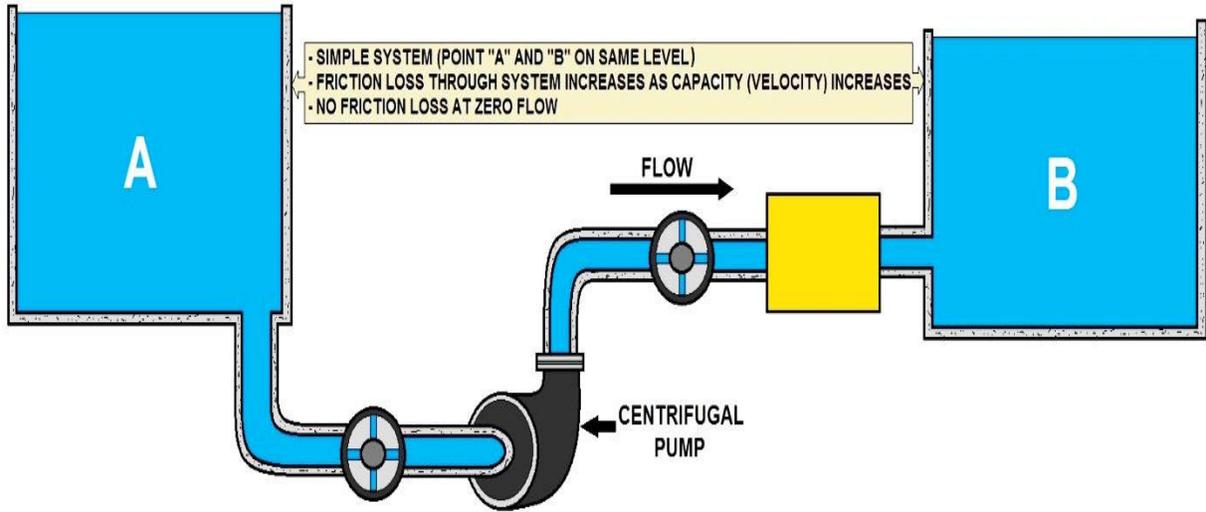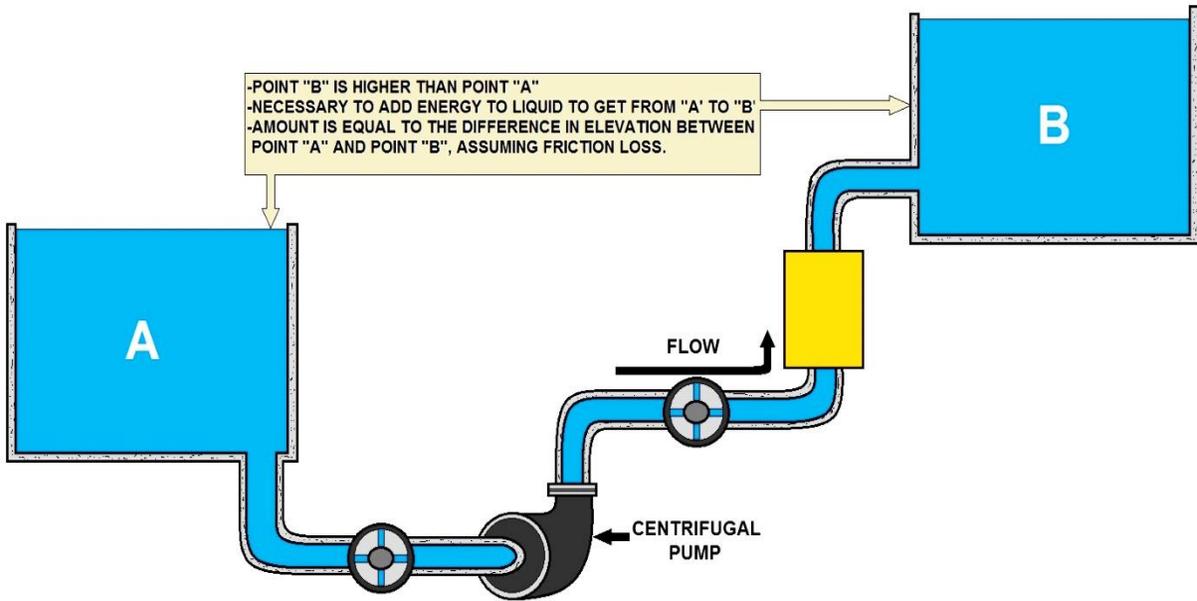
CENTRIFUGAL PUMP

CENTRIFUGAL PUMP CURVE CHARACTERISITICS

Screw or Auger Pump

The Archimedes' screw, Archimedean screw, or screwpump is a machine historically used for transferring water from a low-lying body of water into irrigation ditches. It was one of several inventions and discoveries traditionally attributed to Archimedes in the 3rd century BC.

FILL POINT

THRESHOLD LEVEL

SCREWS ROTATE IN A TIGHT
FITTING FIXED CHANNEL
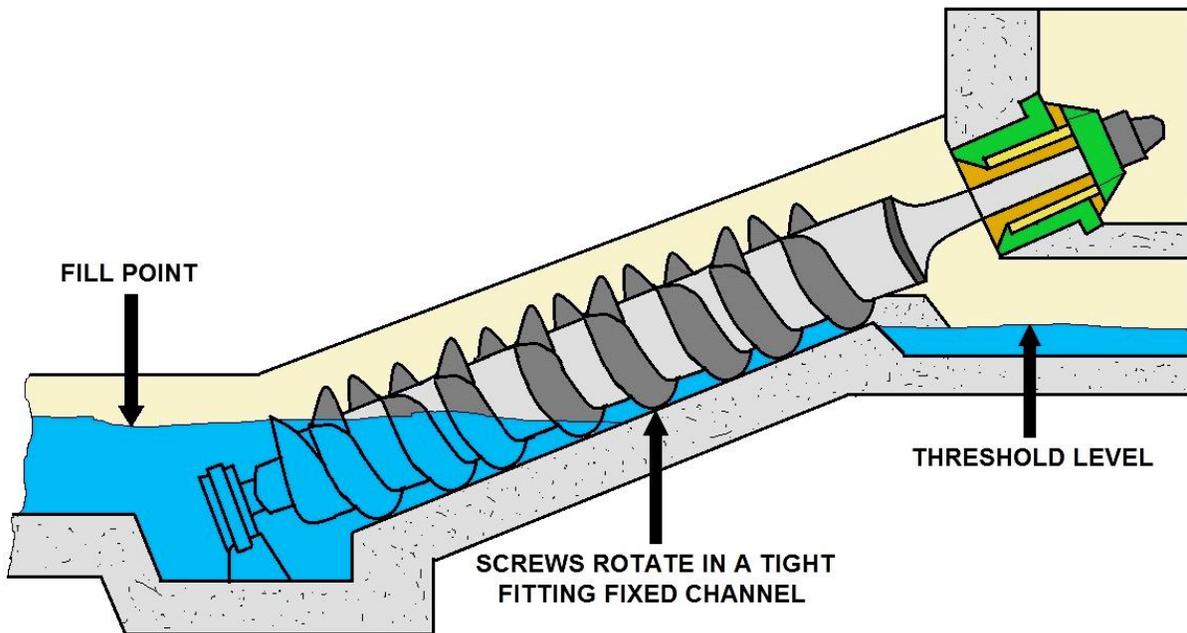
AUGER PUMP

The machine consists of a screw inside a hollow pipe. Some attribute its invention to Archimedes in the 3rd century BC, while others attribute it to Nebuchadnezzar II in the 7th century BC. A screw can be thought of as an inclined plane (another simple machine) wrapped around a cylinder.

The screw is turned (usually by a windmill or by manual labor). As the bottom end of the tube turns, it scoops up a volume of water. This amount of water will slide up in the spiral tube as the shaft is turned, until it finally pours out from the top of the tube and feeds the irrigation system.

The contact surface between the screw and the pipe does not need to be perfectly water-tight because of the relatively large amount of water being scooped at each turn with respect to the angular speed of the screw.

Also, water leaking from the top section of the screw leaks into the previous one and so on. So a sort of equilibrium is achieved while using the machine, thus preventing a decrease in efficiency.

The "screw" does not necessarily need to turn inside the casing, but can be allowed to turn with it in one piece.

A screw could be sealed with pitch or some other adhesive to its casing, or, cast as a single piece in bronze, as some researchers have postulated as being the devices used to irrigate Nebuchadnezzar II's Hanging Gardens of Babylon. Depictions of Greek and Roman water screws show the screws being powered by a human treading on the outer casing to turn the entire apparatus as one piece, which would require that the casing be rigidly attached to the screw.

In this type of pump, a large screw provides the mechanical action to move the liquid from the suction side to the discharge side of the pump. Here are some typical characteristics of screw pumps:

- Most screw pumps rotate in the 30 to 60 rpm range, although some screw pumps are faster.
- The slope of the screw is normally either 30° or 38°.

The maximum lift for the larger diameter pumps is about 30 feet. The smaller diameter pumps have lower lift capabilities.
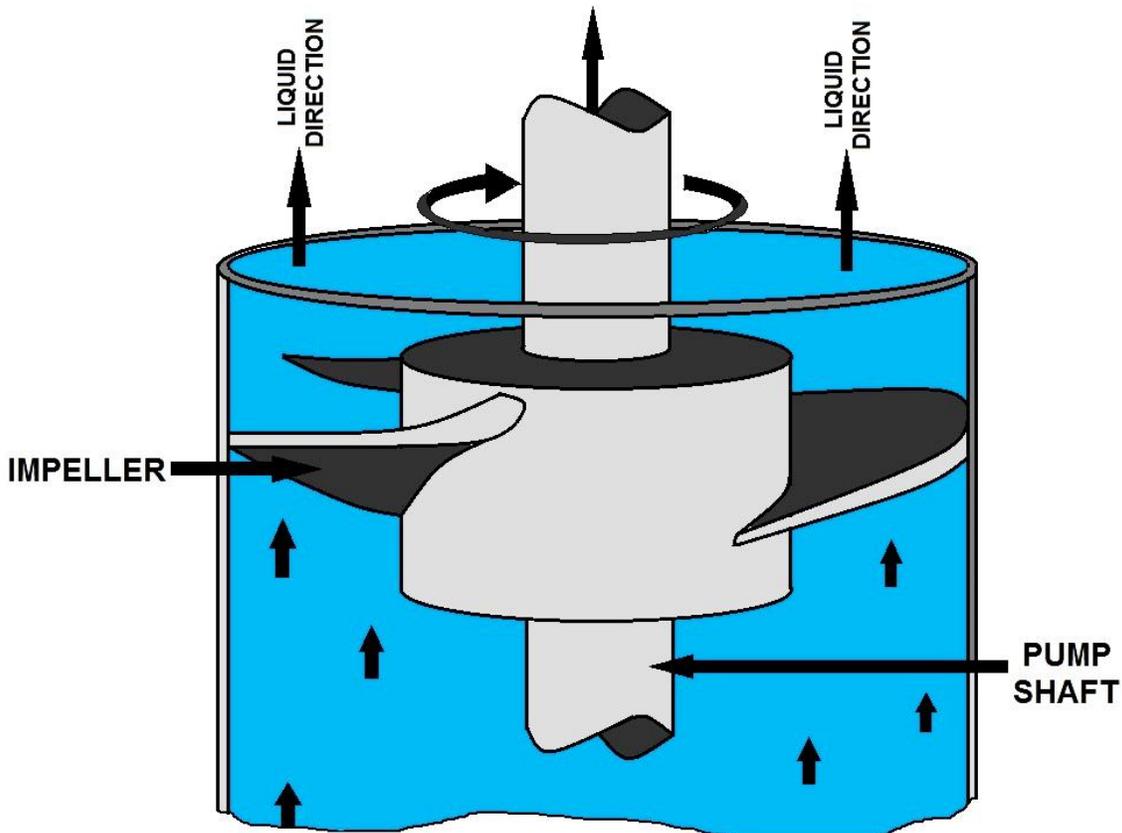
AXIAL FLOW PUMP PRINCIPAL
(IMPELLER FORCES LIQUID IN DIRECTION PARALLEL TO SHAFT)

Reciprocating Pumps

Typical reciprocating pumps are
- plunger pumps
- diaphragm pumps

A plunger pump consists of a cylinder with a reciprocating plunger in it. The suction and discharge valves are mounted in the head of the cylinder. In the suction stroke the plunger retracts and the suction valves open causing suction of fluid into the cylinder. In the forward stroke the plunger pushes the liquid out of the discharge valve.

With only one cylinder the fluid flow varies between maximum flow when the plunger moves through the middle positions and zero flow when the plunger is at the end positions. A lot of energy is wasted when the fluid is accelerated in the piping system. Vibration and "water hammer" may be a serious problem. In general the problems are compensated for by using two or more cylinders not working in phase with each other.

In diaphragm pumps, the plunger pressurizes hydraulic oil which is used to flex a diaphragm in the pumping cylinder. Diaphragm valves are used to pump hazardous and toxic fluids. An example of the piston displacement pump is the common hand soap pump.

Gear Pump
This uses two meshed gears rotating in a closely fitted casing. Fluid is pumped around the outer periphery by being trapped in the tooth spaces. It does not travel back on the meshed part, since the teeth mesh closely in the center. Widely used on car engine oil pumps. It is also used in various hydraulic power packs.

Progressing Cavity Pump
Widely used for pumping difficult materials such as sewage sludge contaminated with large particles, this pump consists of a helical shaped rotor, about ten times as long as its width. This can be visualized as a central core of diameter x, with typically a curved spiral wound around of thickness half x, although of course in reality it is made from one casting.

This shaft fits inside a heavy duty rubber sleeve, of wall thickness typically x also. As the shaft rotates, fluid is gradually forced up the rubber sleeve. Such pumps can develop very high pressure at quite low volumes.

Diaphragm Pumps
A diaphragm pump is a positive displacement pump that uses a combination of the reciprocating action of a rubber, thermoplastic or Teflon diaphragm and suitable non-return check valves to pump a fluid. Sometimes this type of pump is also called a membrane pump. Diaphragm Pumps are used extensively in many industries and can handle a very wide variety of liquids. Diaphragm Pumps are in the category of "positive displacement" pumps because their flow rates do not vary much with the discharge "head" (or pressure) the pump is working against (for a given pump speed).

Diaphragm Pumps can transfer liquids with low, medium or high viscosities and also liquids with a large solids content. They can also handle many aggressive chemicals such as acids because they can be constructed with a wide variety of body materials and diaphragms.

There are three main types of diaphragm pumps:
- ✓ Those in which the diaphragm is sealed with one side in the fluid to be pumped, and the other in air or hydraulic fluid. The diaphragm is flexed, causing the volume of the pump chamber to increase and decrease. A pair of non-return check valves prevent reverse flow of the fluid.
- ✓ Those employing volumetric positive displacement where the prime mover of the diaphragm is electro-mechanical, working through a crank or geared motor drive. This method flexes the diaphragm through simple mechanical action, and one side of the diaphragm is open to air.
- ✓ Those employing one or more unsealed diaphragms with the fluid to be pumped on both sides. The diaphragm(s) again are flexed, causing the volume to change.

When the volume of a chamber of either type of pump is increased (the diaphragm moving up), the pressure decreases, and fluid is drawn into the chamber.

When the chamber pressure later increases from decreased volume (the diaphragm moving down), the fluid previously drawn in is forced out.

Finally, the diaphragm moving up once again draws fluid into the chamber, completing the cycle. This action is similar to that of the cylinder in an internal combustion engine. The most popular type of diaphragm pump is the Air-Operated Diaphragm Pump.

These pumps use compressed air as their power supply. They also include two chambers with a diaphragm, inlet check valve and outlet check valve in each chamber. The air supply is shifted from one chamber to another with an air spool valve that is built into the pump.

This continual shifting of air from one chamber to another (to the backside of the diaphragm) forces liquid out of one chamber and into the discharge piping while the other chamber is being filled with liquid. There is some pulsation of discharge flow in Air-Operated Diaphragm Pumps. This pulsating flow can be reduced somewhat by using pulsation dampeners in the discharge piping.

Characteristics
Diaphragm Pumps:
- ✓ have good suction lift characteristics, some are low pressure pumps with low flow rates; others are capable of higher flow rates, dependent on the effective working diameter of the diaphragm and its stroke length. They can handle sludges and slurries with a relatively high amount of grit and solid content.
- ✓ suitable for discharge pressure up to 1,200 bar.
- ✓ have good dry running characteristics.
- ✓ can be used to make artificial hearts.
- ✓ are used to make air pumps for the filters on small fish tanks.
- ✓ can be up to 97% efficient.
- ✓ have good self-priming capabilities.
- ✓ can handle highly viscous liquids.
- ✓ are available for industrial, chemical and hygienic applications.
- ✓ cause a pulsating flow that may cause water hammer.

Vapor Pressure and Cavitation

Cavitation is the formation and then immediate implosion of cavities in a liquid – i.e. small liquid-free zones ("bubbles") – that are the consequence of forces acting upon the liquid. It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities where the pressure is relatively low. Cavitation is a significant cause of wear in some engineering contexts. When entering high pressure areas, cavitation bubbles that implode on a metal surface cause cyclic stress. These results in surface fatigue of the metal causing a type of wear also called "cavitation". The most common examples of this kind of wear are pump impellers and bends when a sudden change in the direction of liquid occurs. Cavitation is usually divided into two classes of behavior: inertial (or transient) cavitation and non-inertial cavitation.
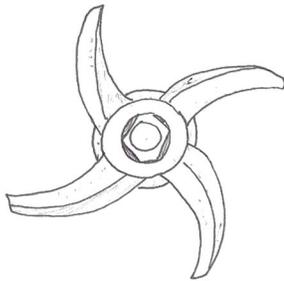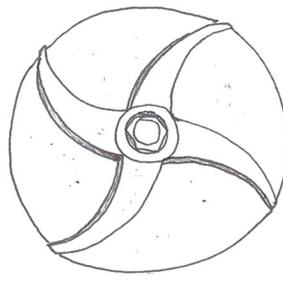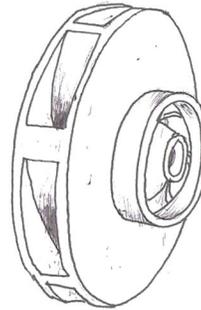
| OPEN | SEMI-OPEN | CLOSED |

IMPELLER TYPES

Inertial Cavitation
Inertial cavitation is the process where a void or bubble in a liquid rapidly collapses, producing a shock wave. Inertial cavitation occurs in nature in the strikes of mantis shrimps and pistol shrimps, as well as in the vascular tissues of plants. In man-made objects, it can occur in control valves, pumps, propellers and impellers.

Non-inertial Cavitation
Non-inertial cavitation is the process in which a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field. Such cavitation is often employed in ultrasonic cleaning baths and can also be observed in pumps, propellers, etc. Since the shock waves formed by cavitation are strong enough to significantly damage moving parts, cavitation is usually an undesirable phenomenon. It is specifically avoided in the design of machines such as turbines or propellers, and eliminating cavitation is a major field in the study of fluid dynamics.

To understand Cavitation, you must first understand vapor pressure. Vapor pressure is the pressure required to boil a liquid at a given temperature. Soda water is a good example of a high vapor pressure liquid. Even at room temperature the carbon dioxide entrained in the soda is released. In a closed container, the soda is pressurized, keeping the vapor entrained.

Temperature affects vapor pressure as well, raises the water's temperature to 212°F and the vapors are released because at that increased temperature the vapor pressure is greater than the atmospheric pressure.

Pump cavitation occurs when the pressure in the pump inlet drops below the vapor pressure of the liquid. Vapor bubbles form at the inlet of the pump and are moved to the discharge of the pump where they collapse, often taking small pieces of the pump with them. Cavitation is often characterized by:
- ✓ Loud noise often described as a grinding or "marbles" in the pump.
- ✓ Loss of capacity (bubbles are now taking up space where liquid should be).
- ✓
- ✓ Pitting damage to parts as material is removed by the collapsing bubbles.

Noise is a nuisance and lower flows will slow your process, but pitting damage will ultimately decrease the life of the pump.

In general, cavitation performance is related to some "critical" value:
NPSHA (=available) > NPSHc or NPSHR (=critical or required)
Typical "critical" characteristics identified for centrifugal pumps:
• Incipient cavitation (NPSHi)
• Developed cavitation causing 3% head drop (NPSH3%)
• Developed cavitation causing complete head breakdown(vapor lock).

Choice of NPSHR is rather arbitrary, but usually NPSHR=NPSH3%
Alternative choices:
      • NPSHR=NPSH1% or NPSHR=NPSH5%
      • NPSHR=NPSHi (cavitation free operation)

Cavitation causes or may cause:
      • Performance loss (head drop)
      • Material damage (cavitation erosion)
      • Vibrations
      • Noise
      • Vapor lock (if suction pressure drops below break-off value)

The definition of NPSHA is simple: Static head + surface pressure head - the vapor pressure of your product - the friction losses in the piping, valves and fittings. But to really understand it, you first have to understand a couple of other concepts:
- ✓ Cavitation is what net positive suction head (NPSH) is all about, so you need to know a little about cavitation.
- ✓ Vapor Pressure is another term we will be using. The product's vapor pressure varies with the fluid's temperature.
- ✓ Specific gravity play an important part in all calculations involving liquid. You have to be familiar with the term.
- ✓ You have to be able to read a pump curve to learn the N.P.S.H. required for your pump.
- ✓ You need to understand how the liquid's velocity affects its pressure or head.
- ✓ It is important to understand why we use the term Head instead of Pressure when we make our calculations.
- ✓ Head loss is an awkward term, but you will need to understand it.

You will have to be able to calculate the head loss through piping, valves and fittings.
- ✓ You must know the difference between gage pressure and absolute pressure.
- ✓ Vacuum is often a part of the calculations, so you are going to have to be familiar with the terms we use to describe vacuum.

Let's look at each of these concepts in a little more detail:
- ✓ Cavitation means cavities or holes in liquid. Another name for a hole in a liquid is a bubble, so cavitation is all about bubbles forming and collapsing.
- ✓ Bubbles take up space so the capacity of our pump drops.
- ✓ Collapsing bubbles can damage the impeller and volute. This makes cavitation a problem for both the pump and the mechanical seal.
- ✓ Vapor pressure is about liquids boiling. If I asked you, "at what temperature does water boil?" You could say 212° F. or 100° C., but that is only true at atmospheric pressure. Every product will boil (make bubbles) at some combination of pressure and temperature. If you know the temperature of your product you need to know its vapor pressure to prevent boiling and the formation of bubbles. In the charts section of this web site you will find a vapor pressure chart for several common liquids.
- ✓ Specific gravity is about the weight of the fluid. Using 4°C (39° F) as our temperature standard we assign fresh water a value of one. If the fluid floats on this fresh water it has a specific gravity is less than one. If the fluid sinks in this water the specific gravity of the fluid is greater than one.
- ✓ Look at any pump curve and make sure you can locate the values for head, capacity, best efficiency point (B.E.P.), efficiency, net positive suction head (NPSH), and horse power required. If you cannot do this, have someone show you where they are located.
- ✓ Liquid velocity is another important concept. As a liquid's velocity increases, its pressure (90° to the flow) decreases. If the velocity decreases the pressure increases. The rule is : velocity times pressure must remain a constant.
- ✓ "Head" is the term we use instead of pressure. The pump will pump any liquid to a given height or head depending upon the diameter and speed of the impeller. The amount of pressure you get depends upon the weight (specific gravity) of the liquid. The pump manufacturer does not know what liquid the pump will be pumping so he gives you only the head that the pump will generate. You have to figure out the pressure using a formula described later on in this paper.
- ✓ Head (feet) is a convenient term because when combined with capacity (gallons or pounds per minute) you come up with the conversion for horsepower (foot pounds per minute).
- ✓ "Head loss through the piping, valves and fittings" is another term we will be using. Pressure drop is a more comfortable term for most people, but the term "pressure" is not used in most pump calculations so you could substitute the term "head drop" or "loss of head" in the system. To calculate this loss you will need to be able to read charts like those you will find in the "charts you can use" section in the home page of this web site. They are labeled Friction loss for water and Resistance coefficients for valves and fittings.
- ✓ Gage and absolute pressure. Add atmospheric pressure to the gage pressure and you get absolute pressure.
- ✓ Vacuum is a pressure less than atmospheric. At sea level atmospheric pressure is 14.7 psi. (760 mm of Mercury). Vacuum gages are normally calibrated in inches or millimeters of mercury.

