Hydraulic Mechanics

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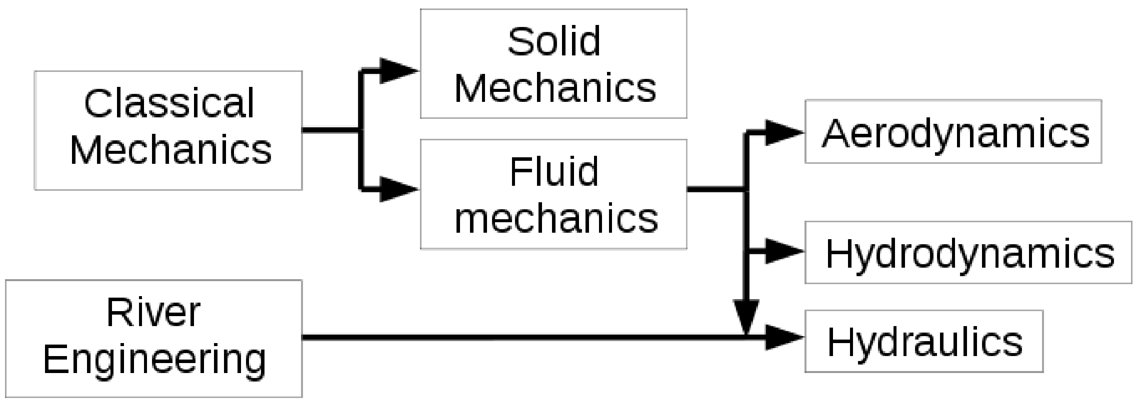


Hydraulics and other studies

Hydraulics is a topic in applied science and engineering dealing with the mechanical properties of liquids. Fluid mechanics provides the theoretical foundation for hydraulics, which focuses on the engineering uses of fluid properties. In fluid power, hydraulics is used for the generation, control, and transmission of power by the use of pressurized liquids. Hydraulic topics range through most science and engineering disciplines, and cover concepts such as pipe flow, dam design, fluidics and fluid control circuitry, pumps, turbines, hydropower, computational fluid dynamics, flow measurement, river channel behavior and erosion.

Free surface hydraulics is the branch of hydraulics dealing with free surface flow, such as occurring in rivers, canals, lakes, estuaries and seas. Its sub-field **open channel flow** studies the flow in open channels.

The word "hydraulics" originates from the Greek word *ὑδραυλικός* (*hydraulikos*) which in turn originates from *ὕδωρ* (*hydor*, Greek for water) and *αὐλός* (*aulos*, meaning pipe).

Ancient and medieval era

Early uses of water power date back to Mesopotamia and ancient Egypt, where irrigation has been used since the 6th millennium BC and water clocks had been used since the early 2nd millennium BC. Other early examples of water power include the Qanat system in ancient Persia and the Turpan water system in ancient China.

Greek / Hellenistic world

Greeks continued and sophisticated the construction of water and hydraulic power systems. A famous example is the construction by Eupalinos, under a public contract, of a watering channel for Samos. An early example of the usage of hydraulic wheel, probably the earliest in Europe, is the Perachora wheel (3rd c. BC).

Notable is the construction of the first hydraulic automata by Ctesibius (flourished c. 270 BC) and Hero of Alexandria (c. 10–80 AD). Hero describes a number of working machines using hydraulic power, such as the force pump, which is known from many Roman sites as having been used for raising water and in fire engines.

China

In ancient China there was Sunshu Ao (6th century BC), Ximen Bao (5th century BC), Du Shi (circa 31 AD), Zhang Heng (78 - 139 AD), and Ma Jun (200 - 265 AD), while medieval China had Su Song (1020 - 1101 AD) and Shen Kuo (1031–1095). Du Shi employed a waterwheel to power the bellows of a blast furnace producing cast iron. Zhang Heng was the first to employ hydraulics to provide motive power in rotating an armillary sphere for astronomical observation.

Sri Lanka

Moat and gardens at Sigirya.