To calculate the net positive suction head (NPSH) of your pump and determine if you are going to have a cavitation problem, you will need access to several additional pieces of information:

- ✓ The curve for your pump. This pump curve is supplied by the pump manufacturer. Someone in your plant should have a copy. The curve is going to show you the Net Positive Suction Head (NPSH) required for your pump at a given capacity. Each pump is different so make sure you have the correct pump curve and use the numbers for the impeller diameter on your pump. Keep in mind that this NPSH required was for cold, fresh water.
- ✓ A chart or some type of publication that will give you the vapor pressure of the fluid you are pumping.
- ✓ If you would like to be a little more exact, you can use a chart to show the possible reduction in NPSH required if you are pumping hot water or light hydrocarbons.
- ✓ You need to know the specific gravity of your fluid. Keep in mind that the number is temperature sensitive. You can get this number from a published chart, ask some knowledgeable person at your plant, or take a reading on the fluid using a hydrometer.
- ✓ Charts showing the head loss through the size of piping you are using between the source and the suction eye of your pump. You will also need charts to calculate the loss in any fittings, valves, or other hardware that might have been installed in the suction piping.
- ✓ Is the tank you are pumping from at atmospheric pressure or is it pressurized in some manner? Maybe it is under a vacuum ?
- ✓ You need to know the atmospheric pressure at the time you are making your calculation. We all know atmospheric pressure changes throughout the day, but you have to start somewhere.

The formulas for converting pressure to head and head back to pressure in the imperial system are as follows:

o sg. = specific gravity
o pressure = pounds per square inch
o head = feet
You also need to know the formulas that show you how to convert vacuum readings to feet of head. Here are a few of them:

To convert surface pressure to feet of liquid; use one of the following formulas:

- ✓ Inches of mercury x 1.133 / specific gravity = feet of liquid

- ✓ Pounds per square inch x 2.31 / specific gravity = feet of liquid

- ✓ Millimeters of mercury / (22.4 x specific gravity) = feet of liquid

There are different ways to think about net positive suction head (NPSH) but they all have two terms in common.

- ✓ NPSHA (net positive suction head available)

- ✓ NPSHR (net positive suction head required)

Peristaltic Pumps

A peristaltic pump is a type of positive displacement pump used for pumping a variety of fluids. The fluid is contained within a flexible tube fitted inside a circular pump casing (though linear peristaltic pumps have been made). A rotor with a number of "rollers", "shoes" or "wipers" attached to the external circumference compresses the flexible tube. As the rotor turns, the part of the tube under compression closes (or "occludes") thus forcing the fluid to be pumped to move through the tube. Additionally, as the tube opens to its natural state after the passing of the cam ("restitution") fluid flow is induced to the pump. This process is called peristalsis and is used in many biological systems such as the gastrointestinal tract.

Priming a Pump
Liquid and slurry pumps can lose prime and this will require the pump to be primed by adding liquid to the pump and inlet pipes to get the pump started. Loss of "prime" is usually due to ingestion of air into the pump. The clearances and displacement ratios in pumps used for liquids and other more viscous fluids cannot displace the air due to its lower density.

Plunger Pumps
Plunger pumps are reciprocating positive displacement pumps. They consist of a cylinder with a reciprocating plunger in them. The suction and discharge valves are mounted in the head of the cylinder. In the suction stroke the plunger retracts and the suction valves open causing suction of fluid into the cylinder. In the forward stroke the plunger pushes the liquid out of the discharge valve.

Efficiency and Common Problems
With only one cylinder in plunger pumps, the fluid flow varies between maximum flow when the plunger moves through the middle positions and zero flow when the plunger is at the end positions.

A lot of energy is wasted when the fluid is accelerated in the piping system. Vibration and "water hammer" may be a serious problem. In general the problems are compensated for by using two or more cylinders not working in phase with each other.

Priming a Pump
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Compressed-Air-Powered Double-Diaphragm Pumps
One modern application of positive displacement diaphragm pumps is compressed-air-powered double-diaphragm pumps. Run on compressed air these pumps are intrinsically safe by design, although all manufacturers offer ATEX certified models to comply with industry regulation. Commonly seen in all areas of industry from shipping to processing, Wilden Pumps, Graco, SandPiper or ARO are generally the larger of the brands.

They are relatively inexpensive and can be used for almost any duty from pumping water out of bunds, to pumping hydrochloric acid from secure storage (dependent on how the pump is manufactured – elastomers / body construction). Lift is normally limited to roughly 6m although heads can reach almost 200 Psi.

Impulse Pumps

Impulse pumps use pressure created by gas (usually air). In some impulse pumps the gas trapped in the liquid (usually water), is released and accumulated somewhere in the pump, creating a pressure which can push part of the liquid upwards.
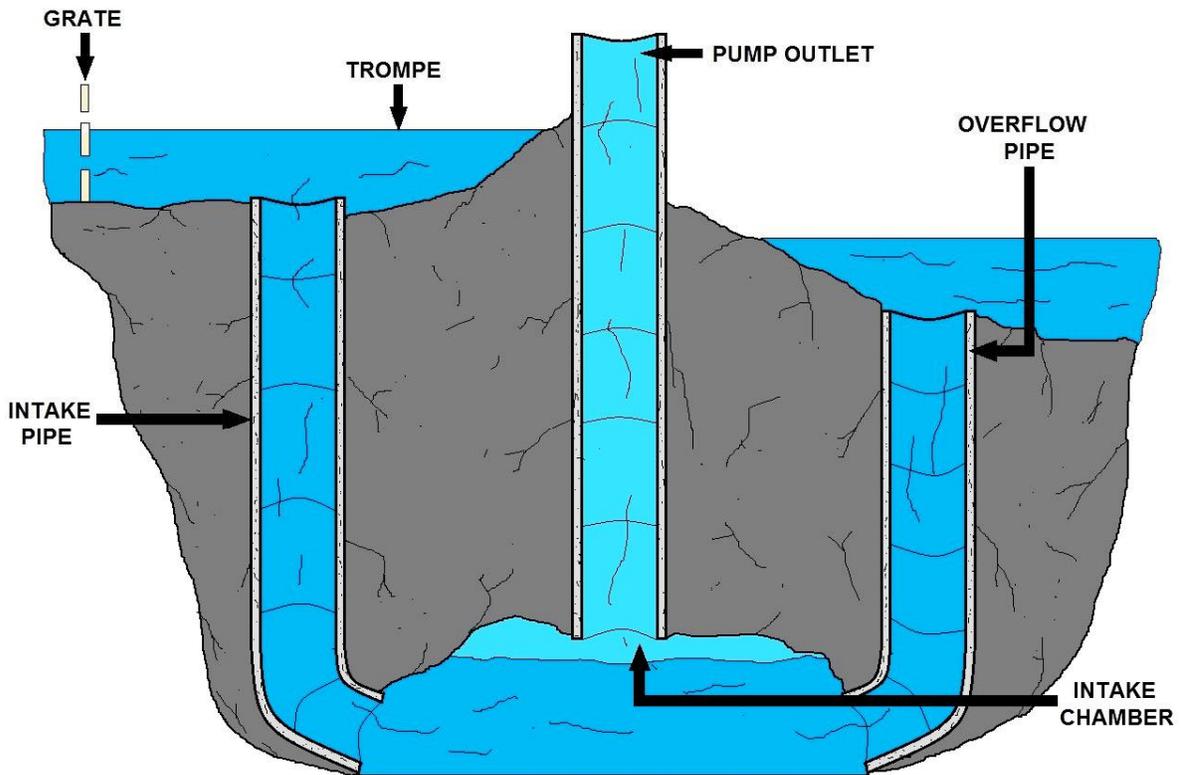
PULSER PUMP

Impulse pumps include:
- ✓ Hydraulic ram pumps - uses pressure built up internally from released gas in liquid flow.

- ✓ Pulser pumps - run with natural resources, by kinetic energy only.

- ✓ Airlift pumps - run on air inserted into pipe, pushing up the water, when bubbles move upward, or on pressure inside pipe pushing water up.

Hydraulic Ram Pumps
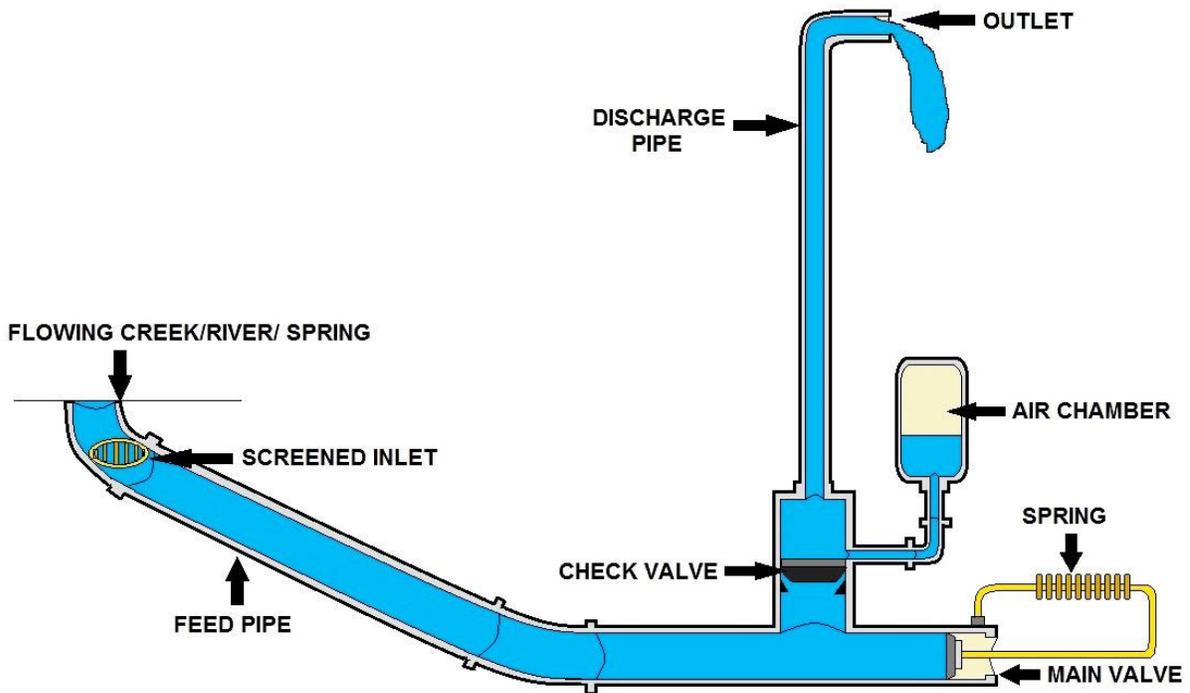
HYDRAULIC RAM PUMP

A hydraulic ram is a water pump powered by hydropower. It functions as a hydraulic transformer that takes in water at one "hydraulic head" (pressure) and flow-rate, and outputs water at a higher hydraulic-head and lower flow-rate. The device uses the water hammer effect to develop pressure that allows a portion of the input water that powers the pump to be lifted to a point higher than where the water originally started.

The hydraulic ram is sometimes used in remote areas, where there is both a source of low-head hydropower, and a need for pumping water to a destination higher in elevation than the source. In this situation, the ram is often useful, since it requires no outside source of power other than the kinetic energy of flowing water.

Velocity Pumps
Rotodynamic pumps (or dynamic pumps) are a type of velocity pump in which kinetic energy is added to the fluid by increasing the flow velocity. This increase in energy is converted to a gain in potential energy (pressure) when the velocity is reduced prior to or as the flow exits the pump into the discharge pipe.

This conversion of kinetic energy to pressure can be explained by the First law of thermodynamics or more specifically by Bernoulli's principle. Dynamic pumps can be further subdivided according to the means in which the velocity gain is achieved.

These types of pumps have a number of characteristics:
1. Continuous energy
2. Conversion of added energy to increase in kinetic energy (increase in velocity)
3. Conversion of increased velocity (kinetic energy) to an increase in pressure head

One practical difference between dynamic and positive displacement pumps is their ability to operate under closed valve conditions. Positive displacement pumps physically displace the fluid; hence closing a valve downstream of a positive displacement pump will result in a continual build up in pressure resulting in mechanical failure of either pipeline or pump. Dynamic pumps differ in that they can be safely operated under closed valve conditions (for short periods of time).
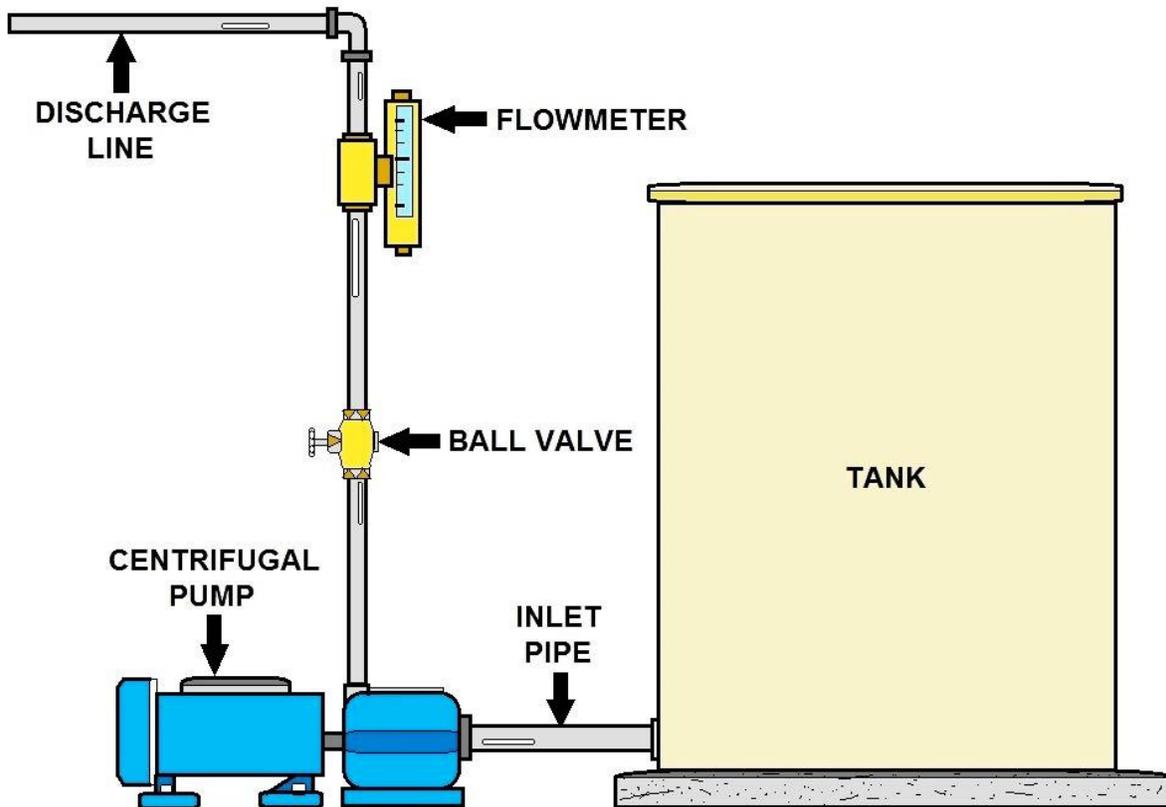
GRAVITY FEED SYSTEM

Gravity Pumps
Gravity pumps include the syphon and Heron's fountain – and there also important qanat or foggara systems which simply use downhill flow to take water from far-underground aquifers in high areas to consumers at lower elevations. The hydraulic ram is also sometimes referred to as a gravity pump.

Gravity
The ability of water to flow from higher to lower elevations makes a gravity system the one to utilize whenever possible. With no moving parts or energy inputs, these systems can provide dependable, low-maintenance service. To allow for flow resistance in the pipe, a minimum delivery pipe diameter 1 1/4 in. should be used where the grade is over l%. For grades between 0.5% and 1.0%, a 1 1/2 in. minimum size is recommended. Grades less than 0.2% are not recommended for gravity systems. Lay the delivery pipe on a uniform grade to prevent airlocks from forming. Water tank volume should reflect livestock numbers and water demand. If necessary, add gravel to ensure the tank area is stable to withstand herd traffic. A float at the water tank or an overflow outlet would control these conditions. Put a shade canopy over the tank to control seasonal algae growth.
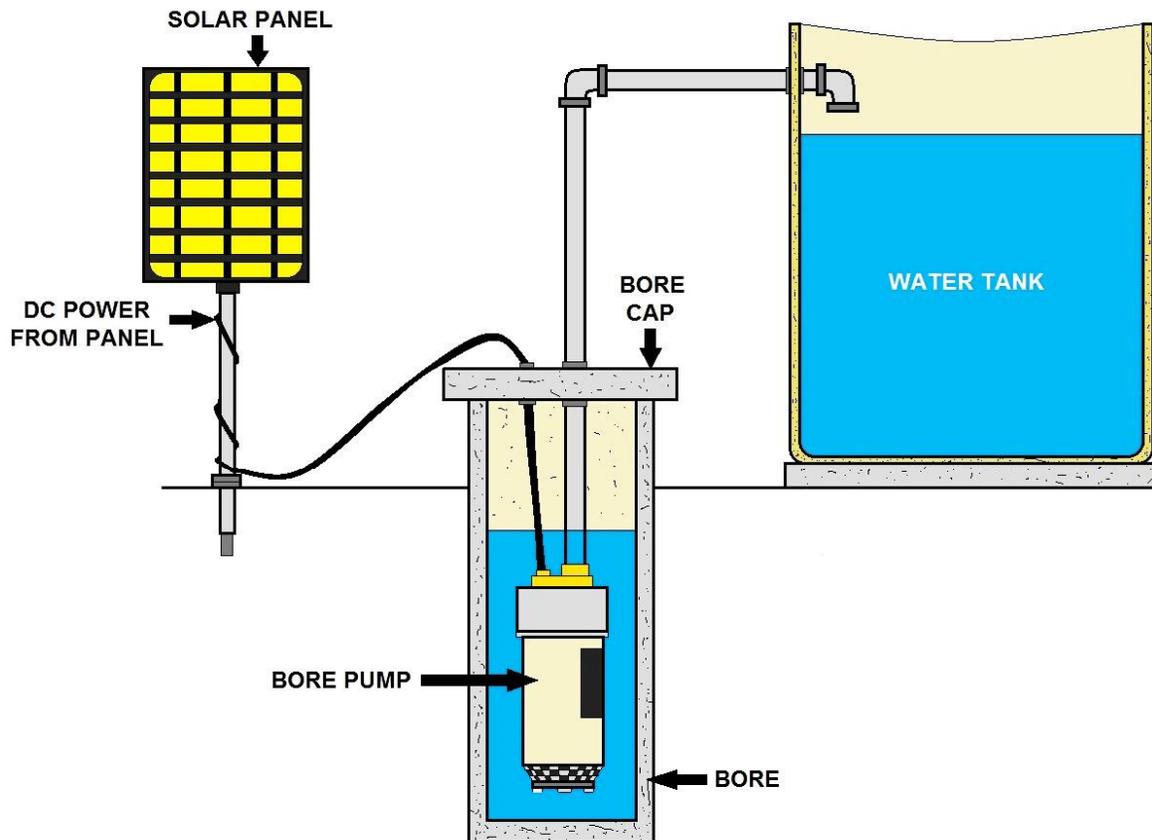
SOLAR WATER PUMP

Solar Power
Photovoltaic (PV) or solar panels can be used to power pumping systems for a wide range of output requirements. Solar systems can be very reliable and low in maintenance, but are expensive and require good design for practical service. Two system designs can be used depending upon the application.

Both systems involve storing energy to compensate for variances in solar radiation intensity. Systems that use energy storage in the form of pumped water held in an elevated reservoir have the advantage of design simplicity. Solar panels supply power to the water pump through a maximum power point device to deliver water to the reservoir only during periods of bright sunlight. Water from the reservoir is gravity fed to the stock trough and controlled by a float valve. Battery systems also store energy for use during periods of low sunlight intensity. Through a sequencing device, solar panels charge the batteries that power the water pump. Pump operation is controlled by an electric float switch to allow flow on demand to the stock trough. Proper design of a solar system is critical to meet the specific needs of the user. Consider a suntracker if you are concerned about space for sufficient number of panels. A tracker follows the sun as the day progresses and maximizes panel exposure to the sun.

Heissler Pump

This pump was designed by Paul Heissler of Frankford, Ontario. It is an inexpensive system and can be built from materials around the farm. It has a 12 volt submersible pump sitting in shallow water driven by a tractor battery. A 45 gallon drum acts as a reservoir with a float to control water level. A small trough is attached. Water flows into the trough by gravity as the livestock drink it down. The pump will deliver 22 gallons per minute. The battery is covered to protect it from the weather. This unit sits on top of the reservoir. The height and distance water is pumped limits the use of the Heissler pump. The more energy required for pumping water the more often the battery needs recharging. The battery charge has lasted 24 days, drawing water up 10 ft and providing water to 44 head of cattle.

Hydraulic Rams

Hydraulic ram pumps have been used since the 1700s. New designs with the same principles are being used today. Falling water is required to operate a hydraulic ram pump. If installed correctly the pump moves water as high as 10 times the fall. The weight of falling water drives a lesser amount to an elevation above the source of supply. The pump operates on the basis of the falling water opening and closing 2 valves with air pressure forcing the water to its destination.

The volume of water a ram pumps depends on the size of the pump, the fall between the source of supply and the ram, the height to which the water is to be raised and the quantity of water available. Output ranges from 700 to 3,000 gallons per day depending on these factors. A small stream is an excellent source to water livestock. Water needs to flow into the pump at 1 to 5 gallons per minute. A fall of 2 ft. or more is sufficient to drive a ram capable of pumping water to a stock trough at considerable elevation and distance. As the pumping rate is constant but generally slow, a storage reservoir may be necessary to accommodate high demand periods.

Hydraulic ram pumps are a time-tested technology that uses the energy of a large amount of water falling a small height to lift a small amount of that water to a much greater height. In this way, water from a spring or stream in a valley can be pumped to a village or irrigation scheme on the hillside.

Depending on the difference in heights between the inlet pipe and the outlet pipe, these water pumps will lift 1-20 percent of the water that flows into it. In general, a ram can pump approximately one tenth of the received water volume to a height ten times greater than the intake. A hydraulic ram pump is useful where the water source flows constantly and the usable fall from the water source to the pump location is at least 91 cm (3 ft).
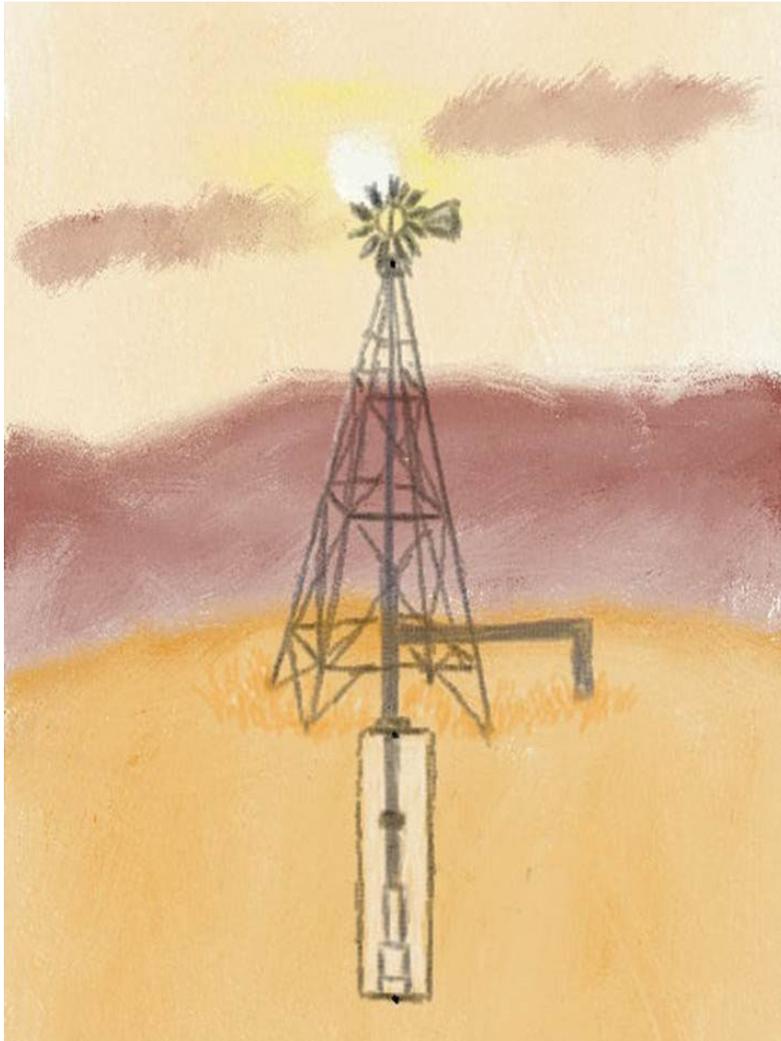
Wind Mills

In the past, windmills have been a proven part of the farm enterprise and could find greater use for livestock water purposes today. Though now a fairly expensive technology, currently manufactured windmills are reliable and need little maintenance, equal to their antique counterparts. Old windmills can be successfully rebuilt and may offer a practical alternative to the expense of new equipment. Modern windmills will operate in a stream, pond or shallow well. The pump sits on the surface or in the water.

An airline connects the pump to the windmill. Air pressure generated by the windmill activates the pump. Water is pumped when there is wind. The windmill can be located up to 300 ft. from the water source and at the best location to catch the wind. It can lift water up to 20 ft. and pump 5 gallons per minute. As wind is a variable energy source, use a storage reservoir to provide a supply for periods of low wind velocity. Locate the storage reservoir within 1,000 ft. of the water source.
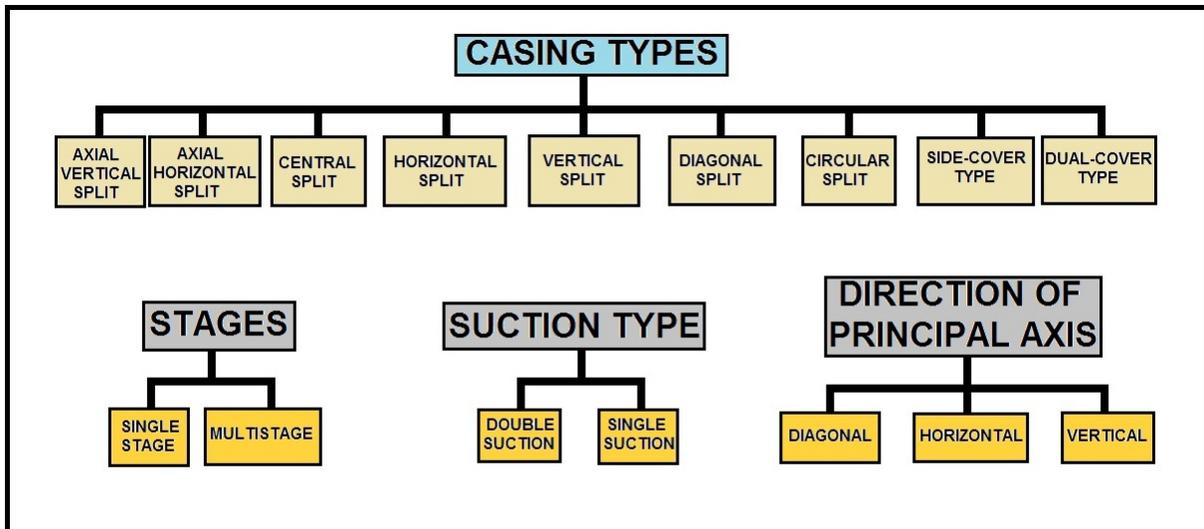
PUMP CONFIGURATIONS
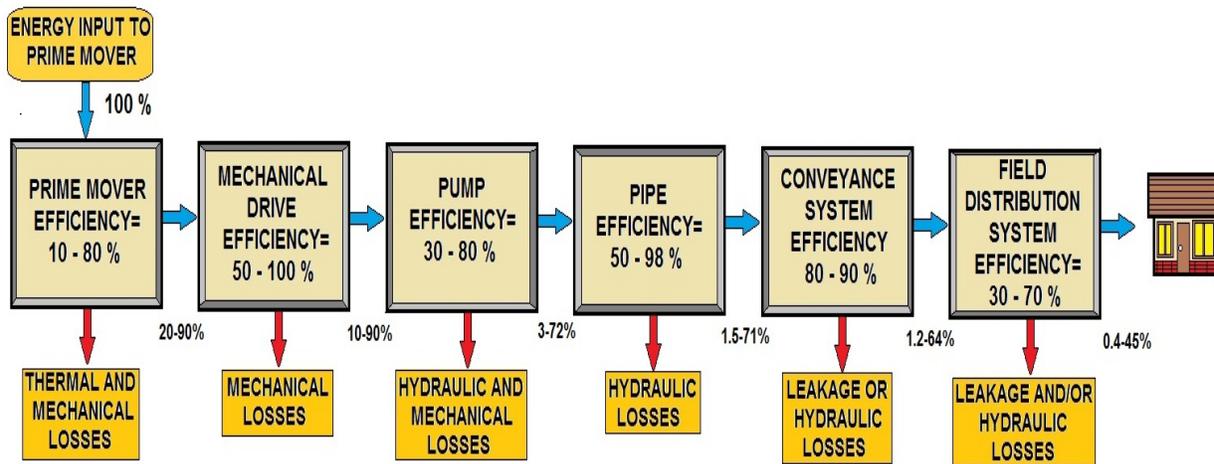
PUMPING EFFICIENCY

Understanding Pump NPSH

NPSH is an initialism for Net Positive Suction Head. In any cross-section of a generic hydraulic circuit, the NPSH parameter shows the difference between the actual pressure of a liquid in a pipeline and the liquid's vapor pressure at a given temperature. NPSH is an important parameter to take into account when designing a circuit: whenever the liquid pressure drops below the vapor pressure, liquid boiling occurs, and the final effect will be cavitation: vapor bubbles may reduce or stop the liquid flow, as well as damage the system.

Centrifugal pumps are particularly vulnerable especially when pumping heated solution near the vapor pressure, whereas positive displacement pumps are less affected by cavitation, as they are better able to pump two-phase flow (the mixture of gas and liquid), however, the resultant flow rate of the pump will be diminished because of the gas volumetrically displacing a disproportion of liquid. Careful design is required to pump high temperature liquids with a centrifugal pump when the liquid is near its boiling point.

The violent collapse of the cavitation bubble creates a shock wave that can literally carve material from internal pump components (usually the leading edge of the impeller) and creates noise often described as "pumping gravel". Additionally, the inevitable increase in vibration can cause other mechanical faults in the pump and associated equipment.

A somewhat simpler informal way to understand NPSH…
Fluid can be pushed down a pipe with a great deal of force. The only limit is the ability of the pipe to withstand the pressure. However, a liquid cannot be pulled up a pipe with much force because bubbles are created as the liquid evaporates into a gas. The greater the vacuum created, the larger the bubble, so no more liquid will flow into the pump. Rather than thinking in terms of the pump's ability to pull the fluid, the flow is limited by the ability of gravity and air pressure to push the fluid into the pump. The atmosphere pushes down on the fluid, and if the pump is below the tank, the weight of the fluid from gravity above the pump inlet also helps. Until the fluid reaches the pump, those are the only two forces providing the push. Friction loss and vapor pressure must also be considered. Friction loss limits the ability of gravity and air pressure to push the water toward the pump at high speed. Vapor pressure refers to the point at which bubbles form in the liquid. NPSH is a measure of how much spare pull you have before the bubbles form.

Some helpful information regarding atmospheric pressure; Atmospheric pressure is always naturally occurring and is always around us. At sea level, it equates to 101.325 kPa or approximately 14 Psi OR 10 meters of liquid pressure head. As we move higher up mountains, the air gets thinner and the atmospheric pressure reduces.

This should be taken into account when designing pumping systems. The reason there is atmospheric pressure is simply due to earth's gravity and its position in our solar system. It is a natural phenomenon and we are very lucky to have it as water wells and bores with shallow aquifers allow us to use this atmospheric pressure to our advantage.

We all know that pressure gauges exist on pumping systems and other machines to give us an indication of what performances are being achieved. We also use known pressures versus known performance in order to create a reference for system designs. An example would be an experienced pump technician or plumber knowing that a pressure of between 300 kPa and 500 kPa will provide adequate and comfortable pressure for household use.

A typical pressure gauge reads what is known as 'Gage Pressure,' or pressure relative to atmospheric pressure. An 'Absolute Pressure' gauge displays atmospheric pressure (typically 100 kPa or 14 psi or 10 meters of liquid pressure head) before any system had been connected. Manufacturers set typical gage pressure gauges to read ZERO at sea level as a standard, assuming designers will make allowances for the atmospheric pressure calculations themselves. Knowing this simple fact can make NPSH easier to understand.

If we now know that there is 100 kPa or 10 meters of head pressure, plus or minus whatever the gage pressure gauge shows, then we can safely see that this gives us an instant advantage of 10 meters of head pressure at sea level. This means we can borrow against this and drop a maximum of 10 meters into or under the ground (or below sea level) reducing the gauge to zero and still get natural 'push' into our pump. Great for wells and bores with shallow aquifers within this depth! It is important to note that to get to exactly 10 meters may be difficult, but with the correct pipework and system design, it is possible to get very close.

Once NPSH is fully understood, sizing and controlling pumps and pumping machines is a much simpler task.

NPSH is the liquid suction force at the intake of a pump. In other words, the force of a liquid naturally "pushing" into a pump from gravity pressure plus liquid head pressure only - into a single pump intake.

This means;
NPSH = the net (left over) positive pressure of suction force into a pump intake after friction loss has occurred. Liquid head height or liquid head pressure + gravity pressure, minus friction loss, leaves a net head pressure of force into the pump.

If we want to pump some amount of liquid, we have to ensure that this liquid can reach the center line of the suction point of the pump. NPSH represents the head (pressure and gravity head) of liquid in the suction line of the pump that will overcome the friction along the suction line.

NPSHR is the amount of liquid pressure required at the intake port of a pre-designed and manufactured pump.
This is known as NPSHR (Net Positive Suction Head Required). The pump manufacturer will usually clearly have a NPSH curve to assist you in the correct installation.

NPSHA is the amount (A = available) to the pump intake after pipe friction losses and head pressures have been taken into account.

The reason for this requirement?
When the pump is receiving liquid at intake port and the impeller is pushing the liquid out the discharge port, they are effectively trying to tear each other apart because the pump is changing the liquid movement by a pressure increase at the impeller vanes, (general pump installations). Insufficient NPSHR will cause a low or near-vacuum pressure (negative NPSHA) to exist at the pump intake.

This will cause the liquid to boil and cause cavitation, and the pump will not receive the liquid fast enough because it will be attempting to pump vapor. Cavitation will lower pump performance and damage pump internals.

At low temperatures the liquid can "hold together" (remain fluid) relatively easily, hence a lower NPSH requirement. However at higher temperatures, the higher vapor pressure starts the boiling process much quicker, hence a high NPSH requirement.

- ✓ Water will boil at lower temperatures under lower pressures. Conversely its boiling point is higher at higher pressures.

- ✓ Water boils at 100 degrees Celsius at sea level and an atmospheric pressure of 1 bar.

- ✓ Vapor Pressure is the pressure of a gas in equilibrium with its liquid phase at a given temperature. If the vapor pressure at a given temperature is greater than the pressure of the atmosphere above the liquid, then the liquid will boil. (This is why water boils at a lower temperature high in the mountains).

- ✓ At normal atmospheric pressure minus 5 psi (or -0.35 bar) water will boil at 89 degrees Celsius.

- ✓ At normal atmospheric pressure minus 10 psi (or -0.7 bar) water will boil at 69 degrees Celsius.

- ✓ At a positive pressure of +12 psi or +0.82 bar above atmospheric, water will boil at 118 degrees Celsius.

- ✓ Liquid temperature greatly affects NPSH and must be taken into account when expensive installations are being designed.

- ✓ A pump designed with a NPSHR suitable for cold water may cavitate when pumping hot water
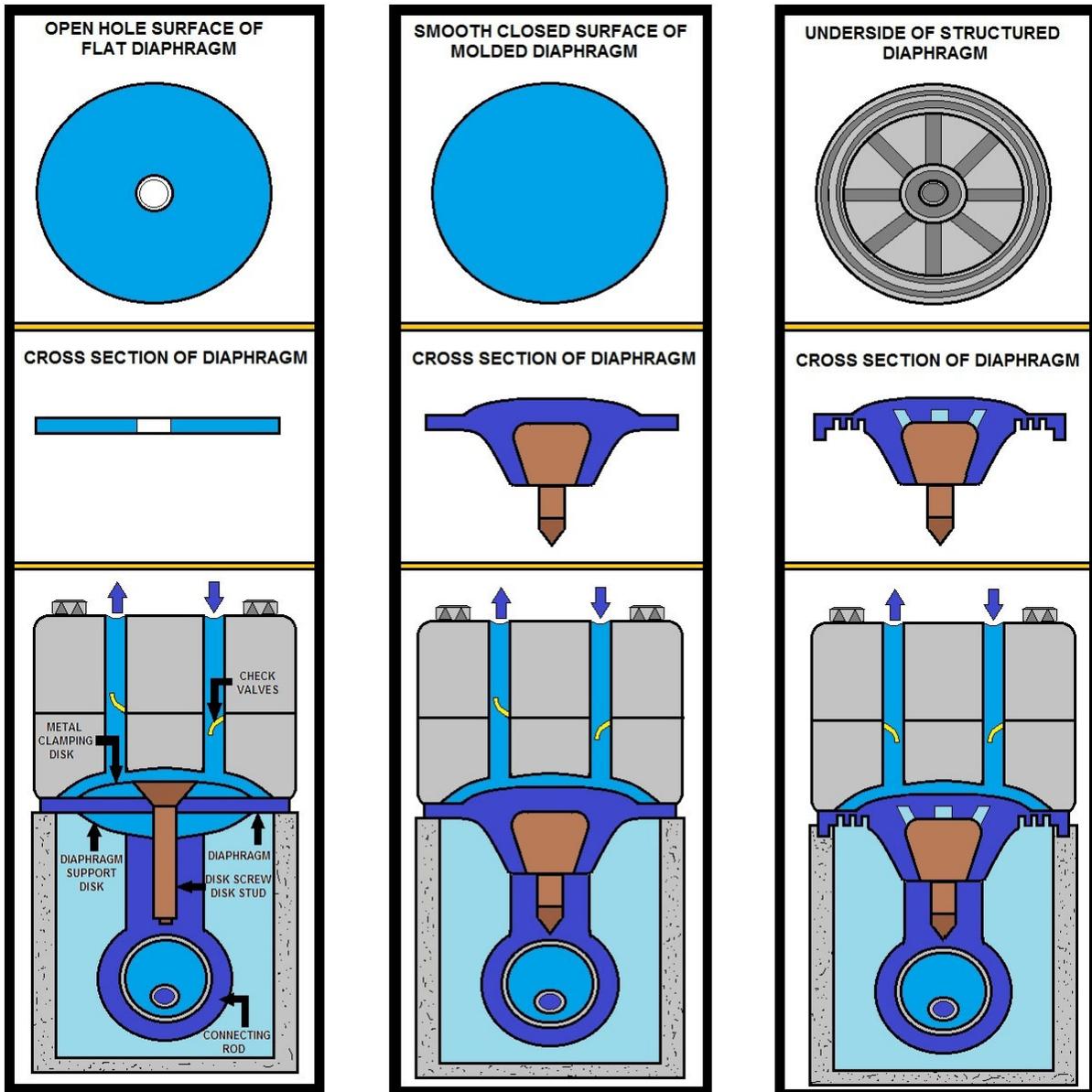
TYPES OF DIAPHRAGM PUMPS

More on Positive Displacement Pumps

A positive displacement pump causes a fluid to move by trapping a fixed amount of it and then forcing (displacing) that trapped volume into the discharge pipe. Some positive displacement pumps work using an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pump as the cavity on the suction side expands and the liquid flows out of the discharge as the cavity collapses. The volume is constant given each cycle of operation.

Positive Displacement Pump Behavior and Safety
Positive displacement pumps, unlike centrifugal or roto-dynamic pumps, will in theory produce the same flow at a given speed (RPM) no matter what the discharge pressure. Thus, positive displacement pumps are "constant flow machines". However due to a slight increase in internal leakage as the pressure increases, a truly constant flow rate cannot be achieved.

A positive displacement pump must not be operated against a closed valve on the discharge side of the pump, because it has no shut-off head like centrifugal pumps. A positive displacement pump operating against a closed discharge valve will continue to produce flow and the pressure in the discharge line will increase, until the line bursts or the pump is severely damaged, or both.

A relief or safety valve on the discharge side of the positive displacement pump is therefore necessary. The relief valve can be internal or external. The pump manufacturer normally has the option to supply internal relief or safety valves. The internal valve should in general only be used as a safety precaution, an external relief valve installed in the discharge line with a return line back to the suction line or supply tank is recommended.

Priming a Pump
Liquid and slurry pumps can lose prime and this will require the pump to be primed by adding liquid to the pump and inlet pipes to get the pump started. Loss of "prime" is usually due to ingestion of air into the pump. The clearances and displacement ratios in pumps used for liquids and other more viscous fluids cannot displace the air due to its lower density.

Positive Displacement Types
A positive displacement pump causes a liquid or gas to move by trapping a fixed amount of fluid or gas and then forcing (displacing) that trapped volume into the discharge pipe. Positive displacement pumps can be further classified as either rotary-type (for example the rotary vane) or lobe pumps similar to oil pumps used in car engines. Moreover, these pumps give a non-pulsating output or displacement unlike the reciprocating pumps and hence are called positive displacement pumps.

The positive displacement pump operates by alternating of filling a cavity and then displacing a given volume of liquid. The positive displacement pump delivers a constant volume of liquid for each cycle against varying discharge pressure or head.

The positive displacement pump can be classified as:
- ✓ Reciprocating pumps - piston, plunger and diaphragm
- ✓ Power pumps
- ✓ Steam pumps
- ✓ Rotary pumps - gear, lobe, screw, vane, regenerative (peripheral) and progressive cavity

A positive displacement pump can be further classified according to the mechanism used to move the fluid:

- ✓ Rotary-type positive displacement: internal gear, screw, shuttle block, flexible vane or sliding vane, circumferential piston, flexible impeller, helical twisted roots (e.g. the Wendelkolben pump) or liquid ring vacuum pumps.
- ✓ Reciprocating-type positive displacement: piston or diaphragm pumps.
- ✓ Linear-type positive displacement: rope pumps and chain pumps.

Rotary Positive Displacement Pumps
Positive displacement rotary pumps move fluid using a rotating mechanism that creates a vacuum that captures and draws in the liquid.

Advantages: Rotary pumps are very efficient because they naturally remove air from the lines, eliminating the need to bleed the air from the lines manually.

Drawbacks: Because of the nature of the pump, the clearance between the rotating pump and the outer edge must be very close, requiring that it rotate at a slow, steady speed. If rotary pumps are operated at high speeds, the fluids will cause erosion, eventually developing enlarged clearances through which liquid can pass, reducing the efficiency of the pump.

Rotary positive displacement pumps can be grouped into three main types:
- ✓ Gear pumps - a simple type of rotary pump where the liquid is pushed between two gears.

- ✓ Screw pumps - the shape of the internals of this pump usually two screws turning against each other pump the liquid.

- ✓ Rotary vane pumps - similar to scroll compressors, consisting of a cylindrical rotor encased in a similarly shaped housing. As the rotor orbits, the vanes trap fluid between the rotor and the casing, drawing the fluid through the pump.

Reciprocating Positive Displacement Pumps

Hand-operated, reciprocating, positive displacement, and Slovakia (walking beam pump).

Reciprocating pumps are those which cause the fluid to move using one or more oscillating pistons, plungers or membranes (diaphragms), and restrict motion of the fluid to the one desired direction by valves.

Pumps in this category range from "simplex", with one cylinder, to in some cases "quad" (four) cylinders or more. Many reciprocating-type pumps are "duplex" (two) or "triplex" (three) cylinder. They can be either "single-acting" with suction during one direction of piston motion and discharge on the other, or "double-acting" with suction and discharge in both directions. The pumps can be powered manually, by air or steam, or by a belt driven by an engine. This type of pump was used extensively in the early days of steam propulsion (19th century) as boiler feed water pumps. Reciprocating pumps are now typically used for pumping highly viscous fluids including concrete and heavy oils, and special applications demanding low flow rates against high resistance. Reciprocating hand pumps were widely used for pumping water from wells; the common bicycle pump and foot pumps for inflation use reciprocating action.

These positive displacement pumps have an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pumps as the cavity on the suction side expands and the liquid flows out of the discharge as the cavity collapses. The volume is constant given each cycle of operation.

Typical reciprocating pumps are:
- ✓ Plunger pumps - a reciprocating plunger pushes the fluid through one or two open valves, closed by suction on the way back.
- ✓ Diaphragm pumps - similar to plunger pumps, where the plunger pressurizes hydraulic oil which is used to flex a diaphragm in the pumping cylinder. Diaphragm valves are used to pump hazardous and toxic fluids.
- ✓ Piston displacement pumps - usually simple devices for pumping small amounts of liquid or gel manually. An example is the common hand soap pump.
- ✓ Radial piston pump

Various Positive Displacement Pumps
The positive displacement principle applies in the following types of pumps:
- ✓ Rotary lobe pump
- ✓ Progressive cavity pump
- ✓ Rotary gear pump
- ✓ Piston pump
- ✓ Diaphragm pump
- ✓ Screw pump
- ✓ Gear pump
- ✓ Hydraulic pump
- ✓ Vane pump
- ✓ Regenerative (peripheral) pump
- ✓ Peristaltic pump
- ✓ Rope pump
- ✓ Flexible impeller
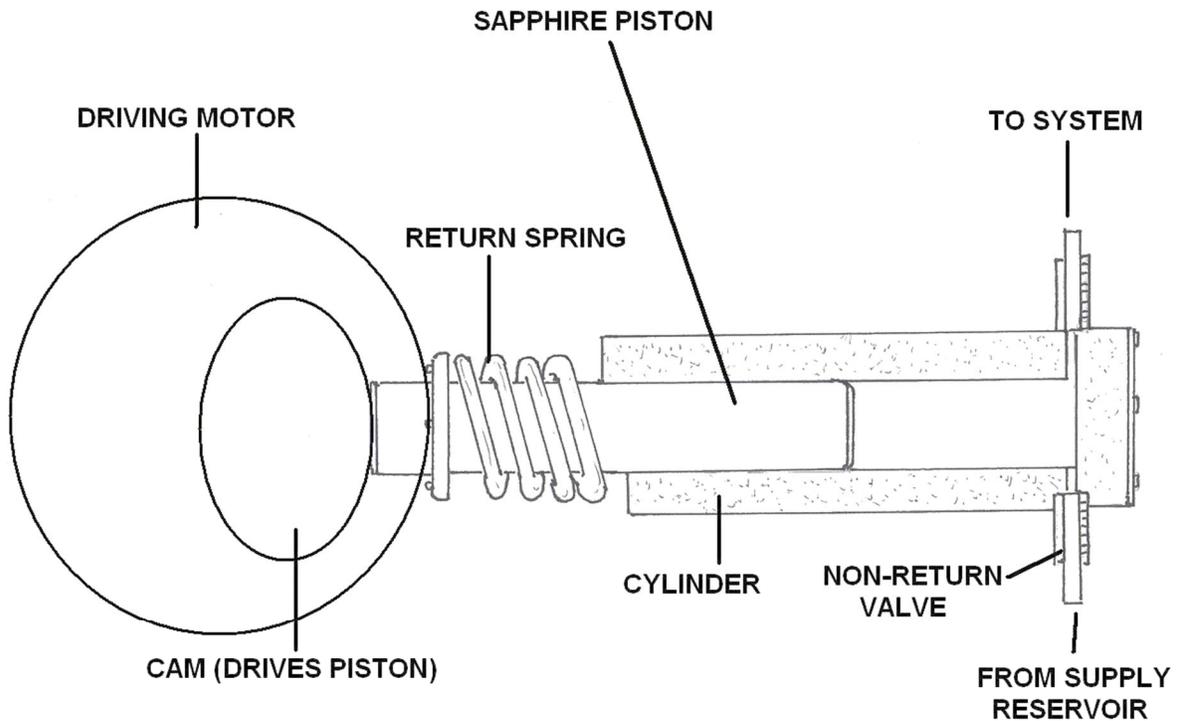
PLUNGER PUMP
(single-piston reciprocating pump)

Centrifugal or Roto-Dynamic Pump
The centrifugal or roto-dynamic pump produce a head and a flow by increasing the velocity of the liquid through the machine with the help of a rotating vane impeller. Centrifugal pumps include radial, axial and mixed flow units.