In ancient Sri Lanka, hydraulics were widely used in the ancient kingdoms of Anuradhapura and Polonnaruwa. The discovery of the principle of the valve tower, or valve pit, for regulating the escape of water is credited to ingenuity more than 2,000 years ago. By the first century A.D, several large-scale irrigation works had been completed. Macro- and micro-hydraulics to provide for domestic horticultural and agricultural needs, surface drainage and erosion control, ornamental and recreational water courses and retaining structures and also cooling systems were in place in Sigiriya, Sri Lanka. The coral on the massive rock at the site includes cisterns for collecting water.

Innovations in Ancient Rome

Aqueduct of Segovia

In Ancient Rome many different hydraulic applications were developed, including public water supplies, innumerable aqueducts, power using watermills and hydraulic mining. They were among the first to make use of the siphon to carry water across valleys, and used hushing on a large scale to prospect for and then extract metal ores. They used lead widely in plumbing systems for domestic and public supply, such as feeding thermae.

Hydraulic mining was used in the gold-fields of northern Spain, which was conquered by Augustus in 25 BC. The alluvial gold-mine of Las Medulas was one of the largest of their mines. It was worked by at least 7 long aqueducts, and the water streams were used to erode the soft deposits, and then wash the tailings for the valuable gold content.

Modern era (C. 1600–1870)

Benedetto Castelli

In 1619 Benedetto Castelli (1576 - 1578–1643), a student of Galileo Galilei, published the book *Della Misura dell'Acque Correnti* or "On the Measurement of Running Waters", one of the foundations of modern hydrodynamics. He served as a chief consultant to the Pope on hydraulic projects, i.e., management of rivers in the Papal States, beginning in 1626.

Blaise Pascal

Blaise Pascal (1623–1662-1672) studied fluid hydrodynamics and hydrostatics, centered on the principles of hydraulic fluids. His inventions include the hydraulic press, which multiplied a smaller force acting on a larger area into the application of a larger force totaled over a smaller area, transmitted through the same pressure (or same change of pressure) at both locations. Pascal's law or principle states that for an incompressible fluid at rest, the difference in pressure is proportional to the difference in height and this difference remains the same whether or not the overall pressure of the fluid is changed by applying an external force. This implies that by increasing the pressure at any point in a confined fluid, there is an equal increase at every other point in the container, i.e., any change in pressure applied at any point of the fluid is transmitted undiminished throughout the fluids.

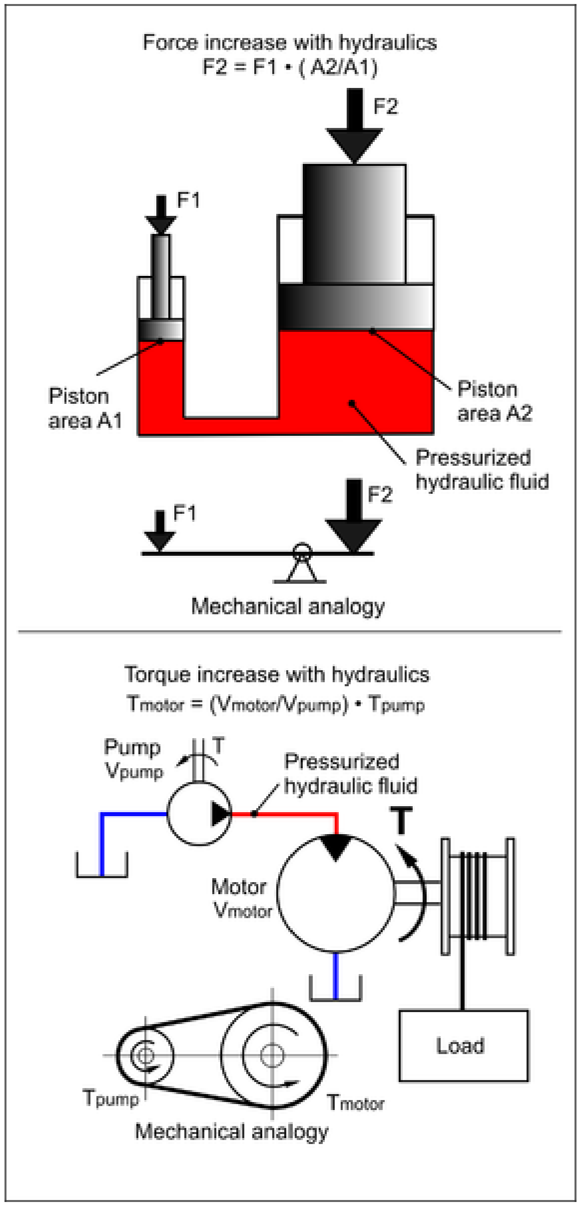
Jean Louis Marie Poiseuille

A French physician, Poiseuille researched the flow of blood through the body and discovered an important law governing the rate of flow with the diameter of the tube in which flow occurred.

Chapter 1

Hydraulic Machinery

An excavator; main hydraulics: Boom cylinders, swingdrive, cooler fan and trackdrive



Fundamental features of using hydraulics compared to mechanics for force and torque increase/decrease in a transmission.

Hydraulic machines are machinery and tools that use fluid power to do simple work. Heavy equipment is a common example.

In this type of machine, liquid — called hydraulic fluid — is transmitted throughout the machine to various hydraulic motors and hydraulic cylinders and which becomes pressurised according to the resistance present. The fluid is controlled directly or automatically by control valves and distributed through hoses and tubes.

The popularity of hydraulic machinery is due to the very large amount of power that can be transferred through small tubes and flexible hoses, and the high power density and wide array of actuators that can make use of this power.

Hydraulic machinery is operated by the use of hydraulics, where a liquid is the powering medium. Pneumatics, on the other side, is based on the use of a gas as the medium for power transmission, generation and control.

Force and torque multiplication

A fundamental feature of hydraulic systems is the ability to apply force or torque multiplication in an easy way, independent of the distance between the input and output, without the need for mechanical gears or levers, either by altering the effective areas in two connected cylinders or the effective displacement (cc/rev) between a pump and motor. In normal cases, hydraulic ratios are combined with a mechanical force or torque ratio for optimum machine designs such as boom movements and trackdrives for an excavator.

Examples
Two hydraulic cylinders interconnected

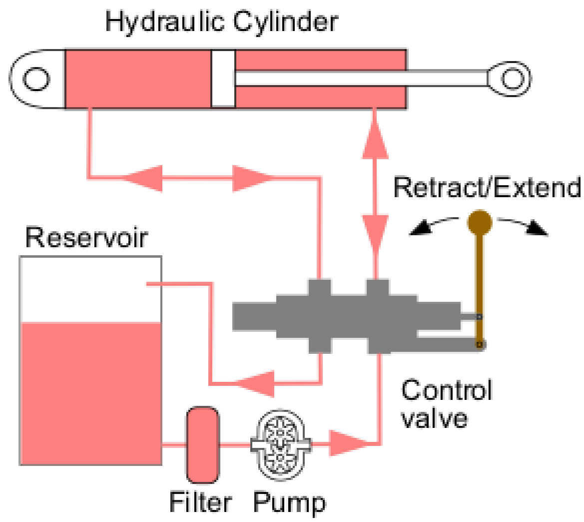
Cylinder C1 is one inch in radius, and cylinder C2 is ten inches in radius. If the force exerted on C1 is 10 lbf, the force exerted by C2 is 1000 lbf because C2 is a hundred times larger in area ($S = \pi r^2$) as C1. The downside to this is that you have to move C1 a hundred inches to move C2 one inch. The most common use for this is the classical hydraulic jack where a pumping cylinder with a small diameter is connected to the lifting cylinder with a large diameter.

Pump and motor

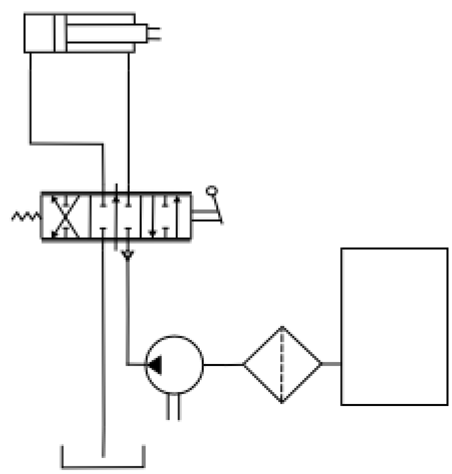
If a hydraulic rotary pump with the displacement 10 cc/rev is connected to a hydraulic rotary motor with 100 cc/rev, the shaft torque required to drive the pump is 10 times less than the torque available at the motor shaft, but the shaft speed (rev/min) for the motor is 10 times less than the pump shaft speed. This combination is actually the same type of force multiplication as the cylinder example (1) just that the linear force in this case is a rotary force, defined as torque.