Centrifugal pumps can further be classified as
- ✓ end suction pumps
- ✓ in-line pumps
- ✓ double suction pumps
- ✓ vertical multistage pumps
- ✓ horizontal multistage pumps
- ✓ submersible pumps
- ✓ self-priming pumps
- ✓ axial-flow pumps
- ✓ regenerative pumps

The fact of the matter is that there are three types of problems mostly encountered with centrifugal pumps:
- ✓ design errors
- ✓ poor operation
- ✓ poor maintenance practices

Working Mechanism of a Centrifugal Pump

A centrifugal pump is one of the simplest pieces of equipment in any process plant. Its purpose is to convert energy of a prime mover (an electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

Note: All of the forms of energy involved in a liquid flow system are expressed in terms of feet of liquid i.e. head.

Generation of Centrifugal Force

The process liquid enters the suction nozzle and then into eye (center) of a revolving device known as an impeller. When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and provides centrifugal acceleration. As liquid leaves the eye of the impeller a low-pressure area is created causing more liquid to flow toward the inlet. Because the impeller blades are curved, the fluid is pushed in a tangential and radial direction by the centrifugal force. This force acting inside the pump is the same one that keeps water inside a bucket that is rotating at the end of a string.

Selecting between Centrifugal or Positive Displacement Pumps

Selecting between a Centrifugal Pump or a Positive Displacement Pump is not always straight forward.

Flow Rate and Pressure Head

The two types of pumps behave very differently regarding pressure head and flow rate: The Centrifugal Pump has varying flow depending on the system pressure or head. The Positive Displacement Pump has more or less a constant flow regardless of the system pressure or head. Positive Displacement pumps generally gives more pressure than Centrifugal pumps. Depending on how the measurement is taken suction lift and head may also be referred to as static or dynamic. Static indicates the measurement does not take into account the friction caused by water moving through the hose or pipes. Dynamic indicates that losses due to friction are factored into the performance. The following terms are usually used when referring to lift or head.

Static Suction Lift - The vertical distance from the water line to the centerline of the impeller.

Static Discharge Head - The vertical distance from the discharge outlet to the point of discharge or liquid level when discharging into the bottom of a water tank.

Dynamic Suction Head - The Static Suction Lift plus the friction in the suction line. Also referred to as a Total Suction Head.

Dynamic Discharge Head - The Static Discharge Head plus the friction in the discharge line. Also referred to as Total Discharge Head.

Total Dynamic Head - The Dynamic Suction Head plus the Dynamic Discharge Head. Also referred to as Total Head.

Capacity and Viscosity

Another major difference between the pump types is the effect of viscosity on the capacity:
- ✓ In the Centrifugal Pump the flow is reduced when the viscosity is increased.

- ✓ In the Positive Displacement Pump the flow is increased when viscosity is increased

Liquids with high viscosity fills the clearances of a Positive Displacement Pump causing a higher volumetric efficiency and a Positive Displacement Pump is better suited for high viscosity applications. A Centrifugal Pump becomes very inefficient at even modest viscosity.

Mechanical Efficiency
The pumps behaves different considering mechanical efficiency as well.
- ✓ Changing the system pressure or head has little or no effect on the flow rate in the Positive Displacement Pump.

- ✓ Changing the system pressure or head has a dramatic effect on the flow rate in the Centrifugal Pump.

Net Positive Suction Head - NPSH
Another consideration is the Net Positive Suction Head NPSH.
- ✓ In a Centrifugal Pump, NPSH varies as a function of flow determined by pressure.

- ✓ In a Positive Displacement Pump, NPSH varies as a function of flow determined by speed. Reducing the speed of the Positive Displacement Pump, reduces the NPSH.

Darcy-Weisbach Formula

Flow of fluid through a pipe
The flow of liquid through a pipe is resisted by viscous shear stresses within the liquid and the turbulence that occurs along the internal walls of the pipe, created by the roughness of the pipe material. This resistance is usually known as pipe friction and is measured is feet or meters head of the fluid, thus the term head loss is also used to express the resistance to flow.

Many factors affect the head loss in pipes, the viscosity of the fluid being handled, the size of the pipes, the roughness of the internal surface of the pipes, the changes in elevations within the system and the length of travel of the fluid. The resistance through various valves and fittings will also contribute to the overall head loss. A method to model the resistances for valves and fittings is described elsewhere. In a well-designed system the resistance through valves and fittings will be of minor significance to the overall head loss, many designers choose to ignore the head loss for valves and fittings at least in the initial stages of a design.

Much research has been carried out over many years and various formulas to calculate head loss have been developed based on experimental data. Among these is the Chézy formula which dealt with water flow in open channels. Using the concept of 'wetted perimeter' and the internal diameter of a pipe the Chézy formula could be adapted to estimate the head loss in a pipe, although the constant 'C' had to be determined experimentally.

The Darcy-Weisbach equation
Weisbach first proposed the equation we now know as the Darcy-Weisbach formula or Darcy-Weisbach equation:

$$hf = f (L/D) \times (v2/2g)$$

where:
hf = head loss (m)
f = friction factor
L = length of pipe work (m)
d = inner diameter of pipe work (m)
v = velocity of fluid (m/s)
g = acceleration due to gravity (m/s²)

or:
hf = head loss (ft)
f = friction factor
L = length of pipe work (ft)
d = inner diameter of pipe work (ft)
v = velocity of fluid (ft/s)
g = acceleration due to gravity (ft/s²)

The Moody Chart
In 1944 LF Moody plotted the data from the Colebrook equation and this chart which is now known as 'The Moody Chart' or sometimes the Friction Factor Chart, enables a user to plot the Reynolds number and the Relative Roughness of the pipe and to establish a reasonably accurate value of the friction factor for turbulent flow conditions.

The Moody Chart encouraged the use of the Darcy-Weisbach friction factor and this quickly became the method of choice for hydraulic engineers. Many forms of head loss calculator were

developed to assist with the calculations, amongst these a round slide rule offered calculations for flow in pipes on one side and flow in open channels on the reverse side.

The development of the personnel computer from the 1980's onwards reduced the time needed to perform the friction factor and head loss calculations, which in turn has widened the use of the Darcy-Weisbach formula to the point that all other formula are now largely unused.

This dimensionless chart is used to work out pressure drop, ΔP(Pa) (or head loss, h_f(m)) and flow rate through pipes. Head loss can be calculated using the Darcy–Weisbach equation:

$$h_f = f \frac{l}{d} \frac{V^2}{2g};$$

not to be confused with the Fanning equation and the Fanning friction factor:

$$h_f = 4f \frac{l}{d} \frac{V^2}{2g},$$

which uses a friction-factor equal to one fourth the Darcy-Weisbach friction factor. Pressure drop can then be evaluated as:

$$\Delta P = f \frac{\rho V^2}{2} \frac{l}{d},$$

$\Delta P = \rho g h_f$ for directly from

where ρ is the density of the fluid, V is the average velocity in the pipe, f is the friction factor from the Moody chart, l is the length of the pipe and d is the pipe diameter.
The basic chart plots Darcy–Weisbach friction factor against Reynolds number for a variety of relative roughnesses and flow regimes. The relative roughness being the ratio of the mean

height of roughness of the pipe to the pipe diameter or $\frac{\epsilon}{d}$.
The Moody chart can be divided into two regimes of flow: laminar and turbulent. For the laminar flow regime, the Darcy–Weisbach friction factor was determined analytically by

$$\frac{64}{Re}$$

Poiseuille and $\frac{64}{Re}$ is used. In this regime roughness has no discernible effect. For the turbulent flow regime, the relationship between the friction factor and the Reynolds number is more complex and is governed by the Colebrook equation which is implicit in f:

$$\frac{1}{\sqrt{f}} = -2.0 \log_{10} \left(\frac{\frac{\epsilon}{d}}{3.7} + \frac{2.51}{Re\sqrt{f}} \right), \text{turbulent flow.}$$

In 1944, Lewis Ferry Moody plotted the Darcy–Weisbach friction factor into what is now known as the Moody chart.

The Fanning friction factor is 1/4 the Darcy–Weisbach one and the equation for pressure drop has a compensating factor of four.

Understanding Pump Vapor Pressure and Temperature

The boiling point is the temperature at which the liquid changes to the gaseous state. This point depends on external pressure. The normal boiling point is defined when the external pressure over the liquid = 1 atm.

Think about this:
What is the boiling point of water? What does it depend on?

Water boils at 100 degrees C at one atm external pressure (sea level). As the pressure is lowered, the boiling point is reduced.

Also, as the external pressure drops, the temperature where the vapor pressure = the external pressure, is lower.

The table shows the relationship between vapor pressure and temperature. Vapor pressure increases with an increase in temperature.

Temperature (°C)	Vapor Pressure (Torr)
100	760
50	93
20	17.5
0	5.5 (sublimation from ice)

Critical Temperature
Is there a point at which the gas can become a vapor and condense when the pressure increases?

Let's use Boyle's Law to explain.
Boyle's Law states that for a fixed amount of gas (n) at a constant temperature (T), the pressure (P) is inversely proportional to its volume (V). If the volume of the gas decreases, the pressure of the gas increases proportionally. This holds true because of the compressibility property of gases.

But what if the volume of a gas were to decrease and in the process the gas condenses into liquid droplets?

In such a situation, the saturated vapor pressure of the gas has been reached and the gas is now considered a vapor.

AIR VESSEL

PISTON MOVING UPWARDS ↑

DISCHARGE (LIQUID) →

SUCTION VALVE CLOSED →

← **DISCHARGE VALVE OPEN**

SUCTION VALVE OPEN →

SUCTION (LIQUID) →

← **DISCHARGE VALVE CLOSED**
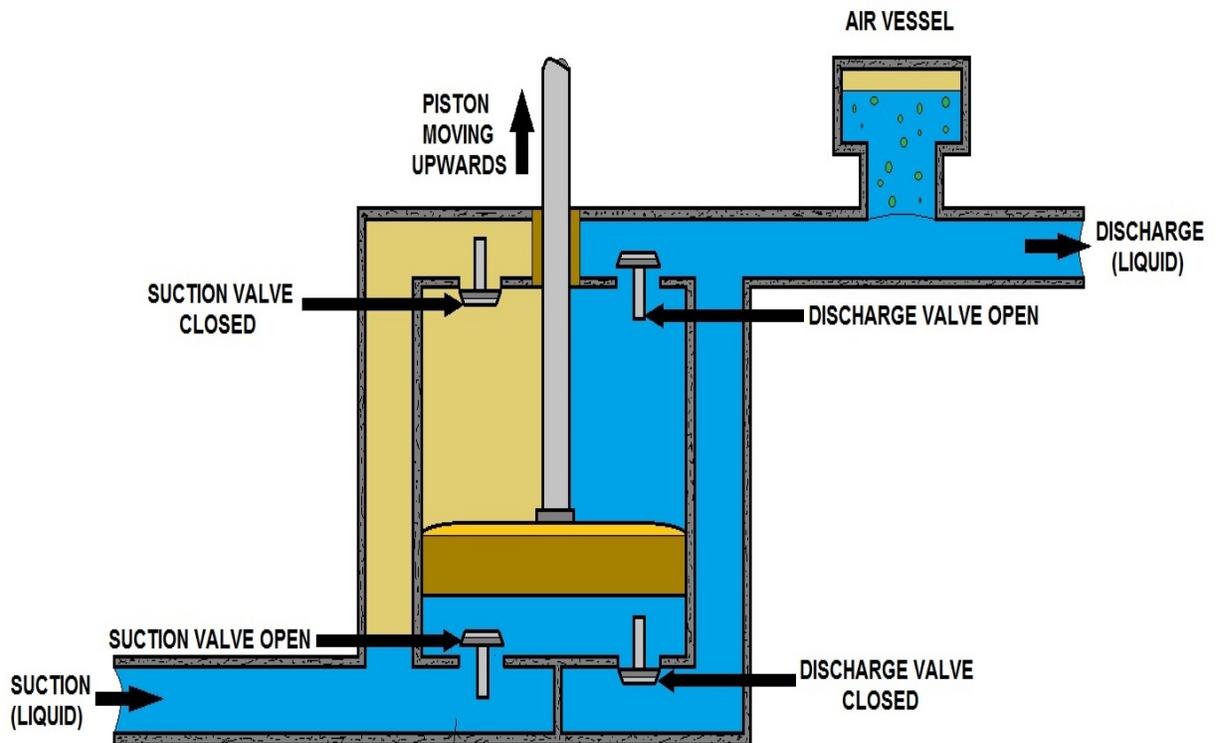
POSITIVE DISPLACEMENT PUMP
RECIPROCATING PISTON TYPE

Valveless Pumps

Valveless pumping assists in fluid transport in various biomedical and engineering systems. In a valveless pumping system, no valves are present to regulate the flow direction. The fluid pumping efficiency of a valveless system, however, is not necessarily lower than that having valves. In fact, many fluid-dynamical systems in nature and engineering more or less rely upon valveless pumping to transport the working fluids therein. For instance, blood circulation in the cardiovascular system is maintained to some extent even when the heart's valves fail. Meanwhile, the embryonic vertebrate heart begins pumping blood long before the development of discernible chambers and valves. In microfluidics, valveless impedance pumps have been fabricated, and are expected to be particularly suitable for handling sensitive biofluids.

Multiphase pumping applications also referred to as tri-phase, have grown due to increased oil drilling activity. In addition, the economics of multiphase production is attractive to upstream operations as it leads to simpler, smaller in-field installations, reduced equipment costs and improved production rates. In essence, the multiphase pump can accommodate all fluid stream properties with one piece of equipment, which has a smaller footprint.

Often, two smaller multiphase pumps are installed in series rather than having just one massive pump.

For midstream and upstream operations, multiphase pumps can be located onshore or offshore and can be connected to single or multiple wellheads. Basically, multiphase pumps are used to transport the untreated flow stream produced from oil wells to downstream processes or gathering facilities. This means that the pump may handle a flow stream (well stream) from 100 percent gas to 100 percent liquid and every imaginable combination in between. The flow stream can also contain abrasives such as sand and dirt.

Multiphase pumps are designed to operate under changing/fluctuating process conditions. Multiphase pumping also helps eliminate emissions of greenhouse gases as operators strive to minimize the flaring of gas and the venting of tanks where possible.

Types and Features of Multiphase Pumps
Helico-Axial Pumps (Centrifugal) A rotodynamic pump with one single shaft requiring two mechanical seals. This pump utilizes an open-type axial impeller. This pump type is often referred to as a "Poseidon Pump" and can be described as a cross between an axial compressor and a centrifugal pump.

'Twin Screw (Positive Displacement)'
The twin screw pump is constructed of two intermeshing screws that force the movement of the pumped fluid. Twin screw pumps are often used when pumping conditions contain high gas volume fractions and fluctuating inlet conditions. Four mechanical seals are required to seal the two shafts.

Progressive Cavity Pumps (Positive Displacement)
Progressive cavity pumps are single-screw types typically used in shallow wells or at the surface. This pump is mainly used on surface applications where the pumped fluid may contain a considerable amount of solids such as sand and dirt.

Electric Submersible Pumps (Centrifugal)
These pumps are basically multistage centrifugal pumps and are widely used in oil well applications as a method for artificial lift. These pumps are usually specified when the pumped fluid is mainly liquid.

Buffer Tank
A buffer tank is often installed upstream of the pump suction nozzle in case of a slug flow. The buffer tank breaks the energy of the liquid slug, smoothes any fluctuations in the incoming flow and acts as a sand trap. As the name indicates, multiphase pumps and their mechanical seals can encounter a large variation in service conditions such as changing process fluid composition, temperature variations, high and low operating pressures and exposure to abrasive/erosive media. The challenge is selecting the appropriate mechanical seal arrangement and support system to ensure maximized seal life and its overall effectiveness.[

Types of Positive Displacement Pumps
Positive-displacement pumps are another category of pumps. Types of positive-displacement pumps are reciprocating, metering, and rotary pumps. Positive-displacement pumps operate by forcing a fixed volume of fluid from the inlet pressure section of the pump into the discharge zone of the pump. These pumps generally tend to be larger than equal-capacity dynamic pumps. Positive-displacement pumps frequently are used in hydraulic systems at pressures ranging up to 5000 psi. A principal advantage of hydraulic power is the high power density (power per unit weight) that can be achieved. They also provide a fixed displacement per revolution and, within mechanical limitations, infinite pressure to move fluids.

A positive displacement pump causes a fluid to move by trapping a fixed amount of it then forcing (displacing) that trapped volume into the discharge pipe.
  or
A positive displacement pump has an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pump as the cavity on the suction side expands and the liquid flows out of the discharge as the cavity collapses. The volume is constant given each cycle of operation.

A positive displacement pump can be further classified according to the mechanism used to move the fluid:

• Rotary-type, internal gear, screw, shuttle block, flexible vane or sliding vane, circumferential piston, helical twisted roots (e.g. the Wendelkolben pump) or liquid ring vacuum pumps. Positive displacement rotary pumps are pumps that move fluid using the principles of rotation. The vacuum created by the rotation of the pump captures and draws in the liquid. Rotary pumps are very efficient because they naturally remove air from the lines, eliminating the need to bleed the air from the lines manually.

Positive displacement rotary pumps also have their weaknesses. Because of the nature of the pump, the clearance between the rotating pump and the outer edge must be very close, requiring that the pumps rotate at a slow, steady speed. If rotary pumps are operated at high speeds, the fluids will cause erosion. Rotary pumps that experience such erosion eventually show signs of enlarged clearances, which allow liquid to slip through and detract from the efficiency of the pump.

Positive displacement rotary pumps can be grouped into three main types. Gear pumps are the simplest type of rotary pumps, consisting of two gears laid out side-by-side with their teeth enmeshed. The gears turn away from each other, creating a current that traps fluid between the teeth on the gears and the outer casing, eventually releasing the fluid on the discharge side of the pump as the teeth mesh and go around again. Many small teeth maintain a constant flow of fluid, while fewer, larger teeth create a tendency for the pump to discharge fluids in short, pulsing gushes.

Screw Pumps
Screw pumps are a more complicated type of rotary pumps, featuring two or three screws with opposing thread —-that is, one screw turns clockwise, and the other counterclockwise. The screws are each mounted on shafts that run parallel to each other; the shafts also have gears on them that mesh with each other in order to turn the shafts together and keep everything in place. The turning of the screws, and consequently the shafts to which they are mounted, draws the fluid through the pump. As with other forms of rotary pumps, the clearance between moving parts and the pump's casing is minimal.

Moving Vane Pumps
Moving vane pumps are the third type of rotary pumps, consisting of a cylindrical rotor encased in a similarly shaped housing. As the rotor turns, the vanes trap fluid between the rotor and the casing, drawing the fluid through the pump.
• Reciprocating-type, for example, piston or diaphragm pumps.

Positive displacement pumps have an expanding cavity on the suction side and a decreasing cavity on the discharge side. Liquid flows into the pumps as the cavity on the suction side expands and the liquid flows out of the discharge as the cavity collapses. The volume is constant given each cycle of operation. In a reciprocating pump, a volume of liquid is drawn into the cylinder through the suction valve on the intake stroke and is discharged under positive pressure through the outlet valves on the discharge stroke.

The discharge from a reciprocating pump is pulsating and changes only when the speed of the pump is changed. This is because the intake is always a constant volume. Often an air chamber is connected on the discharge side of the pump to provide a more even flow by evening out the pressure surges. Reciprocating pumps are often used for sludge and slurry.

One construction style of a reciprocating pump is the direct-acting steam pump. These consist of a steam cylinder end in line with a liquid cylinder end, with a straight rod connection between the steam piston and the pump piston or plunger. These pistons are double acting which means that each side pumps on every stroke.

Another construction style is the power pump which converts rotary motion to low speed reciprocating motion using a speed reducing gear. The power pump can be either single or double-acting. A single-acting design discharges liquid only on one side of the piston or plunger. Only one suction and one discharge stroke per revolution of the crankshaft can occur.

The double-acting design takes suction and discharges on both sides of the piston resulting in two suctions and discharges per crankshaft revolution. Power pumps are generally very efficient and can develop high pressures. These pumps do however tend to be expensive.

The positive displacement pumps can be divided into two main classes
- reciprocating
- rotary

The positive displacement principle applies whether the pump is a
- rotary lobe pump
- Progressive cavity pump
- rotary gear pump
- piston pump
- diaphragm pump
- screw pump
- gear pump
- Hydraulic pump
- vane pump
- regenerative (peripheral) pump
- peristaltic pump

Positive displacement pumps, unlike centrifugal or roto-dynamic pumps, will produce the same flow at a given speed (RPM) no matter what the discharge pressure.
- Positive displacement pumps are "constant flow machines"

A positive displacement pump must not be operated against a closed valve on the discharge side of the pump because it has no shut-off head like centrifugal pumps.

A positive displacement pump operating against a closed discharge valve, will continue to produce flow until the pressure in the discharge line are increased until the line bursts or the pump is severely damaged - or both.

A relief or safety valve on the discharge side of the positive displacement pump is therefore necessary.

The relief valve can be internal or external. The pump manufacturer normally has the option to supply internal relief or safety valves.

The internal valve should in general only be used as a safety precaution, an external relief valve installed in the discharge line with a return line back to the suction line or supply tank is recommended.

Metering Pumps
Metering pumps provide precision control of very low flow rates. Flow rates are generally less than 1/2 gallon per minute. They are usually used to control additives to the main flow stream. They are also called proportioning or controlled-volume pumps.

Metering pumps are available in either a diaphragm or packed plunger style, and are designed for clean service and dirty liquid can easily clog the valves and nozzle connections.

Hydraulic Glossary

A

Absolute Pressure: The pressure above zone absolute, i.e. the sum of atmospheric and gauge pressure. In vacuum related work it is usually expressed in millimeters of mercury. (mmHg).

Aerodynamics: The study of the flow of gases. The Ideal Gas Law - For a perfect or ideal gas the change in density is directly related to the change in temperature and pressure as expressed in the Ideal Gas Law.

Aeronautics: The mathematics and mechanics of flying objects, in particular airplanes.

Air Break: A physical separation which may be a low inlet into the indirect waste receptor from the fixture, or device that is indirectly connected. You will most likely find an air break on waste fixtures or on non-potable lines. You should never allow an air break on an ice machine.

Air Gap Separation: A physical separation space that is present between the discharge vessel and the receiving vessel, for an example, a kitchen faucet.

Altitude-Control Valve: If an overflow occurs on a storage tank, the operator should first check the altitude-control valve. Altitude-Control Valve is designed to, 1. Prevent overflows from the storage tank or reservoir, or 2. Maintain a constant water level as long as water pressure in the distribution system is adequate.

Angular Motion Formulas: Angular velocity can be expressed as (angular velocity = constant):

$$\omega = \theta / t \text{ (2a)}$$

where
ω= angular velocity (rad/s)
θ = angular displacement (rad)
t = time (s)

Angular velocity can be expressed as (angular acceleration = constant):
$$\omega = \omega_o + \alpha t \text{ (2b)}$$

where
ω_o = angular velocity at time zero (rad/s)
α = angular acceleration (rad/s^2)

Angular displacement can be expressed as (angular acceleration = constant):
$$\theta = \omega_o t + 1/2 \, \alpha t^2 \text{ (2c)}$$

Combining 2a and 2c:
$$\omega = (\omega_o{}^2 + 2 \, \alpha \, \theta)^{1/2}$$

Angular acceleration can be expressed as:
$$\alpha = d\omega / dt = d^2\theta / dt^2 \text{ (2d)}$$

where
$d\theta$ = change of angular displacement (rad)
dt = change in time (s)

Atmospheric Pressure: Pressure exerted by the atmosphere at any specific location. (Sea level pressure is approximately 14.7 pounds per square inch absolute, 1 bar = 14.5psi.)

B

Backflow Prevention: To stop or prevent the occurrence of, the unnatural act of reversing the normal direction of the flow of liquid, gases, or solid substances back in to the public potable (drinking) water supply. See Cross-connection control.

Backflow: To reverse the natural and normal directional flow of a liquid, gases, or solid substances back in to the public potable (drinking) water supply. This is normally an undesirable effect.

Backsiphonage: A liquid substance that is carried over a higher point. It is the method by which the liquid substance may be forced by excess pressure over or into a higher point. Is a condition in which the pressure in the distribution system is less than atmospheric pressure. In other words, something is "sucked" into the system because the main is under a vacuum.

Bernoulli's Equation: Describes the behavior of moving fluids along a streamline. The Bernoulli Equation can be considered to be a statement of the conservation of energy principle appropriate for flowing fluids. The qualitative behavior that is usually labeled with the term "***Bernoulli effect***" is the lowering of fluid pressure in regions where the flow velocity is increased. This lowering of pressure in a constriction of a flow path may seem counterintuitive, but seems less so when you consider pressure to be energy density. In the high velocity flow through the constriction, kinetic energy must increase at the expense of pressure energy.

Energy per unit volume before = Energy per unit volume after

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g h_2$$

| Pressure Energy | Kinetic Energy per unit volume | Potential Energy per unit volume |

The often cited example of the Bernoulli Equation or "Bernoulli Effect" is the reduction in pressure which occurs when the fluid speed increases.

Flow velocity V_1

Flow velocity V_2

$A_2 < A_1$

$V_2 > V_1$

$P_2 < P_1$!

P_2

Increased fluid speed, decreased internal pressure.

P_1

A special form of the Euler's equation derived along a fluid flow streamline is often called the **Bernoulli Equation.**

$$\frac{\partial}{\partial s}\left(\frac{v^2}{2}+\frac{p}{\rho}+g\cdot h\right)=0 \qquad (1)$$

where

v = flow speed
p = pressure
ρ = density
g = gravity
h = height

$$\frac{v^2}{2}+\frac{p}{\rho}+g\cdot h = \text{Constant} \qquad (2)$$

$$\frac{v^2}{2\cdot g}+\frac{p}{\gamma}+h = \text{Constant} \qquad (3)$$

where

$$\gamma = \rho\cdot g$$

$$\frac{\rho\cdot v^2}{2}+p = \text{Constant} \qquad (4)$$

$$\frac{\rho\cdot v^2}{2}=p_d \qquad (5)$$

$$\frac{\rho\cdot v_1^2}{2}+p_1 = \frac{\rho\cdot v_2^2}{2}+p_2 = \text{Constant} \qquad (6)$$

For steady state incompressible flow the Euler equation becomes (1). If we integrate (1) along the streamline it becomes (2). (2) can further be modified to (3) by dividing by gravity.

Head of Flow: Equation (3) is often referred to as the **head** because all elements have the unit of length.

Bernoulli's Equation Continued:
Dynamic Pressure
(2) and (3) are two forms of the Bernoulli Equation for steady state incompressible flow. If we assume that the gravitational body force is negligible, (3) can be written as (4). Both elements in the equation have the unit of pressure and it's common to refer the flow velocity component as the **dynamic pressure** of the fluid flow (5).

Since energy is conserved along the streamline, (4) can be expressed as (6). Using the equation we see that increasing the velocity of the flow will reduce the pressure, decreasing the velocity will increase the pressure.

This phenomena can be observed in a **venturi meter** where the pressure is reduced in the constriction area and regained after. It can also be observed in a **pitot tube** where the **stagnation** pressure is measured. The stagnation pressure is where the velocity component is zero.

Bernoulli's Equation Continued:
Pressurized Tank
If the tanks are pressurized so that product of gravity and height (g h) is much less than the pressure difference divided by the density, (e4) can be transformed to (e6).
The velocity out from the tanks depends mostly on the pressure difference.

Example - outlet velocity from a pressurized tank
The outlet velocity of a pressurized tank where

p_1 = 0.2 MN/m^2, p_2 = 0.1 MN/m^2 A_2/A_1 = 0.01, h = 10 m

can be calculated as
V_2 = [(2/(1-(0.01)^2) ((0.2 - 0.1)x10^6 /1x10^3 + 9.81 x 10)]$^{1/2}$ = *19.9 m/s*

Coefficient of Discharge - Friction Coefficient
Due to friction the real velocity will be somewhat lower than this theoretical example. If we introduce a **friction coefficient** c (coefficient of discharge), (e5) can be expressed as (e5b). The coefficient of discharge can be determined experimentally. For a sharp edged opening it may be as low as 0.6. For smooth orifices it may be between 0.95 and 1.

Bingham Plastic Fluids: Bingham Plastic Fluids have a yield value which must be exceeded before it will start to flow like a fluid. From that point the viscosity will decrease with increase of agitation. Toothpaste, mayonnaise and tomato catsup are examples of such products.

Boundary Layer: The layer of fluid in the immediate vicinity of a bounding surface.

Bulk Modulus and Fluid Elasticity: An introduction to and a definition of the Bulk Modulus Elasticity commonly used to characterize the compressibility of fluids.

The Bulk Modulus Elasticity can be expressed as
$E = - dp / (dV / V)$ (1)

where
E = bulk modulus elasticity
dp = differential change in pressure on the object
dV = differential change in volume of the object
V = initial volume of the object

The Bulk Modulus Elasticity can be alternatively expressed as
$E = - dp / (d\rho / \rho)$ (2)

where
dρ = differential change in density of the object
ρ = initial density of the object

An increase in the pressure will decrease the volume (1). A decrease in the volume will increase the density (2).
* The SI unit of the bulk modulus elasticity is N/m^2 (Pa)
* The imperial (BG) unit is lb$_f$/in^2 (psi)
* 1 lb$_f$/in^2 (psi) = 6.894 10^3 N/m^2 (Pa)

A large Bulk Modulus indicates a relatively incompressible fluid.

Bulk Modulus for some common fluids can be found in the table below:

Bulk Modulus - E	Imperial Units - BG (psi, lb_f/in^2) x 10^5	SI Units (Pa, N/m^2) x 10^9
Carbon Tetrachloride	1.91	1.31
Ethyl Alcohol	1.54	1.06
Gasoline	1.9	1.3
Glycerin	6.56	4.52
Mercury	4.14	2.85
SAE 30 Oil	2.2	1.5
Seawater	3.39	2.35
Water	3.12	2.15

C

Capillarity: (or capillary action) The ability of a narrow tube to draw a liquid upwards against the force of gravity.

The height of liquid in a tube due to capillarity can be expressed as
$h = 2\ \sigma\ cos\theta\ /\ (\rho\ g\ r)$ *(1)*

where
h = height of liquid (ft, m)
σ = surface tension (lb/ft, N/m)
θ = contact angle
ρ = density of liquid (lb/ft³, kg/m³)
g = acceleration due to gravity (32.174 ft/s², 9.81 m/s²)
r = radius of tube (ft, m)

Cauchy Number: A dimensionless value useful for analyzing fluid flow dynamics problems where compressibility is a significant factor.
The Cauchy Number is the ratio between inertial and the compressibility force in a flow and can be expressed as
$C = \rho\ v^2\ /\ E$ *(1)*

where
ρ = density (kg/m³)
v = flow velocity (m/s)
E = bulk modulus elasticity (N/m²)
The bulk modulus elasticity has the dimension pressure and is commonly used to characterize the compressibility of a fluid.

The Cauchy Number is the square root of the Mach Number
$M^2 = Ca$ *(3)*

where
C = Mach Number

Cavitation: Under the wrong condition, cavitation will reduce the components life time dramatically. Cavitation may occur when the local static pressure in a fluid reach a level below the vapor pressure of the liquid at the actual temperature. According to the Bernoulli Equation this may happen when the fluid accelerates in a control valve or around a pump impeller. The vaporization itself does not cause the damage - the damage happens when the vapor almost immediately collapses after evaporation when the velocity is decreased and pressure increased.

Cavitation means that cavities are forming in the liquid that we are pumping. When these cavities form at the suction of the pump several things happen all at once: We experience a loss in capacity. We can no longer build the same head (pressure). The efficiency drops. The cavities or bubbles will collapse when they pass into the higher regions of pressure causing noise, vibration, and damage to many of the components. The cavities form for five basic reasons and it is common practice to lump all of them into the general classification of cavitation.

This is an error because we will learn that to correct each of these conditions we must understand why they occur and how to fix them. Here they are in no particular order: Vaporization, Air ingestion, Internal recirculation, Flow turbulence and finally the Vane Passing Syndrome.

Avoiding Cavitation
Cavitation can in general be avoided by:
* increasing the distance between the actual local static pressure in the fluid - and the vapor pressure of the fluid at the actual temperature

This can be done by:
* reengineering components initiating high speed velocities and low static pressures
* increasing the total or local static pressure in the system
* reducing the temperature of the fluid

Reengineering of Components Initiating High Speed Velocity and Low Static Pressure
Cavitation and damage can be avoided by using special components designed for the actual rough conditions.
* Conditions such as huge pressure drops can - with limitations - be handled by Multi Stage Control Valves
* Difficult pumping conditions - with fluid temperatures close to the vaporization temperature - can be handled with a special pump - working after another principle than the centrifugal pump.

Cavitation Continued: Increasing the Total or Local Pressure in the System
By increasing the total or local pressure in the system, the distance between the static pressure and the vaporization pressure is increased and vaporization and cavitation may be avoided.

The ratio between static pressure and the vaporization pressure, an indication of the possibility of vaporization, is often expressed by the Cavitation Number. Unfortunately it may not always be possible to increase the total static pressure due to system classifications or other limitations. Local static pressure in the component may then be increased by lowering the component in the system. Control valves and pumps should in general be positioned in the lowest part of the system to maximize the static head. This is common for boiler feeding pumps receiving hot condensate (water close to 100 °C) from a condensate receiver.

Cavitation Continued: Reducing the Temperature of the Fluid
The vaporization pressure is highly dependent on the fluid temperature. Water, our most common fluid, is an example:

Temperature (°C)	Vapor Pressure (kN/m^2)
0	0.6
5	0.9
10	1.2
15	1.7
20	2.3
25	3.2
30	4.3
35	5.6
40	7.7
45	9.6
50	12.5
55	15.7
60	20
65	25
70	32.1
75	38.6
80	47.5
85	57.8
90	70
95	84.5
100	101.33

As we can see - the possibility of evaporation and cavitation increases dramatically with the water temperature.

Cavitation can be avoided by locating the components in the coldest part of the system. For example, it is common to locate the pumps in heating systems at the "cold" return lines. The situation is the same for control valves. Where it is possible they should be located on the cold side of heat exchangers.

Cavitations Number: A "special edition" of the dimensionless Euler Number.

The Cavitations Number is useful for analyzing fluid flow dynamics problems where cavitations may occur. The Cavitations Number can be expressed as

$$Ca = (p_r - p_v) / 1/2 \, \rho \, v^2 \text{ (1)}$$

where
Ca = Cavitations number
p_r = reference pressure (Pa)
p_v = vapor pressure of the fluid (Pa)
ρ = density of the fluid (kg/m³)
v = velocity of fluid (m/s)

Centrifugal Pump: A pump consisting of an impeller fixed on a rotating shaft and enclosed in a casing, having an inlet and a discharge connection. The rotating impeller creates pressure in the liquid by the velocity derived from centrifugal force.
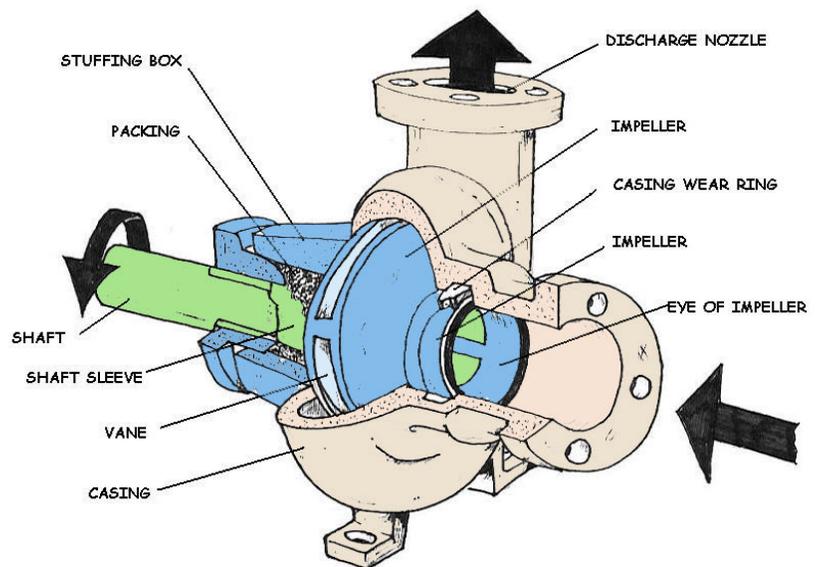
Chezy Formula: Conduits flow and mean velocity. The Chezy formula can be used to calculate mean flow velocity in conduits and is expressed as

$$v = c \, (R \, S)^{1/2} \text{ (1)}$$

where
v = mean velocity (m/s, ft/s)
c = the Chezy roughness and conduit coefficient
R = hydraulic radius of the conduit (m, ft)
S = slope of the conduit (m/m, ft/ft)

In general the Chezy coefficient - c - is a function of the flow Reynolds Number - Re - and the relative roughness - ε/R - of the channel.
ε is the characteristic height of the roughness elements on the channel boundary.

Coanda Effect: The tendency of a stream of fluid to stay attached to a convex surface, rather than follow a straight line in its original direction.

Colebrook Equation: The friction coefficients used to calculate pressure loss (or major loss) in ducts, tubes and pipes can be calculated with the Colebrook equation.

$$1 / \lambda^{1/2} = -2 \log ((2.51 / (Re\ \lambda^{1/2})) + ((k / d_h) / 3.72))\ (1)$$

where
λ = *D'Arcy-Weisbach friction coefficient*
Re = Reynolds Number
k = roughness of duct, pipe or tube surface (m, ft)
d_h = *hydraulic diameter (m, ft)*

The Colebrook equation is only valid at turbulent flow conditions.
Note that the friction coefficient is involved on both sides of the equation and that the equation must be solved by iteration.

The Colebrook equation is generic and can be used to calculate the friction coefficients in different kinds of fluid flows - air ventilation ducts, pipes and tubes with water or oil, compressed air and much more.

Common Pressure Measuring Devices: The Strain Gauge is a common measuring device used for a variety of changes such as head. As the pressure in the system changes, the diaphragm expands which changes the length of the wire attached. This change of length of the wire changes the Resistance of the wire, which is then converted to head. Float mechanisms, diaphragm elements, bubbler tubes, and direct electronic sensors are common types of level sensors.

Compressible Flow: We know that fluids are classified as Incompressible and Compressible fluids. Incompressible fluids do not undergo significant changes in density as they flow. In general, liquids are incompressible; water being an excellent example. In contrast compressible fluids do undergo density changes.

Gases are generally compressible; air being the most common compressible fluid we can find. Compressibility of gases leads to many interesting features such as shocks, which are absent for incompressible fluids. Gas dynamics is the discipline that studies the flow of compressible fluids and forms an important branch of Fluid Mechanics. In this book we give a broad introduction to the basics of compressible fluid flow.

In a compressible flow the compressibility of the fluid must be taken into account. The Ideal Gas Law - For a perfect or ideal gas the change in density is directly related to the change in temperature and pressure as expressed in the Ideal Gas Law. Properties of **Gas Mixtures** - Special care must be taken for gas mixtures when using the ideal gas law, calculating the mass, the individual gas constant or the density.

The Individual and **Universal Gas Constant** - The Individual and Universal Gas Constant is common in fluid mechanics and thermodynamics.

Compression and Expansion of Gases: If the compression or expansion takes place under constant temperature conditions - the process is called **isothermal.** The isothermal process can on the basis of the Ideal Gas Law be expressed as:

$p / \rho = constant$ (1)

where
p = absolute pressure
ρ = density

FLUIDS

Incompressible
$_p$ is constant

Compressible
$_p$ varies

Confined Space Entry: Entry into a confined space requires that all entrants wear a harness and safety line. If an operator is working inside a storage tank and suddenly faints or has a serious problem, there should be two people outside standing by to remove the injured operator.

Conservation Laws: The conservation laws states that particular measurable properties of an isolated physical system does not change as the system evolves: Conservation of energy (including mass). Fluid Mechanics and Conservation of Mass - The law of conservation of mass states that mass can neither be created or destroyed.

Contaminant: Any natural or man-made physical, chemical, biological, or radiological substance or matter in water, which is at a level that may have an adverse effect on public health, and which is known or anticipated to occur in public water systems.

Contamination: To make something bad; to pollute or infect something. To reduce the quality of the potable (drinking) water and create an actual hazard to the water supply by poisoning or through spread of diseases.

Corrosion: The removal of metal from copper, other metal surfaces and concrete surfaces in a destructive manner. Corrosion is caused by improperly balanced water or excessive water velocity through piping or heat exchangers.

Cross-Contamination: The mixing of two unlike qualities of water. For example, the mixing of good water with a polluting substance like a chemical.

D

Darcy-Weisbach Equation: The **pressure loss** (or major loss) in a pipe, tube or duct can be expressed with the D'Arcy-Weisbach equation:

$$\Delta p = \lambda \, (l \, / \, d_h) \, (\rho \, v^2 \, / \, 2) \; (1)$$

where
Δp = pressure loss (Pa, N/m^2, lb$_f$/ft^2)
λ = D'Arcy-Weisbach friction coefficient
l = length of duct or pipe (m, ft)
d_h = hydraulic diameter (m, ft)
ρ = density (kg/m^3, lb/ft^3)

Note! Be aware that there are two alternative friction coefficients present in the literature. One is 1/4 of the other and (1) must be multiplied with four to achieve the correct result. This is important to verify when selecting friction coefficients from Moody diagrams.

Density: Is a physical property of matter, as each element and compound has a unique density associated with it.

Density defined in a qualitative manner as the measure of the relative "heaviness" of objects with a constant volume. For example: A rock is obviously more dense than a crumpled piece of paper of the same size. A Styrofoam cup is less dense than a ceramic cup. Density may also refer to how closely "packed" or "crowded" the material appears to be - again refer to the Styrofoam vs. ceramic cup. Take a look at the two boxes below.
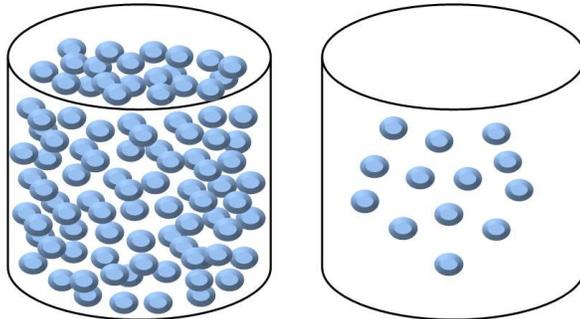
Each box has the same volume. *If each ball has the same mass, which box would weigh more? Why?*

The box that has more balls has more mass per unit of volume. This property of matter is called density. The density of a material helps to distinguish it from other materials. Since mass is usually expressed in grams and volume in cubic centimeters, density is expressed in grams/cubic centimeter. We can calculate density using the formula:

Density= Mass/Volume

The density can be expressed as

$$\rho = m \, / \, V = 1 \, / \, v_g \; (1)$$

where
ρ = density (kg/m^3)

m = mass (kg)
V = volume (m³)
v_g = specific volume (m³/kg)

The SI units for density are kg/m^3. The imperial (BG) units are lb/ft^3 ($slugs/ft^3$). While people often use pounds per cubic foot as a measure of density in the U.S., pounds are really a measure of force, not mass. Slugs are the correct measure of mass. You can multiply slugs by 32.2 for a rough value in pounds. The higher the density, the tighter the particles are packed inside the substance. Density is a physical property constant at a given temperature and density can help to identify a substance.

Example - Use the Density to Identify the Material:
An unknown liquid substance has a mass of 18.5 g and occupies a volume of 23.4 ml. (milliliter).

The density can be calculated as

ρ = [18.5 (g) / 1000 (g/kg)] / [23.4 (ml) / 1000 (ml/l) 1000 (l/m³)]
  = 18.5 10⁻³ (kg) / 23.4 10⁻⁶ (m³)
  = 790 kg/m³

If we look up densities of some common substances, we can find that ethyl alcohol, or ethanol, has a density of 790 kg/m^3. Our unknown liquid may likely be ethyl alcohol!

Example - Use Density to Calculate the Mass of a Volume
The density of titanium is 4507 kg/m^3 . Calculate the mass of 0.17 m^3 titanium!

  m = 0.17 (m³) 4507 (kg/m³)
    = 766.2 kg

Dilatant Fluids: Shear Thickening Fluids or Dilatant Fluids increase their viscosity with agitation. Some of these liquids can become almost solid within a pump or pipe line. With agitation, cream becomes butter and Candy compounds, clay slurries and similar heavily filled liquids do the same thing.

Disinfect: To kill and inhibit growth of harmful bacterial and viruses in drinking water.

Disinfection: The treatment of water to inactivate, destroy, and/or remove pathogenic bacteria, viruses, protozoa, and other parasites.

Distribution System Water Quality: Can be adversely affected by improperly constructed or poorly located blowoffs of vacuum/air relief valves. Air relief valves in the distribution system lines must be placed in locations that cannot be flooded. This is to prevent water contamination. The common customer complaint of Milky Water or Entrained Air is sometimes solved by the installation of air relief valves. The venting of air is not a major concern when checking water levels in a storage tank. If the vent line on a ground level storage tank is closed or clogged up, a vacuum will develop in the tank may happen to the tank when the water level begins to lower.

Drag Coefficient: Used to express the drag of an object in moving fluid. Any object moving through a fluid will experience a drag - the net force in direction of flow due to the pressure and

shear stress forces on the surface of the object.
The drag force can be expressed as:

$$F_d = c_d \ 1/2 \ \rho \ v^2 \ A \ (1)$$

where
F_d = *drag force (N)*
c_d = *drag coefficient*
ρ = *density of fluid*
v = *flow velocity*
A = *characteristic frontal area of the body*

The drag coefficient is a function of several parameters as shape of the body, Reynolds Number for the flow, Froude number, Mach Number and Roughness of the Surface.
The characteristic frontal area - *A* - depends on the body.

Dynamic or Absolute Viscosity: The viscosity of a fluid is an important property in the analysis of liquid behavior and fluid motion near solid boundaries. The viscosity of a fluid is its resistance to shear or flow and is a measure of the adhesive/cohesive or frictional properties of a fluid. The resistance is caused by intermolecular friction exerted when layers of fluids attempts to slide by another.

Dynamic Pressure: Dynamic pressure is the component of fluid pressure that represents a fluids kinetic energy. The dynamic pressure is a defined property of a moving flow of gas or liquid and can be expressed as

$$p_d = 1/2 \ \rho \ v^2 \ (1)$$

where
p_d = *dynamic pressure (Pa)*
ρ = *density of fluid (kg/m^3)*
v = *velocity (m/s)*

Dynamic, Absolute and Kinematic Viscosity: The viscosity of a fluid is an important property in the analysis of liquid behavior and fluid motion near solid boundaries. The viscosity is the fluid resistance to shear or flow and is a measure of the adhesive/cohesive or frictional fluid property. The resistance is caused by intermolecular friction exerted when layers of fluids attempts to slide by another.

Viscosity is a measure of a fluid's resistance to flow. The knowledge of viscosity is needed for proper design of required temperatures for storage, pumping or injection of fluids.

Common used units for viscosity are
- CentiPoises (cp) = CentiStokes (cSt) × Density
- SSU[1] = Centistokes (cSt) × 4.55
- Degree Engler[1] × 7.45 = Centistokes (cSt)
- Seconds Redwood[1] × 0.2469 = Centistokes (cSt)

[1]centistokes greater than 50

There are two related measures of fluid viscosity - known as **dynamic** (**or absolute**) and **kinematic** viscosity.

Dynamic (absolute) Viscosity: The tangential force per unit area required to move one horizontal plane with respect to the other at unit velocity when maintained a unit distance apart by the fluid. The shearing stress between the layers of non-turbulent fluid moving in straight parallel lines can be defined for a Newtonian fluid as:

The dynamic or absolute viscosity can be expressed like

$$\tau = \mu \, dc/dy \quad (1)$$

where
τ = shearing stress
μ = dynamic viscosity

Equation (1) is known as the **Newton's Law of Friction**.

In the SI system the dynamic viscosity units are **N s/m^2**, **Pa s** or **kg/m s** where
- *1 Pa s = 1 N s/m^2 = 1 kg/m s*

The dynamic viscosity is also often expressed in the metric CGS (centimeter-gram-second) system as **g/cm.s**, **dyne.s/cm^2** or **poise (p)** where
- *1 poise = dyne s/cm^2 = g/cm s = 1/10 Pa s*

For practical use the Poise is to large and its usual divided by 100 into the smaller unit called the **centiPoise (cP)** where
- *1 p = 100 cP*

Water at 68.4°F (20.2°C) has an absolute viscosity of one - 1 - centiPoise.

E

E. Coli, *Escherichia coli*: A bacterium commonly found in the human intestine. For water quality analyses purposes, it is considered an indicator organism. These are considered evidence of water contamination. Indicator organisms may be accompanied by pathogens, but do not necessarily cause disease themselves.

Elevation Head: The energy possessed per unit weight of a fluid because of its elevation. 1 foot of water will produce .433 pounds of pressure head.

Energy: The ability to do work. Energy can exist in one of several forms, such as heat, light, mechanical, electrical, or chemical. Energy can be transferred to different forms. It also can exist in one of two states, either potential or kinetic.

Energy and Hydraulic Grade Line: The hydraulic grade and the energy line are graphical forms of the Bernoulli equation. For steady, in viscid, incompressible flow the total energy remains constant along a stream line as expressed through the Bernoulli **Equation:**

p + 1/2 ρ v² + γ h = constant along a streamline (1)

where
p = static pressure (relative to the moving fluid)
ρ = density
γ = specific weight
v = flow velocity
g = acceleration of gravity
h = elevation height

Each term of this equation has the dimension *force per unit area* - psi, lb/ft² or N/m².

The Head

By dividing each term with the specific weight - *γ = ρ g* - (1) can be transformed to express the "head":

p / γ + v² / 2 g + h = constant along a streamline = H (2)
where
H = the total head

Each term of this equation has the dimension length - ft, m.

The Total Head

(2) states that the sum of **pressure head** - *p / γ* -, **velocity head** - *v² / 2 g* - and **elevation head** - *h* - is constant along the stream line. This constant can be called **the total head** - *H* -.

The total head in a flow can be measured by the stagnation pressure using a pitot tube.

Energy and Hydraulic Grade Line Continued:
The Piezometric Head

The sum of pressure head - *p / γ* - and elevation head - *h* - is called **the piezometric head**. The piezometric head in a flow can be measured through an flat opening parallel to the flow.

Energy and Hydraulic Grade Line Continued:
The Energy Line

The Energy Line is a line that represents the total head available to the fluid and can be expressed as:

EL = H = p / γ + v² / 2 g + h = constant along a streamline (3)

where
EL = Energy Line

For a fluid flow without any losses due to friction (major losses) or components (minor losses) the energy line would be at a constant level. In the practical world the energy line decreases along the flow due to the losses.

A turbine in the flow will reduce the energy line and a pump or fan will increase the energy line.

The Hydraulic Grade Line

The Hydraulic Grade Line is a line that represent the total head available to the fluid minus the velocity head and can be expressed as:

$$HGL = p \, / \, \gamma + h \ (4)$$

where
HGL = Hydraulic Grade Line

The hydraulic grade line lies one velocity head below the energy line.

Entrance Length and Developed Flow: Fluids need some length to develop the velocity profile after entering the pipe or after passing through components such as bends, valves, pumps, and turbines or similar.

The Entrance Length: The entrance length can be expressed with the dimensionless **Entrance Length Number:**

$$El = l_e \, / \, d \ (1)$$

where
El = Entrance Length Number
l_e = length to fully developed velocity profile
d = tube or duct diameter

The Entrance Length Number for Laminar Flow

The Entrance length number correlation with the Reynolds Number for laminar flow can be expressed as:

$$El_{laminar} = 0.06 \, Re \ (2)$$

where
Re = Reynolds Number

The Entrance Length Number for Turbulent Flow

The Entrance length number correlation with the Reynolds Number for turbulent flow can be expressed as:

$$El_{turbulent} = 4.4 \, Re^{1/6} \ (3)$$

Entropy in Compressible Gas Flow: Calculating entropy in compressible gas flow
Entropy change in compressible gas flow can be expressed as

$$ds = c_v \, ln(T_2 \, / \, T_1) + R \, ln(\rho_1 \, / \, \rho_2) \ (1)$$
or
$$ds = c_p \, ln(T_2 \, / \, T_1) - R \, ln(p_2 \, / \, p_1) \ (2)$$

where
ds = entropy change
c_v = specific heat capacity at a constant volume process
c_p = specific heat capacity at a constant pressure process
T = absolute temperature

R = individual gas constant
ρ = density of gas
p = absolute pressure

Equation of Continuity: The Law of Conservation of Mass states that mass can be neither created nor destroyed. Using the Mass Conservation Law on a **steady flow** process - flow where the flow rate doesn't change over time - through a control volume where the stored mass in the control volume doesn't change - implements that inflow equals outflow. This statement is called **the Equation of Continuity.** Common application where **the Equation of Continuity** can be used are pipes, tubes and ducts with flowing fluids and gases, rivers, overall processes as power plants, diaries, logistics in general, roads, computer networks and semiconductor technology and more.

The Equation of Continuity and can be expressed as:

$$m = \rho_{i1} \, v_{i1} \, A_{i1} + \rho_{i2} \, v_{i2} \, A_{i2} + .. + \rho_{in} \, v_{in} \, A_{im}$$
$$= \rho_{o1} \, v_{o1} \, A_{o1} + \rho_{o2} \, v_{o2} \, A_{o2} + .. + \rho_{om} \, v_{om} \, A_{om} \ (1)$$

where
m = mass flow rate (kg/s)
ρ = density (kg/m^3)
v = speed (m/s)
A = area (m^2)
With uniform density equation (1) can be modified to
$$q = v_{i1} \, A_{i1} + v_{i2} \, A_{i2} + .. + v_{in} \, A_{im}$$
$$= v_{o1} \, A_{o1} + v_{o2} \, A_{o2} + .. + v_{om} \, A_{om} \ (2)$$

where
q = flow rate (m^3/s)
$$\rho_{i1} = \rho_{i2} = . . = \rho_{in} = \rho_{o1} = \rho_{o2} = . . = \rho_{om}$$

Example - Equation of Continuity
10 m^3/h of water flows through a pipe of 100 mm inside diameter. The pipe is reduced to an inside dimension of 80 mm. Using equation (2) the velocity in the 100 mm pipe can be calculated as

(10 m^3/h)(1 / 3600 h/s) = v$_{100}$ (3.14 x 0.1 (m) x 0.1 (m) / 4)
or
v$_{100}$ = (10 m^3/h)(1 / 3600 h/s) / (3.14 x 0.1 (m) x 0.1 (m) / 4)
= <u>0.35</u> m/s
Using equation (2) the velocity in the 80 mm pipe can be calculated
(10 m^3/h)(1 / 3600 h/s) = v$_{80}$ (3.14 x 0.08 (m) x 0.08 (m) / 4)
or
v$_{100}$ = (10 m^3/h)(1 / 3600 h/s) / (3.14 x 0.08 (m) x 0.08 (m) / 4)
= <u>0.55</u> m/s

Equation of Mechanical Energy: The Energy Equation is a statement of the first law of thermodynamics. The energy equation involves energy, heat transfer and work. With certain limitations the mechanical energy equation can be compared to the Bernoulli Equation and transferred to the Mechanical Energy Equation in Terms of Energy per Unit Mass.

The mechanical energy equation for a **pump or a fan** can be written in terms of **energy per unit mass**:

$$p_{in} / \rho + v_{in}^2 / 2 + g\,h_{in} + w_{shaft} = p_{out} / \rho + v_{out}^2 / 2 + g\,h_{out} + w_{loss} \quad (1)$$

where
p = static pressure
ρ = density
v = flow velocity
g = acceleration of gravity
h = elevation height
w_{shaft} = net shaft energy inn per unit mass for a pump, fan or similar
w_{loss} = loss due to friction

The energy equation is often used for incompressible flow problems and is called **the Mechanical Energy Equation** or **the Extended Bernoulli Equation**.

The mechanical energy equation for a **turbine** can be written as:

$$p_{in} / \rho + v_{in}^2 / 2 + g\,h_{in} = p_{out} / \rho + v_{out}^2 / 2 + g\,h_{out} + w_{shaft} + w_{loss} \quad (2)$$

where
w_{shaft} = net shaft energy out per unit mass for a turbine or similar

Equation (1) and (2) dimensions are
energy per unit mass (ft^2/s^2 = ft lb/slug or m^2/s^2 = N m/kg)

Efficiency
According to (1) a larger amount of loss - w_{loss} - result in more shaft work required for the same rise of output energy. The efficiency of a **pump or fan process** can be expressed as:

$$\eta = (w_{shaft} - w_{loss}) / w_{shaft} \quad (3)$$

The efficiency of a **turbine process** can be expressed as:
$$\eta = w_{shaft} / (w_{shaft} + w_{loss}) \quad (4)$$

The Mechanical Energy Equation in Terms of Energy per Unit Volume
The mechanical energy equation for a **pump or a fan** (1) can also be written in terms of **energy per unit volume** by multiplying (1) with fluid density - ρ:

$$p_{in} + \rho\,v_{in}^2 / 2 + \gamma\,h_{in} + \rho\,w_{shaft} = p_{out} + \rho\,v_{out}^2 / 2 + \gamma\,h_{out} + w_{loss} \quad (5)$$

where
γ = ρ g = specific weight

The dimensions of equation (5) are
energy per unit volume ($ft.lb/ft^3$ = lb/ft^2 or $N.m/m^3$ = N/m^2)

The Mechanical Energy Equation in Terms of Energy per Unit Weight involves Heads
The mechanical energy equation for a **pump or a fan** (1) can also be written in terms of **energy per unit weight** by dividing with gravity - g:

$$p_{in} / \gamma + v_{in}^2 / 2g + h_{in} + h_{shaft} = p_{out} / \gamma + v_{out}^2 / 2g + h_{out} + h_{loss} \quad (6)$$

where
γ = ρ g = specific weight
h_{shaft} = w_{shaft} / g = net shaft energy head inn per unit mass for a pump, fan or similar
h_{loss} = w_{loss} / g = loss head due to friction

The dimensions of equation (6) are

energy per unit weight (ft.lb/lb = ft or N.m/N = m)

Head is the energy per unit weight.

h_{shaft} can also be expressed as:
h_{shaft} = w_{shaft} / g = W_{shaft} / m g = W_{shaft} / γ Q (7)

where
W_{shaft} = shaft power
m = mass flow rate
Q = volume flow rate

Example - Pumping Water
Water is pumped from an open tank at level zero to an open tank at level 10 ft. The pump adds four horsepowers to the water when pumping 2 ft³/s.
Since v_{in} = v_{out} = 0, p_{in} = p_{out} = 0 and h_{in} = 0 - equation (6) can be modified to:

h_{shaft} = h_{out} + h_{loss}
or
h_{loss} = h_{shaft} - h_{out} (8)

Equation (7) gives:

h_{shaft} = W_{shaft} / γ Q = (4 hp)(550 ft.lb/s/hp) / (62.4 lb/ft³)(2 ft³/s) = 17.6 ft
* specific weight of water 62.4 lb/ft³
* 1 hp (English horse power) = 550 ft. lb/s

Combined with (8):
h_{loss} = (17.6 ft) - (10 ft) = 7.6 ft

The pump efficiency can be calculated from (3) modified for head:
η = ((17.6 ft) - (7.6 ft)) / (17.6 ft)= 0.58

Equations in Fluid Mechanics: Common fluid mechanics equations - Bernoulli, conservation of energy, conservation of mass, pressure, Navier-Stokes, ideal gas law, Euler equations, Laplace equations, Darcy-Weisbach Equation and the following:
The Bernoulli Equation
* The Bernoulli Equation - A statement of the conservation of energy in a form useful for solving problems involving fluids. For a non-viscous, incompressible fluid in steady flow, the sum of pressure, potential and kinetic energies per unit volume is constant at any point.

Conservation laws
- The conservation laws states that particular measurable properties of an isolated physical system does not change as the system evolves.
- Conservation of energy (including mass)
- Fluid Mechanics and Conservation of Mass - The law of conservation of mass states that mass can neither be created nor destroyed.
- The Continuity Equation - The Continuity Equation is a statement that mass is conserved.

Darcy-Weisbach Equation
- Pressure Loss and Head Loss due to Friction in Ducts and Tubes - Major loss - head loss or pressure loss - due to friction in pipes and ducts.

Euler Equations
- In fluid dynamics, the Euler equations govern the motion of a compressible, inviscid fluid. They correspond to the Navier-Stokes equations with zero viscosity, although they are usually written in the form shown here because this emphasizes the fact that they directly represent conservation of mass, momentum, and energy.

Laplace's Equation
- The Laplace Equation describes the behavior of gravitational, electric, and fluid potentials.

Ideal Gas Law
- The Ideal Gas Law - For a perfect or ideal gas, the change in density is directly related to the change in temperature and pressure as expressed in the Ideal Gas Law.
- Properties of Gas Mixtures - Special care must be taken for gas mixtures when using the ideal gas law, calculating the mass, the individual gas constant or the density.
- The Individual and Universal Gas Constant - The Individual and Universal Gas Constant is common in fluid mechanics and thermodynamics.

Navier-Stokes Equations
- The motion of a non-turbulent, Newtonian fluid is governed by the Navier-Stokes equations. The equation can be used to model turbulent flow, where the fluid parameters are interpreted as time-averaged values.

Mechanical Energy Equation
- The Mechanical Energy Equation - The mechanical energy equation in Terms of Energy per Unit Mass, in Terms of Energy per Unit Volume and in Terms of Energy per Unit Weight involves Heads.

Pressure
- Static Pressure and Pressure Head in a Fluid - Pressure and pressure head in a static fluid.

Euler Equations: In fluid dynamics, the Euler equations govern the motion of a compressible, inviscid fluid. They correspond to the Navier-Stokes equations with zero viscosity, although they are usually written in the form shown here because this emphasizes the fact that they directly represent conservation of mass, momentum, and energy.

Euler Number: The Euler numbers, also called the secant numbers or zig numbers, are defined for $|x| < \pi/2$ by

$$\operatorname{sech} x - 1 \equiv -\frac{E_1^* x^2}{2!} + \frac{E_2^* x^4}{4!} - \frac{E_3^* x^6}{6!} + \dots$$

$$\sec x - 1 \equiv \frac{E_1^* x^2}{2!} + \frac{E_2^* x^4}{4!} + \frac{E_3^* x^6}{6!} + \dots,$$

where $\operatorname{sech}(z)$ the hyperbolic secant and sec is the secant. Euler numbers give the number of odd alternating permutations and are related to Genocchi numbers. The base *e* of the natural logarithm is sometimes known as Euler's number. A different sort of Euler number, the Euler number of a finite complex K, is defined by

$$\chi(K) = \sum (-1)^p \operatorname{rank}(C_p(K)).$$

This Euler number is a topological invariant. To confuse matters further, the Euler characteristic is sometimes also called the "Euler number," and numbers produced by the prime-generating polynomial $n^2 - n + 41$ are sometimes called "Euler numbers" (Flannery and Flannery 2000, p. 47).

F

Fecal Coliform: A group of bacteria that may indicate the presence of human or animal fecal matter in water.

Filtration: A series of processes that physically remove particles from water.

Flood Rim: The point of an object where the water would run over the edge of something and begin to cause a flood. See Air Break.

Fluids: A fluid is defined as a substance that continually deforms (flows) under an applied shear stress regardless of the magnitude of the applied stress. It is a subset of the phases of matter and includes liquids, gases, plasmas and, to some extent, plastic solids. Fluids are also divided into liquids and gases. Liquids form a free surface (that is, a surface not created by their container) while gases do not.

The distinction between solids and fluids is not so obvious. The distinction is made by evaluating the viscosity of the matter: for example silly putty can be considered either a solid or a fluid, depending on the time period over which it is observed. Fluids share the properties of not resisting deformation and the ability to flow (also described as their ability to take on the shape of their containers).

These properties are typically a function of their inability to support a shear stress in static equilibrium. While in a solid, stress is a function of strain, in a fluid, stress is a function of rate of strain. A consequence of this behavior is Pascal's law which entails the important role of pressure in characterizing a fluid's state. Based on how the stress depends on the rate of strain and its derivatives, fluids can be characterized as: Newtonian fluids: where stress is directly proportional to rate of strain, and Non-Newtonian fluids : where stress is proportional to rate of strain, its higher powers and derivatives (basically everything other than Newtonian fluid).

The behavior of fluids can be described by a set of partial differential equations, which are based on the conservation of mass, linear and angular momentum (Navier-Stokes equations) and energy. The study of fluids is fluid mechanics, which is subdivided into fluid dynamics and fluid statics depending on whether the fluid is in motion or not. Fluid **Related Information**: The Bernoulli Equation - A statement of the conservation of energy in a form useful for solving problems involving fluids. For a non-viscous, incompressible fluid in steady flow, the sum of pressure, potential and kinetic energies per unit volume is constant at any point. Equations in Fluid Mechanics - Continuity, Euler, Bernoulli, Dynamic and Total Pressure. Laminar, Transitional or Turbulent Flow? - It is important to know if the fluid flow is laminar, transitional or turbulent when calculating heat transfer or pressure and head loss.

Friction Head: The head required to overcome the friction at the interior surface of a conductor and between fluid particles in motion. It varies with flow, size, type and conditions of conductors and fittings, and the fluid characteristics.

G
Gas: A gas is one of the four major phases of matter (after solid and liquid, and followed by plasma) that subsequently appear as solid material when they are subjected to increasingly higher temperatures. Thus, as energy in the form of heat is added, a solid (e.g., ice) will first melt to become a liquid (e.g., water), which will then boil or evaporate to become a gas (e.g., water vapor).

In some circumstances, a solid (e.g., "dry ice") can directly turn into a gas: this is called sublimation. If the gas is further heated, its atoms or molecules can become (wholly or partially) ionized, turning the gas into a plasma. Relater Gas Information: The Ideal Gas Law - For a perfect or ideal gas the change in density is directly related to the change in temperature and pressure as expressed in the Ideal Gas Law. Properties of Gas Mixtures - Special care must be taken for gas mixtures when using the ideal gas law, calculating the mass, the individual gas constant or the density. The Individual and Universal Gas Constant - The Individual and Universal Gas Constant is common in fluid mechanics and thermodynamics.

Gauge Pressure: Pressure differential above or below ambient atmospheric pressure.

H
Hazardous Atmosphere: An atmosphere which by reason of being explosive, flammable, poisonous, corrosive, oxidizing, irritating, oxygen deficient, toxic, or otherwise harmful, may cause death, illness, or injury.

Hazen-Williams Factor: Hazen-Williams factor for some common piping materials. Hazen-Williams coefficients are used in the Hazen-Williams equation for friction loss calculation in ducts and pipes.

Hazen-Williams Equation - Calculating Friction Head Loss in Water Pipes
Friction head loss (ft H2O per 100 ft pipe) in water pipes can be obtained by using the empirical Hazen-Williams equation. The Darcy-Weisbach equation with the Moody diagram are considered to be the most accurate model for estimating frictional head loss in steady pipe flow. Since the approach requires a not so efficient trial and error solution, an alternative empirical head loss calculation that does not require the trial and error solutions, as the Hazen-Williams equation, may be preferred:

$$f = 0.2083 \ (100/c)^{1.852} \ q^{1.852} / d_h^{4.8655} \ (1)$$

where
f = friction head loss in feet of water per 100 feet of pipe (ft_{h20}/100 ft pipe)
c = Hazen-Williams roughness constant
q = volume flow (gal/min)
d_h = inside hydraulic diameter (inches)

Note that the Hazen-Williams formula is empirical and lacks physical basis. Be aware that the roughness constants are based on "normal" condition with approximately 1 m/s (3 ft/sec).

The Hazen-Williams formula is not the only empirical formula available. Manning's formula is common for gravity driven flows in open channels.

The flow velocity may be calculated as:

$$v = 0.4087 \ q / d_h^2$$

where
v = flow velocity (ft/s)

The Hazen-Williams formula can be assumed to be relatively accurate for piping systems where the Reynolds Number is above 10^5 (turbulent flow).
- 1 ft (foot) = 0.3048 m
- 1 in (inch) = 25.4 mm
- 1 gal (US)/min =6.30888×10^{-5} m³/s = 0.0227 m³/h = 0.0631 dm³(liter)/s = 2.228×10^{-3} ft³/s = 0.1337 ft³/min = 0.8327 Imperial gal (UK)/min

Note! The Hazen-Williams formula gives accurate head loss due to friction for fluids with kinematic viscosity of approximately 1.1 cSt. More about fluids and kinematic viscosity.

The results for the formula are acceptable for cold water at 60° F (15.6° C) with kinematic viscosity 1.13 cSt. For hot water with a lower kinematic viscosity (0.55 cSt at 130° F (54.4° C)) the error will be significant. Since the Hazen Williams method is only valid for water flowing at ordinary temperatures between 40 to 75° F, the Darcy Weisbach method should be used for other liquids or gases.

Head: The height of a column or body of fluid above a given point expressed in linear units. Head if often used to indicate gauge pressure. Pressure is equal to the height times the density of the liquid. The measure of the pressure of water expressed in feet of height of water. 1 psi = 2.31 feet of water. There are various types of heads of water depending upon what is being measured. Static (water at rest) and Residual (water at flow conditions).

Hydraulics: Hydraulics is a branch of science and engineering concerned with the use of

liquids to perform mechanical tasks.

Hydrodynamics: Hydrodynamics is the fluid dynamics applied to liquids, such as water, alcohol, and oil.

I

Ideal Gas: The Ideal Gas Law - For a perfect or ideal gas the change in density is directly related to the change in temperature and pressure as expressed in the Ideal Gas Law. Properties of Gas Mixtures - Special care must be taken for gas mixtures when using the ideal gas law, calculating the mass, the individual gas constant or the density. The Individual and Universal Gas Constant - The Individual and Universal Gas Constant is common in fluid mechanics and thermodynamics.

Isentropic Compression/Expansion Process: If the compression or expansion takes place under constant volume conditions - the process is called **isentropic.** The isentropic process on the basis of the Ideal Gas Law can be expressed as:

$p / \rho^k = constant$ (2)

where
$k = c_p / c_v$ - the ratio of specific heats - the ratio of specific heat at constant pressure - c_p - to the specific heat at constant volume - c_v

Irrigation: Water that is especially furnished to help provide and sustain the life of growing plants. It comes from ditches. It is sometimes treated with herbicides and pesticides to prevent the growth of weeds and the development of bugs in a lawn and a garden.

K

Kinematic Viscosity: The ratio of absolute or dynamic viscosity to density - a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid with its mass density as

$v = \mu / \rho$ (2)

where
v = kinematic viscosity
μ = absolute or dynamic viscosity
ρ = density

In the SI-system the theoretical unit is m^2/s or commonly used **Stoke (St)** where
* $1 St = 10^{-4} m^2/s$

Since the Stoke is an unpractical large unit, it is usual divided by 100 to give the unit called **Centistokes (cSt)** where
$1 St = 100 cSt$
$1 cSt = 10^{-6} m^2/s$

Since the specific gravity of water at 68.4°F (20.2°C) is almost one - 1, the kinematic viscosity of water at 68.4°F is for all practical purposes 1.0 cSt.
Kinetic Energy: The ability of an object to do work by virtue of its motion. The energy terms that are used to describe the operation of a pump are pressure and head.

Knudsen Number: Used by modelers who wish to express a non-dimensionless speed.

L

Laminar Flow: The resistance to flow in a liquid can be characterized in terms of the viscosity of the fluid if the flow is smooth. In the case of a moving plate in a liquid, it is found that there is a layer or lamina which moves with the plate, and a layer which is essentially stationary if it is next to a stationary plate. There is a gradient of velocity as you move from the stationary to the moving plate, and the liquid tends to move in layers with successively higher speed. This is called laminar flow, or sometimes "streamlined" flow. Viscous resistance to flow can be modeled for laminar flow, but if the lamina break up into turbulence, it is very difficult to characterize the fluid flow.

Lamina of flow with higher velocities

Moving plate

Stationary plate
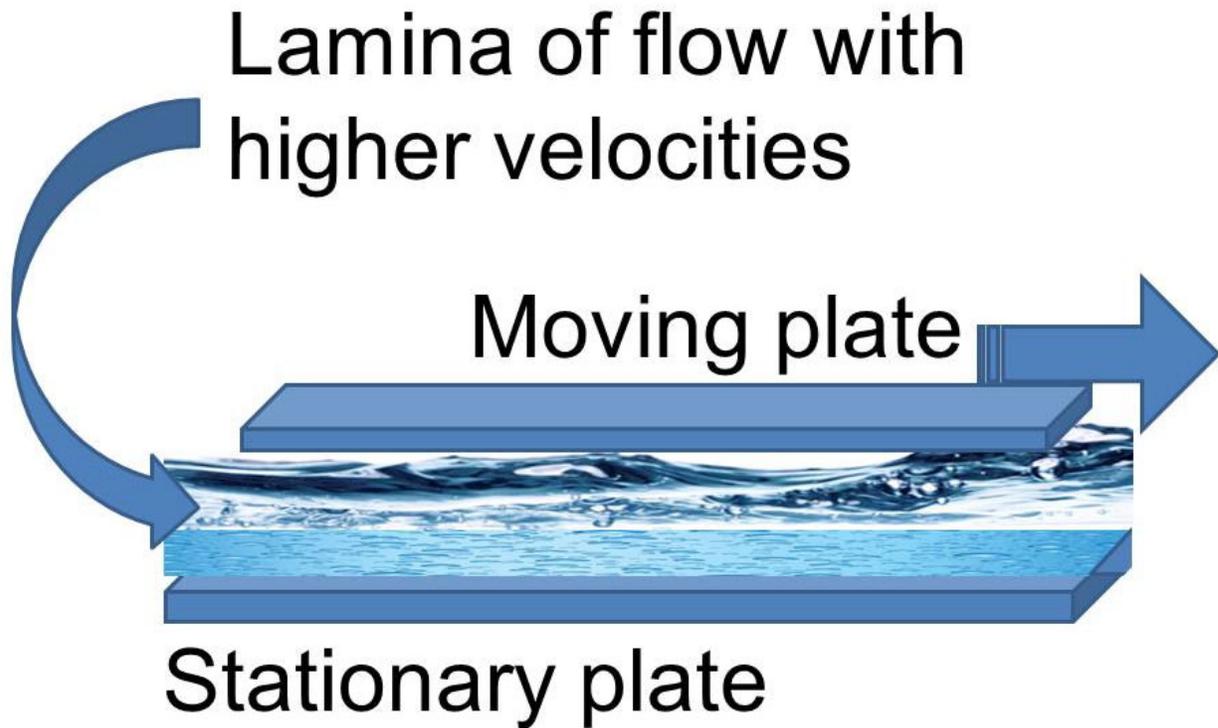
The common application of laminar flow would be in the smooth flow of a viscous liquid through a tube or pipe. In that case, the velocity of flow varies from zero at the walls to a maximum along the centerline of the vessel. The flow profile of laminar flow in a tube can be calculated by dividing the flow into thin cylindrical elements and applying the viscous force to them. Laminar, Transitional or Turbulent Flow? - It is important to know if the fluid flow is laminar, transitional or turbulent when calculating heat transfer or pressure and head loss.

Laplace's Equation: Describes the behavior of gravitational, electric, and fluid potentials.

The scalar form of Laplace's equation is the partial differential equation
$$\nabla^2 \psi = 0,$$ (1)
where ∇^2 is the Laplacian.
Note that the operator ∇^2 is commonly written as $\triangle$ by mathematicians (Krantz 1999, p. 16). Laplace's equation is a special case of the Helmholtz differential equation
$$\nabla^2 \psi + k^2 \psi = 0$$ (2)

with $k = 0$, or Poisson's equation
$$\nabla^2 \psi = -4 \pi \rho$$ (3)
with $\rho = 0$.

The vector Laplace's equation is given by
$$\nabla^2 \mathbf{F} = \mathbf{0}.$$ (4)

A function ψ which satisfies Laplace's equation is said to be harmonic. A solution to Laplace's equation has the property that the average value over a spherical surface is equal to the value at the center of the sphere (Gauss's harmonic function theorem). Solutions have no local maxima or minima. Because Laplace's equation is linear, the superposition of any two solutions is also a solution.

Lift (Force): Lift consists of the sum of all the aerodynamic forces normal to the direction of the external airflow.

Liquids: An in-between state of matter. They can be found in between the solid and gas states. They don't have to be made up of the same compounds. If you have a variety of materials in a liquid, it is called a solution. One characteristic of a liquid is that it will fill up the shape of a container. If you pour some water in a cup, it will fill up the bottom of the cup first and then fill the rest. The water will also take the shape of the cup. It fills the bottom first because of **gravity**. The top part of a liquid will usually have a flat surface. That flat surface is because of gravity too. Putting an ice cube (solid) into a cup will leave you with a cube in the middle of the cup; the shape won't change until the ice becomes a liquid.
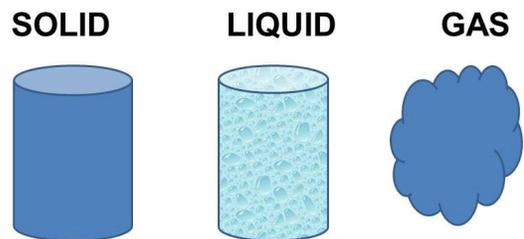
Another trait of liquids is that they are difficult to compress.

SOLID   **LIQUID**   **GAS**

MORE   **LESS**
EFFORT NEEDED TO COMPRESS

When you compress something, you take a certain amount and force it into a smaller space. Solids are very difficult to compress and gases are very easy. Liquids are in the middle but tend to be difficult. When you compress something, you force the atoms closer together. When pressure go up, substances are compressed. Liquids already have their atoms close together, so they are hard to compress. Many shock absorbers in cars compress liquids in tubes.

A special force keeps liquids together. Solids are stuck together and you have to force them apart. Gases bounce everywhere and they try to spread themselves out. Liquids actually want to stick together. There will always be the occasional evaporation where extra energy gets a molecule excited and the molecule leaves the system. Overall, liquids have **cohesive** (sticky) forces at work that hold the molecules together. Related Liquid Information: Equations in Fluid Mechanics - Continuity, Euler, Bernoulli, Dynamic and Total Pressure

M

Mach Number: When an object travels through a medium, then its Mach number is the ratio of the object's speed to the speed of sound in that medium.

Magnetic Flow Meter: Inspection of magnetic flow meter instrumentation should include checking for corrosion or insulation deterioration.

Manning Formula for Gravity Flow: Manning's equation can be used to calculate cross-sectional average velocity flow in open channels

$v = k_n/n\ R^{2/3}\ S^{1/2}$ (1)

where
v = cross-sectional average velocity (ft/s, m/s)
k_n = 1.486 for English units and k_n = 1.0 for SI units
A = cross sectional area of flow (ft^2, m^2)
n = Manning coefficient of roughness
R = hydraulic radius (ft, m)
S = slope of pipe (ft/ft, m/m)

The volume flow in the channel can be calculated as
$q = A\ v = A\ k_n/n\ R^{2/3}\ S^{1/2}$ (2)

where
q = volume flow (ft^3/s, m^3/s)
A = cross-sectional area of flow (ft^2, m^2)

Maximum Contamination Levels or (MCLs): The maximum allowable level of a contaminant that federal or state regulations allow in a public water system. If the MCL is exceeded, the water system must treat the water so that it meets the MCL. Or provide adequate backflow protection.

Mechanical Seal: A mechanical device used to control leakage from the stuffing box of a pump. Usually made of two flat surfaces, one of which rotates on the shaft. The two flat surfaces are of such tolerances as to prevent the passage of water between them.

Mg/L: milligrams per liter

Microbe, Microbial: Any minute, simple, single-celled form of life, especially one that causes

disease.

Microbial Contaminants: Microscopic organisms present in untreated water that can cause waterborne diseases.

ML: milliliter

N

Navier-Stokes Equations: The motion of a non-turbulent, Newtonian fluid is governed by the Navier-Stokes equation. The equation can be used to model turbulent flow, where the fluid parameters are interpreted as time-averaged values.

Newtonian Fluid: Newtonian fluid (named for Isaac Newton) is a fluid that flows like water—its shear stress is linearly proportional to the velocity gradient in the direction perpendicular to the plane of shear. The constant of proportionality is known as the viscosity. Water is Newtonian, because it continues to exemplify fluid properties no matter how fast it is stirred or mixed.

Contrast this with a non-Newtonian fluid, in which stirring can leave a "hole" behind (that gradually fills up over time - this behavior is seen in materials such as pudding, or to a less rigorous extent, sand), or cause the fluid to become thinner, the drop in viscosity causing it to flow more (this is seen in non-drip paints). For a Newtonian fluid, the viscosity, by definition, depends only on temperature and pressure (and also the chemical composition of the fluid if the fluid is not a pure substance), not on the forces acting upon it. If the fluid is incompressible and viscosity is constant across the fluid, the equation governing the shear stress. Related Newtonian Information: A Fluid is Newtonian if viscosity is constant applied to shear force. Dynamic, Absolute and Kinematic Viscosity - An introduction to dynamic, absolute and kinematic viscosity and how to convert between CentiStokes (cSt), CentiPoises (cP), Saybolt Universal Seconds (SSU) and degree Engler.

Newton's Third Law: Newton's third law describes the forces acting on objects interacting with each other. Newton's third law can be expressed as

- *"If one object exerts a force **F** on another object, then the second object exerts an equal but opposite force **F** on the first object"*

Force is a convenient abstraction to represent mentally the pushing and pulling interaction between objects.

It is common to express forces as vectors with magnitude, direction and point of application. The net effect of two or more forces acting on the same point is the vector sum of the forces.

Non-Newtonian Fluid: Non-Newtonian fluid viscosity changes with the applied shear force.

O

Oxidizing: The process of breaking down organic wastes into simpler elemental forms or by products. Also used to separate combined chlorine and convert it into free chlorine.

P

Pascal's Law: A pressure applied to a confined fluid at rest is transmitted with equal intensity throughout the fluid.

Pathogens: Disease-causing pathogens; waterborne pathogens. A pathogen is a bacterium, virus or parasite that causes or is capable of causing disease. Pathogens may contaminate water and cause waterborne disease.

pCi/L- *picocuries per liter:* A curie is the amount of radiation released by a set amount of a certain compound. A picocurie is one quadrillionth of a curie.

pH: A measure of the acidity of water. The pH scale runs from 0 to 14 with 7 being the mid-point or neutral. A pH of less than 7 is on the acid side of the scale with 0 as the point of greatest acid activity. A pH of more than 7 is on the basic (alkaline) side of the scale with 14 as the point of greatest basic activity. pH (Power of Hydroxyl Ion Activity).

Pipeline Appurtenances: Pressure reducers, bends, valves, regulators (which are a type of valve), etc.

Peak Demand: The maximum momentary load placed on a water treatment plant, pumping station or distribution system is the Peak Demand.

Pipe Velocities: For calculating fluid pipe velocity.

Imperial units
A fluids flow velocity in pipes can be calculated with Imperial or American units as
$$v = 0.4085 \, q / d^2 \quad (1)$$

where
v = velocity (ft/s)
q = volume flow (US gal. /min)
d = pipe inside diameter (inches)

SI units
A fluids flow velocity in pipes can be calculated with SI units as
$$v = 1.274 \, q / d^2 \quad (2)$$

where
v = velocity (m/s)
q = volume flow (m³/s)
d = pipe inside diameter (m)

Pollution: To make something unclean or impure. Some states will have a definition of pollution that relates to non-health related water problems, like taste and odors. See Contaminated.

Positive Flow Report-back Signal: When a pump receives a signal to start, a light will typically

be illuminated on the control panel indicating that the pump is running. In order to be sure that the pump is actually pumping water, a Positive flow report-back signal should be installed on the control panel.

Potable: Good water which is safe for drinking or cooking purposes. Non-Potable: A liquid or water that is not approved for drinking.

Potential Energy: The energy that a body has by virtue of its position or state enabling it to do work.

PPM: Abbreviation for parts per million.

Prandtl Number: The Prandtl Number is a dimensionless number approximating the ratio of momentum diffusivity and thermal diffusivity and can be expressed as

> $Pr = v / \alpha$ *(1)*
> *where*
> *Pr = Prandtl's number*
> *v = kinematic viscosity (Pa s)*
> *α = thermal diffusivity (W/m K)*

The Prandtl number can alternatively be expressed as

> $Pr = \mu \, c_p / k$ *(2)*
>
> *where*
> *μ = absolute or dynamic viscosity (kg/m s, cP)*
> *c_p = specific heat capacity (J/kg K, Btu/(lb °F))*
> *k = thermal conductivity (W/m K, Btu/(h ft² °F/ft))*

The Prandtl Number is often used in heat transfer and free and forced convection calculations.

Pressure: An introduction to pressure - the definition and presentation of common units as psi and Pa and the relationship between them.

The pressure in a fluid is defined as
"the normal force per unit area exerted on an imaginary or real plane surface in a fluid or a gas"

The equation for pressure can expressed as:
> $p = F / A$ *(1)*
>
> *where*
> *p = pressure [lb/in² (psi) or lb/ft² (psf), N/m² or kg/ms² (Pa)]*
> *F = force [[1], N]*
> *A = area [in² or ft², m²]*

[1] In the English Engineering System special care must be taken for the force unit. The basic unit for mass is the pound mass (lb_m) and the unit for the force is the pound (lb) or pound force (lb_f).

Absolute Pressure
The **absolute pressure** - p_a - is measured relative to the *absolute zero pressure* - the pressure that would occur at absolute vacuum.

Gauge Pressure
A **gauge** is often used to measure the pressure difference between a system and the surrounding atmosphere. This pressure is often called the **gauge pressure** and can be expressed as

$$p_g = p_a - p_o \quad (2)$$

where
p_g = gauge pressure
p_o = atmospheric pressure

Atmospheric Pressure
The atmospheric pressure is the pressure in the surrounding air. It varies with temperature and altitude above sea level.

Standard Atmospheric Pressure
The **Standard Atmospheric Pressure** (atm) is used as a reference for gas densities and volumes. The Standard Atmospheric Pressure is defined at sea-level at 273°K (0°C) and is **1.01325 bar** or 101325 Pa (absolute). The temperature of 293°K (20°C) is also used.

In imperial units the Standard Atmospheric Pressure is 14.696 psi.
- *1 atm = 1.01325 bar = 101.3 kPa = 14.696 psi (lb_f/in^2)= 760 mmHg =10.33 mH_2O = 760 torr = 29.92 in Hg = 1013 mbar = 1.0332 kg_f/cm^2 = 33.90 ftH_2O*

Pressure Head: The height to which liquid can be raised by a given pressure.

Pressure Regulation Valves: Control water pressure and operate by restricting flows. They are used to deliver water from a high pressure to a low-pressure system. The pressure downstream from the valve regulates the amount of flow. Usually, these valves are of the globe design and have a spring-loaded diaphragm that sets the size of the opening.

Pressure Units: Since 1 Pa is a small pressure unit, the unit hectopascal (hPa) is widely used, especially in meteorology. The unit kilopascal (kPa) is commonly used designing technical applications like HVAC systems, piping systems and similar.
- *1 hectopascal = 100 pascal = 1 millibar*
- *1 kilopascal = 1000 pascal*

Some Pressure Levels
- 10 Pa - The pressure at a depth of 1 mm of water
- 1 kPa - Approximately the pressure exerted by a 10 g mass on a 1 cm^2 area
- 10 kPa - The pressure at a depth of 1 m of water, or
  the drop in air pressure when going from sea level to 1000 m elevation
- 10 MPa - A "high pressure" washer forces the water out of the nozzles at this pressure
- 10 GPa - This pressure forms diamonds

Some Alternative Units of Pressure
- *1 bar - 100,000 Pa*
- *1 millibar - 100 Pa*
- *1 atmosphere - 101,325 Pa*

- *1 mm Hg - 133 Pa*
- *1 inch Hg - 3,386 Pa*

A **torr** (torr) is named after Torricelli and is the pressure produced by a column of mercury 1 mm high equals to 1/760th of an atmosphere. 1 atm = 760 torr = 14.696 psi

Pounds per square inch (psi) was common in U.K. but has now been replaced in almost every country except in the U.S. by the SI units. The Normal atmospheric pressure is 14.696 psi, meaning that a column of air on one square inch in area rising from the Earth's atmosphere to space weighs 14.696 pounds.

The **bar** (bar) is common in the industry. One bar is 100,000 Pa, and for most practical purposes can be approximated to one atmosphere even if
1 Bar = 0.9869 atm

There are 1,000 **millibar** (mbar) in one bar, a unit common in meteorology.
1 millibar = 0.001 bar = 0.750 torr = 100 Pa

R
Residual Disinfection/Protection: A required level of disinfectant that remains in treated water to ensure disinfection protection and prevent recontamination throughout the distribution system (i.e., pipes).

Reynolds Number: The Reynolds number is used to determine whether a flow is laminar or turbulent. The Reynolds Number is a non-dimensional parameter defined by the ratio of dynamic pressure (ρu^2) and shearing stress ($\mu u / L$) - and can be expressed as

$Re = (\rho u^2) / (\mu u / L)$
$= \rho u L / \mu$
$= u L / v$ (1)

where
Re = Reynolds Number (non-dimensional)
ρ = density (kg/m^3, lb_m/ft^3)
u = velocity (m/s, ft/s)
μ = dynamic viscosity (Ns/m^2, lb_m/s ft)
L = characteristic length (m, ft)
v = kinematic viscosity (m^2/s, ft^2/s)

Richardson Number: A dimensionless number that expresses the ratio of potential to kinetic energy.

S
Sanitizer: A chemical which disinfects (kills bacteria), kills algae and oxidizes organic matter.

Saybolt Universal Seconds (or SUS, SSU): Saybolt Universal Seconds (or SUS) is used to measure viscosity. The efflux time is Saybolt Universal Seconds (SUS) required for 60 milliliters of a petroleum product to flow through the calibrated orifice of a Saybolt Universal viscometer, under carefully controlled temperature and as prescribed by test method ASTM D 88. This method has largely been replaced by the kinematic viscosity method.
Saybolt Universal Seconds is also called the SSU number (Seconds Saybolt Universal) or SSF number (Saybolt Seconds Furol).

Kinematic viscosity versus dynamic or absolute viscosity can be expressed as

$v = 4.63 \mu / SG$ (3)
where
v = kinematic viscosity (SSU)
μ = dynamic or absolute viscosity (cP)

Scale: Crust of calcium carbonate, the result of unbalanced pool water. Hard insoluble minerals deposited (usually calcium bicarbonate) which forms on pool and spa surfaces and clog filters, heaters and pumps. Scale is caused by high calcium hardness and/or high pH. You will often find major scale deposits inside a backflow prevention assembly.

Shock: Also known as superchlorination or break point chlorination. Ridding a pool of organic waste through oxidization by the addition of significant quantities of a halogen.

Shock Wave: A shock wave is a strong pressure wave produced by explosions or other phenomena that create violent changes in pressure.

Solder: A fusible alloy used to join metallic parts. Solder for potable water pipes shall be lead-free.

Sound Barrier: The sound barrier is the apparent physical boundary stopping large objects from becoming supersonic.

Specific Gravity: The Specific Gravity - *SG* - is a dimensionless unit defined as the ratio of density of the material to the density of water at a specified temperature. Specific Gravity can be expressed as

$SG = = \rho / \rho_{H2O}$ (3)

where
SG = specific gravity
ρ = density of fluid or substance (kg/m³)
ρ_{H2O} = density of water (kg/m³)

It is common to use the density of water at 4° C (39°F) as a reference - at this point the density of water is at the highest. Since Specific Weight is dimensionless it has the same value in the metric SI system as in the imperial English system (BG). At the reference point the Specific Gravity has same numerically value as density.

Example - Specific Gravity
If the density of iron is 7850 kg/m³, 7.85 grams per cubic millimeter, 7.85 kilograms per liter, or 7.85 metric tons per cubic meter - the specific gravity of iron is:
$SG = 7850$ kg/m³/ 1000 kg/m³
 = _7.85_
(the density of water is 1000 kg/m³)

Specific Weight: Specific Weight is defined as weight per unit volume. Weight is a **force**.
* Mass and Weight - the difference! - What is weight and what is mass? An explanation of the difference between weight and mass.

Specific Weight can be expressed as

$\gamma = \rho \, g$ (2)

where
γ = specific weight (kN/m³)
g = acceleration of gravity (m/s²)

The SI-units of specific weight are kN/m³. The imperial units are lb/ft³. The local acceleration *g* is under normal conditions 9.807 m/s² in SI-units and 32.174 ft/s² in imperial units.

Example - Specific Weight Water
Specific weight for water at 60 °F is 62.4 lb/ft³ in imperial units and 9.80 kN/m³ in SI-units.

Example - Specific Weight Some other Materials

Product	Specific Weight - γ	
	Imperial Units (lb/ft³)	SI Units (kN/m³)
Ethyl Alcohol	49.3	7.74
Gasoline	42.5	6.67
Glycerin	78.6	12.4
Mercury	847	133
SAE 20 Oil	57	8.95
Seawater	64	10.1
Water	62.4	9.80

Static Head: The height of a column or body of fluid above a given point

Static Pressure: The pressure in a fluid at rest.

Static Pressure and Pressure Head in Fluids: The pressure indicates the normal force per unit area at a given point acting on a given plane. Since there is no shearing stresses present in a fluid at rest - the pressure in a fluid is independent of direction.

For fluids - liquids or gases - at rest the pressure gradient in the vertical direction depends only on the specific weight of the fluid.

How pressure changes with elevation can be expressed as
$dp = - \gamma \, dz$ (1)

where
dp = change in pressure
dz = change in height
γ = specific weight

The pressure gradient in vertical direction is negative - the pressure decrease upwards.
Specific Weight: Specific Weight can be expressed as:
$\gamma = \rho \, g$ (2)

where

γ = specific weight
g = acceleration of gravity

In general the specific weight - *γ* - is constant for fluids. For gases the specific weight - *γ* - varies with the elevation.

Static Pressure in a Fluid: For an incompressible fluid - as a liquid - the pressure difference between two elevations can be expressed as:

$p_2 - p_1 = -γ (z_2 - z_1)$ (3)

where
p_2 = pressure at level 2
p_1 = pressure at level 1
z_2 = level 2
z_1 = level 1

(3) can be transformed to:
$p_1 - p_2 = γ (z_2 - z_1)$ (4)
or
$p_1 - p_2 = γ h$ (5)

where
$h = z_2 - z_1$ difference in elevation - the depth down from location z_2.
or
$p_1 = γ h + p_2$ (6)

Static Pressure and Pressure Head in Fluids Continued:
The Pressure Head
(6) can be transformed to:
$h = (p_2 - p_1) / γ$ (6)
h express **the pressure head** - the height of a column of fluid of specific weight - *γ* - required to give a pressure difference of ($p_2 - p_1$).

Example - Pressure Head
A pressure difference of 5 psi (lbf/in^2) is equivalent to
5 (lbf/in^2) 12 (in/ft) 12 (in/ft) / 62.4 (lb/ft^3) = 11.6 ft of water
5 (lbf/in^2) 12 (in/ft) 12 (in/ft) / 847 (lb/ft^3) = 0.85 ft of mercury
when specific weight of water is 62.4 (lb/ft^3) and specific weight of mercury is 847 (lb/ft^3).

Streamline - Stream Function: A streamline is the path that an imaginary particle would follow if it was embedded in the flow.

Strouhal Number: A quantity describing oscillating flow mechanisms. **The Strouhal Number** is a dimensionless value useful for analyzing oscillating, unsteady fluid flow dynamics problems.

The Strouhal Number can be expressed as

$$St = \omega\, l\, /\, v\ (1)$$

> *where*
> *St = Strouhal Number*
> *ω = oscillation frequency*
> *l = characteristic length*
> *v = flow velocity*

The Strouhal Number represents a measure of the ratio of inertial forces due to the unsteadiness of the flow or local acceleration to the inertial forces due to changes in velocity from one point to another in the flow field.

The vortices observed behind a stone in a river, or measured behind the obstruction in a vortex flow meter, illustrate these principles.

Stuffing Box: That portion of the pump which houses the packing or mechanical seal.

Submerged: To cover with water or liquid substance.

Supersonic Flow: Flow with speed above the speed of sound, 1,225 km/h at sea level, is said to be supersonic.

Surface Tension: Surface tension is a force within the surface layer of a liquid that causes the layer to behave as an elastic sheet. The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension. The molecules at the surface do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface. This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submersed. Surface tension is typically measured in dynes/cm, the force in dynes required to break a film of length 1 cm. Equivalently, it can be stated as surface energy in ergs per square centimeter. Water at 20°C has a surface tension of 72.8 dynes/cm compared to 22.3 for ethyl alcohol and 465 for mercury.

Surface tension is typically measured in *dynes/cm* or *N/m*.

Liquid	Surface Tension	
	N/m	dynes/cm
Ethyl Alcohol	0.0223	22.3
Mercury	0.465	465
Water 20°C	0.0728	72.75
Water 100°C	0.0599	58.9

Surface tension is the energy required to stretch a unit change of a surface area. Surface tension will form a drop of liquid to a sphere since the sphere offers the smallest area for a definite volume.

Surface tension can be defined as

$$\sigma = F_s / l \quad (1)$$

where
σ = surface tension (N/m)
F_s = stretching force (N)
l = unit length (m)

Alternative Units
Alternatively, surface tension is typically measured in dynes/cm, which is
* the force in dynes required to break a film of length 1 cm
or as surface energy J/m² or alternatively ergs per square centimeter.
* 1 dynes/cm = 0.001 N/m = 0.0000685 lb_f/ft = 0.571 10^{-5} lb_f/in = 0.0022 poundal/ft = 0.00018 poundal/in = 1.0 mN/m = 0.001 J/m² = 1.0 erg/cm² = 0.00010197 kg_f/m

Common Imperial units used are lb/ft and lb/in.
Water surface tension at different temperatures can be taken from the table below:

Temperature (°C)	Surface Tension - σ - (N/m)
0	0.0757
10	0.0742
20	0.0728
30	0.0712
40	0.0696
50	0.0679
60	0.0662
70	0.0644
80	0.0626
90	0.0608
100	0.0588

Surface Tension of some common Fluids
* benzene : 0.0289 (N/m)
* diethyl ether : 0.0728 (N/m)
* carbon tetrachloride : 0.027 (N/m)
* chloroform : 0.0271 (N/m)
* ethanol : 0.0221 (N/m)
* ethylene glycol : 0.0477 (N/m)
* glycerol : 0.064 (N/m)
* mercury : 0.425 (N/m)
* methanol : 0.0227 (N/m)
* propanol : 0.0237 (N/m)
* toluene : 0.0284 (N/m)
* water at 20°C : 0.0729 (N/m)

Surge Tanks: Surge tanks can be used to control Water Hammer. A limitation of

hydropneumatic tanks is that they do not provide much storage to meet peak demands during power outages and you have very limited time to do repairs on equipment.

T

Telemetering Systems: The following are common pressure sensing devices: Helical Sensor, Bourdon Tube, and Bellows Sensor. The most frequent problem that affects a liquid pressure-sensing device is air accumulation at the sensor. A diaphragm element being used as a level sensor would be used in conjunction with a pressure sensor. Devices must often transmit more than one signal. You can use several types of systems including: Polling, Scanning and Multiplexing. Transmitting equipment requires installation where temperature will not exceed 130 degrees F.

Thixotropic Fluids: Shear Thinning Fluids or **Thixotropic Fluids** reduce their viscosity as agitation or pressure is increased at a constant temperature. Ketchup and mayonnaise are examples of thixotropic materials. They appear thick or viscous but are possible to pump quite easily.

Transonic: Flow with speed at velocities just below and above the speed of sound is said to be transonic.

Turbidity: A measure of the cloudiness of water caused by suspended particles.

U

U-Tube Manometer: Pressure measuring devices using liquid columns in vertical or inclined tubes are called manometers. One of the most common is the water filled u-tube manometer used to measure pressure difference in pitot or orifices located in the airflow in air handling or ventilation systems.

V

Valve: A device that opens and closes to regulate the flow of liquids. Faucets, hose bibs, and Ball are examples of valves.

Vane: That portion of an impeller which throws the water toward the volute.

Vapor Pressure: For a particular substance at any given temperature there is a pressure at which the vapor of that substance is in equilibrium with its liquid or solid forms.

Velocity Head: The vertical distance a liquid must fall to acquire the velocity with which it flows through the piping system. For a given quantity of flow, the velocity head will vary indirectly as the pipe diameter varies.

Venturi: A system for speeding the flow of the fluid, by constricting it in a cone-shaped tube. Venturi are used to measure the speed of a fluid, by measuring the pressure changes from one point to another along the venture. A venturi can also be used to inject a liquid or a gas into another liquid. A pump forces the liquid flow through a tube connected to:
- A venturi to increase the speed of the fluid (restriction of the pipe diameter)
- A short piece of tube connected to the gas source
- A second venturi that decrease the speed of the fluid (the pipe diameter increase again)
- After the first venturi the pressure in the pipe is lower, so the gas is sucked in the pipe.

Then the mixture enters the second venturi and slow down. At the end of the system a mixture of gas and liquid appears and the pressure rise again to its normal level in the pipe.

- This technique is used for ozone injection in water.

Velocity increases – Pressure drops

Atmospheric pressure
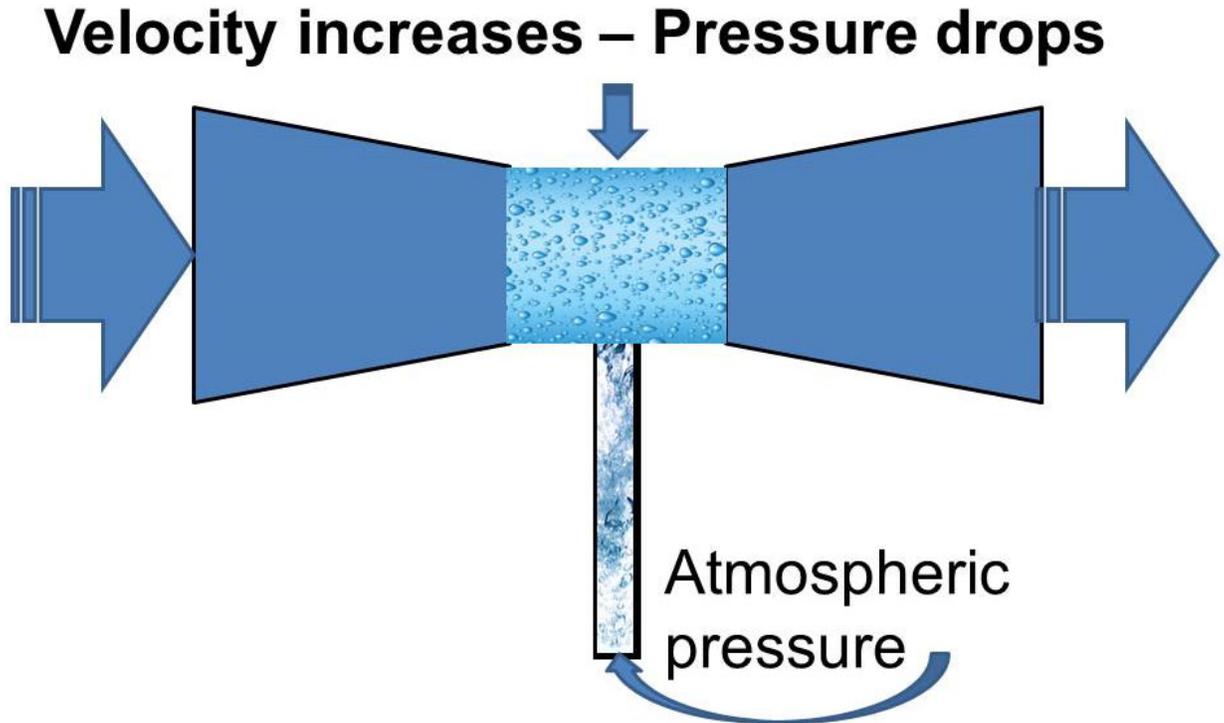
The newest injector design causes complete mixing of injected materials (air, ozone or chemicals), eliminating the need for other in-line mixers. Venturi injectors have no moving parts and are maintenance free. They operate effectively over a wide range of pressures (from 1 to 250 psi) and require only a minimum pressure difference to initiate the vacuum at the suction part. Venturis are often built in thermoplastics (PVC, PE, PVDF), stainless steel or other metals.

The cavitation effect at the injection chamber provides an instantaneous mixing, creating thousands of very tiny bubbles of gas in the liquid. The small bubbles provide and increased gas exposure to the liquid surface area, increasing the effectiveness of the process (i.e. ozonation).

Vibration: A force that is present on construction sites and must be considered. The vibrations caused by backhoes, dump trucks, compactors and traffic on job sites can be substantial.

Viscosity: Informally, viscosity is the quantity that describes a fluid's resistance to flow. Fluids resist the relative motion of immersed objects through them as well as to the motion of layers with differing velocities within them. Formally, viscosity (represented by the symbol η "eta") is the ratio of the shearing stress (F/A) to the velocity gradient ($\Delta v_x/\Delta z$ or dv_x/dz) in a fluid.

$$\eta = \left(\frac{F}{A}\right) \div \left(\frac{\Delta v_x}{\Delta z}\right) \quad \text{or} \quad \eta = \left(\frac{F}{A}\right) \div \left(\frac{dv_x}{dz}\right)$$

The more usual form of this relationship, called Newton's equation, states that the resulting shear of a fluid is directly proportional to the force applied and inversely proportional to its viscosity. The similarity to Newton's second law of motion ($F = ma$) should be apparent.

$$\frac{F}{A} = \eta\,\frac{\Delta v_x}{\Delta z} \quad \text{or} \quad \frac{F}{A} = \eta\,\frac{dv_x}{dz}$$

$$\Updownarrow \qquad\qquad \Updownarrow$$

$$F = m\frac{\Delta v}{\Delta t} \quad \text{or} \quad F = m\frac{dv}{dt}$$

The SI unit of viscosity is the pascal second [Pa·s], which has no special name. Despite its self-proclaimed title as an international system, the International System of Units has had very little international impact on viscosity. The pascal second is rarely used in scientific and technical publications today. The most common unit of viscosity is the dyne second per square centimeter [dyne·s/cm^2], which is given the name poise [P] after the French physiologist Jean Louis Poiseuille (1799-1869). Ten poise equal one pascal second [Pa·s] making the centipoise [cP] and millipascal second [mPa·s] identical.

1 pascal second = 10 poise = 1,000 millipascal second
1 centipoise = 1 millipascal second

There are actually two quantities that are called viscosity. The quantity defined above is sometimes called dynamic viscosity, absolute viscosity, or simple viscosity to distinguish it from the other quantity, but is usually just called viscosity. The other quantity called kinematic viscosity (represented by the symbol v "nu") is the ratio of the viscosity of a fluid to its density.

$$v = \frac{\eta}{\rho}$$

Kinematic viscosity is a measure of the resistive flow of a fluid under the influence of gravity. It is frequently measured using a device called a capillary viscometer -- basically a graduated can with a narrow tube at the bottom. When two fluids of equal volume are placed in identical capillary viscometers and allowed to flow under the influence of gravity, a viscous fluid takes longer than a less viscous fluid to flow through the tube. Capillary viscometers are discussed in more detail later in this section. The SI unit of kinematic viscosity is the square meter per second [m^2/s], which has no special name. This unit is so large that it is rarely used. A more common unit of kinematic viscosity is the square centimeter per second [cm^2/s], which is given the name stoke [St] after the English scientist George Stoke. This unit is also a bit too large and so the most common unit is probably the square millimeter per second [mm^2/s] or centistoke [cSt].

Viscosity and Reference Temperatures: The viscosity of a fluid is highly temperature dependent and for either dynamic or kinematic viscosity to be meaningful, the **reference temperature** must be quoted.

In ISO 8217 the reference temperature for a residual fluid is 100ºC. For a distillate fluid the

reference temperature is 40°C.

- For a liquid - the kinematic viscosity will **decrease** with higher temperature.
- For a gas - the kinematic viscosity will **increase** with higher temperature.

Volute: The spiral-shaped casing surrounding a pump impeller that collects the liquid discharged by the impeller.

Vorticity: Vorticity is defined as the circulation per unit area at a point in the flow field.

Vortex: A vortex is a whirlpool in the water.

W

Water Freezing: The effects of water freezing in storage tanks can be minimized by alternating water levels in the tank.

Water Storage Facility Inspection: During an inspection of your water storage facility, you should inspect the Cathodic protection system including checking the anode's condition and the connections. The concentration of polyphosphates that is used for corrosion control in storage tanks is typically 5 mg/L or less. External corrosion of steel water storage facilities can be reduced with Zinc or aluminum coatings. All storage facilities should be regularly sampled to determine the quality of water that enters and leaves the facility. One tool or piece of measuring equipment is the Jackson turbidimeter, which is a method to measure cloudiness in water.

Wave Drag: Wave drag refers to a sudden and very powerful drag that appears on aircrafts flying at high-subsonic speeds.

Water Purveyor: The individuals or organization responsible to help provide, supply, and furnish quality water to a community.

Water Works: All of the pipes, pumps, reservoirs, dams and buildings that make up a water system.

Waterborne Diseases: A disease, caused by a virus, bacterium, protozoan, or other microorganism, capable of being transmitted by water (e.g., typhoid fever, cholera, amoebic dysentery, gastroenteritis).

Weber Number: A dimensionless value useful for analyzing fluid flows where there is an interface between two different fluids. Since the Weber Number represents an index of the inertial force to the surface tension force acting on a fluid element, it can be useful analyzing thin films flows and the formation of droplets and bubbles.
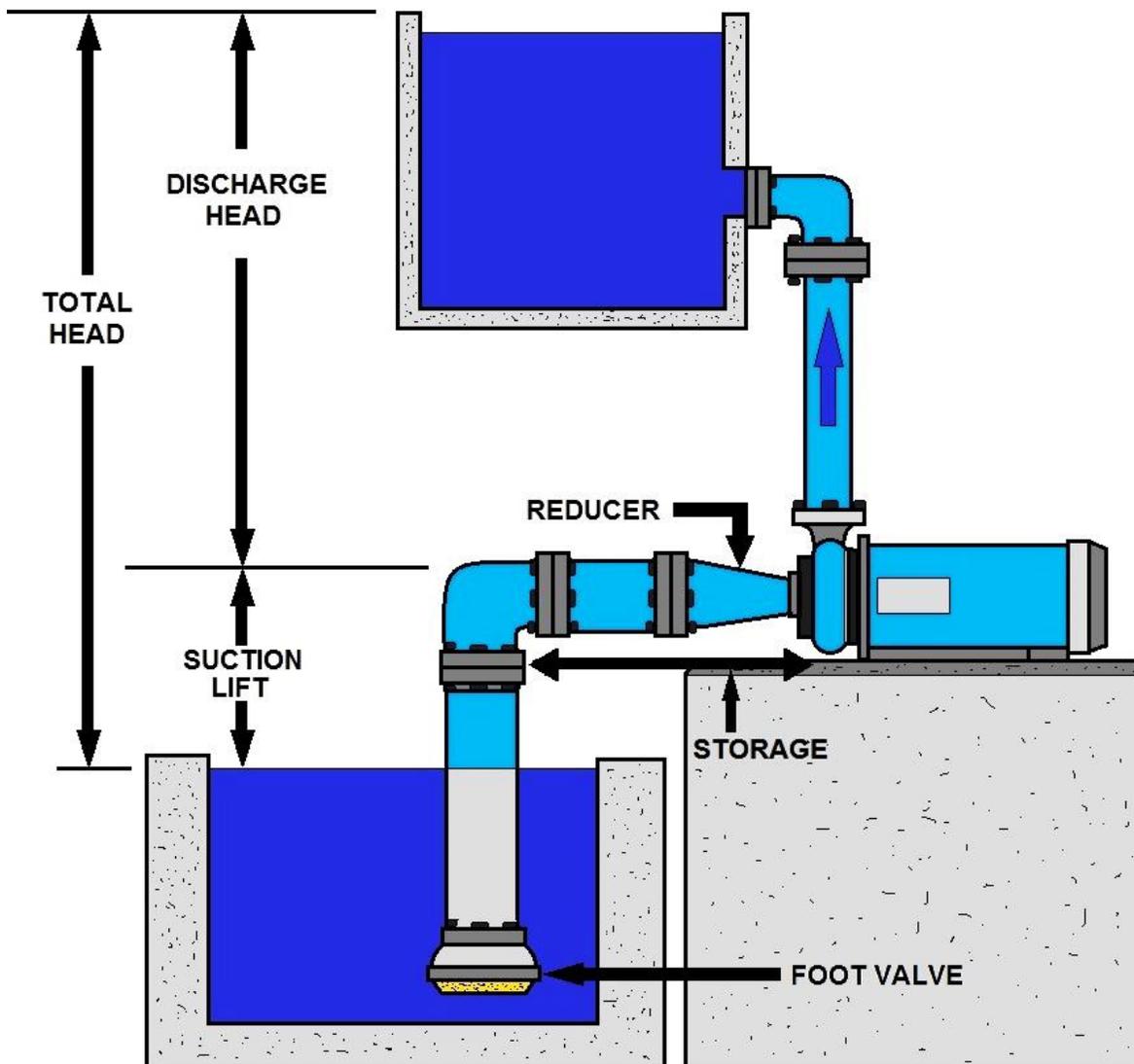
PUMPING FACTORS

Math Conversion Factors

1 PSI = 2.31 Feet of Water
1 Foot of Water = .433 PSI
1.13 Feet of Water = 1 Inch of Mercury
454 Grams = 1 Pound
2.54 CM =Inch
1 Gallon of Water = 8.34 Pounds
1 mg/L = 1 PPM
17.1 mg/L = 1 Grain/Gallon
1% = 10,000 mg/L
694 Gallons per Minute = MGD
1.55 Cubic Feet per Second = 1 MGD
60 Seconds = 1 Minute
1440 Minutes = 1 Day
.746 kW = 1 Horsepower

LENGTH
12 Inches = 1 Foot
3 Feet = 1 Yard
5280 Feet = 1 Mile

AREA
144 Square Inches = 1 Square Foot
43,560 Square Feet =1 Acre
VOLUME
1000 Milliliters = 1 Liter
3.785 Liters = 1 Gallon
231 Cubic Inches = 1 Gallon
7.48 Gallons = 1 Cubic Foot of water
62.38 Pounds = 1 Cubic Foot of water

Dimensions

SQUARE: Area (sq.ft.) = Length X Width
Volume (cu.ft.) = Length (ft) X Width (ft) X Height (ft)

CIRCLE: Area (sq.ft.) = 3.14 X Radius (ft) X Radius (ft)

CYLINDER: Volume (Cu. ft) = 3.14 X Radius (ft) X Radius (ft) X Depth (ft)

PIPE VOLUME: .785 X Diameter ^{2} X Length = ? To obtain gallons multiply by 7.48

SPHERE: $\dfrac{(3.14)\ (Diameter)^3}{(6)}$ Circumference = 3.14 X Diameter

General Conversions

Flowrate

Multiply	—>	to get
to get	<—	Divide
cc/min	1	mL/min
cfm (ft^3/min)	28.31	L/min
cfm (ft^3/min)	1.699	m^3/hr
cfh (ft^3/hr)	472	mL/min
cfh (ft^3/hr)	0.125	GPM
GPH	63.1	mL/min
GPH	0.134	cfh
GPM	0.227	m^3/hr
GPM	3.785	L/min
oz/min	29.57	mL/min

POUNDS PER DAY= Concentration (mg/L) X Flow (MG) X 8.34
AKA **Solids Applied Formula** = Flow X Dose X 8.34

PERCENT EFFICIENCY = $\underline{\text{In – Out}}$ X 100
$\qquad\qquad\qquad\qquad$ In

TEMPERATURE: $\qquad$ ^{0}F = (^{0}C X 9/5) + 32 $\qquad$ 9/5 =1.8
$\qquad\qquad\qquad\quad$ ^{0}C = (^{0}F - 32) X 5/9 $\qquad$ 5/9 = .555

CONCENTRATION: Conc. (A) X Volume (A) = Conc. (B) X Volume (B)

FLOW RATE (Q): Q = A X V (**Q**uantity = **A**rea X **V**elocity)

FLOW RATE (gpm): Flow Rate (gpm) = $\underline{\text{2.83 (Diameter, in)}^2\text{ (Distance, in)}}$
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Height, in

% SLOPE = $\underline{\text{Rise (feet)}}$ X 100
$\qquad\qquad\quad$ Run (feet)

ACTUAL LEAKAGE = $\qquad$ $\underline{\text{Leak Rate (GPD)}}$
$\qquad\qquad\qquad\qquad\qquad$ Length (mi.) X Diameter (in)

VELOCITY = $\underline{\text{Distance (ft)}}$
$\qquad\qquad\qquad$ Time (Sec)

N = Manning's Coefficient of Roughness
R = Hydraulic Radius (ft.)
S = Slope of Sewer (ft/ft.)

HYDRAULIC RADIUS (ft) = $\underline{\text{Cross Sectional Area of Flow (ft)}}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ Wetted pipe Perimeter (ft)

WATER HORSEPOWER = $\underline{\text{Flow (gpm) X Head (ft)}}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ 3960

BRAKE HORSEPOWER = $\underline{\text{Flow (gpm) X Head (ft)}}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ 3960 X Pump Efficiency

MOTOR HORSEPOWER = $\underline{\text{Flow (gpm) X Head (ft)}}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ 3960 X Pump Eff. X Motor Eff.

MEAN OR AVERAGE = $\underline{\text{Sum of the Values}}$
$\qquad\qquad\qquad\qquad\qquad$ Number of Values

TOTAL HEAD (ft) = Suction Lift (ft) X Discharge Head (ft)

SURFACE LOADING RATE = $\underline{\text{Flow Rate (gpm)}}$
$\quad$ (gal/min/sq.ft) $\qquad$ Surface Area (sq. ft)

MIXTURE = $\underline{\text{(Volume 1, gal) (Strength 1, %) + (Volume 2, gal) (Strength 2,%)}}$
STRENGTH (%) $\qquad\qquad$ (Volume 1, gal) + (Volume 2, gal)

INJURY FREQUENCY RATE = $\underline{\text{(Number of Injuries) 1,000,000}}$
$\qquad\qquad\qquad\qquad\qquad\qquad\quad$ Number of hours worked per year

DETENTION TIME (hrs) = $\underline{\text{Volume of Basin (gals) X 24 hrs}}$
$\qquad\qquad\qquad\qquad\qquad\qquad$ Flow (GPD)

SLOPE = $\dfrac{\text{Rise (ft)}}{\text{Run (ft)}}$ **SLOPE (%)** = $\dfrac{\text{Rise (ft)} \times 100}{\text{Run (ft)}}$

POPULATION EQUIVALENT (PE):
   1 PE = .17 Pounds of BOD per Day
   1 PE = .20 Pounds of Solids per Day
   1 PE = 100 Gallons per Day

LEAKAGE (GPD/inch) = $\dfrac{\text{Leakage of Water per Day (GPD)}}{\text{Sewer Diameter (inch)}}$

CHLORINE DEMAND (mg/L) = Chlorine Dose (mg/L) – Chlorine Residual (mg/L)

MANNING'S FORMULA

τQ = Allowable time for decrease in pressure from 3.5 PSI to 2.5 PSI
τq =   As below

$\tau Q = (0.022)\,(d_1^2 L_1)/Q$ $\tau q = \dfrac{[\,0.085\,]}{q}\,[(d_1^2 L1)/(d_1 L_1)]$

Q = 2.0 cfm air loss
θ = .0030 cfm air loss per square foot of internal pipe surface
δ = Pipe diameter (inches)
L = Pipe Length (feet)

$V = \dfrac{1.486}{\nu}\, R^{2/3}\, S^{1/2}$

V = Velocity (ft./sec.)
ν = Pipe Roughness
R = Hydraulic Radius (ft)
S= Slope (ft/ft)

HYDRAULIC RADIUS (ft) = $\dfrac{\text{Flow Area (ft. 2)}}{\text{Wetted Perimeter (ft.)}}$

WIDTH OF TRENCH (ft) = Base (ft) + (2 Sides) X $\dfrac{\text{Depth (ft 2)}}{\text{Slope}}$

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