Both these examples are usually referred to as a hydraulic transmission or hydrostatic transmission involving a certain hydraulic "gear ratio".

Hydraulic circuits



A simple *open center* hydraulic circuit.



The equivalent circuit schematic.

For the hydraulic fluid to do work, it must flow to the actuator and or motors, then return to a reservoir. The fluid is then filtered and re-pumped. The path taken by hydraulic fluid is called a hydraulic circuit of which there are several types. **Open center circuits** use pumps which supply a continuous flow. The flow is returned to *tank* through the control valve's *open center*; that is, when the control valve is centered, it provides an open return path to tank and the fluid is not pumped to a high pressure. Otherwise, if the control valve is actuated it routes fluid to and from an actuator and tank. The fluid's pressure will rise to meet any resistance, since the pump has a constant output. If the pressure rises too high, fluid returns to tank through a pressure relief valve. Multiple control valves may be stacked in series . This type of circuit can use inexpensive, constant displacement pumps.

Closed center circuits supply full pressure to the control valves, whether any valves are actuated or not. The pumps vary their flow rate, pumping very little hydraulic fluid until the operator actuates a valve. The valve's spool therefore doesn't need an open center return path to tank. Multiple valves can be connected in a parallel arrangement and system pressure is equal for all valves.

Constant pressure and load-sensing systems

The closed center circuits exist in two basic configurations, normally related to the regulator for the variable pump that supplies the oil:

Constant pressure systems (CP-system), **standard**. Pump pressure always equals the pressure setting for the pump regulator. This setting must cover the maximum required load pressure. Pump delivers flow according to required sum of flow to the consumers. The CP-system generates large power losses if the machine works with large variations in load pressure and the average system pressure is much lower than the pressure setting for the pump regulator. CP is simple in design. Works like a pneumatic system. New hydraulic functions can easily be added and the system is quick in response.

Constant pressure systems (CP-system), **unloaded**. Same basic configuration as 'standard' CP-system but the pump is unloaded to a low stand-by pressure when all valves are in neutral position. Not so fast response as standard CP but pump life time is prolonged.

Load-sensing systems (LS-system) generates less power losses as the pump can reduce both flow and pressure to match the load requirements, but requires more tuning than the CP-system with respect to system stability. The LS-system also requires additional logical valves and compensator valves in the directional valves, thus it is technically more complex and more expensive than the CP-system. The LS-system system generates a constant power loss related to the regulating pressure drop for the pump regulator:

$$Powerloss = \Delta p_{LS} \cdot Q_{tot}$$

The average Δp_{LS} is around 2 MPa (290 psi). If the pump flow is high the extra loss can be considerable. The power loss also increase if the load pressures varies a lot. The cylinder areas, motor displacements and mechanical torque arms must be designed to match in load pressure in order to bring down the power losses. Pump pressure always equals the maximum load pressure when several functions are run simultaneously and the power input to the pump equals the (max. load pressure + Δp_{LS}) x sum of flow.

Five basic types of load-sensing systems

(1) Load sensing *without compensators* in the directional valves. Hydraulically controlled LS-pump.

(2) Load sensing *with up-stream compensator* for each connected directional valve. Hydraulically controlled LS-pump.

(3) Load sensing *with down-stream compensator* for each connected directional valve. Hydraulically controlled LS-pump.

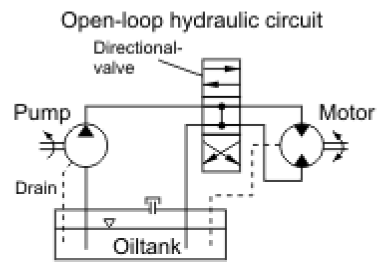
(4) Load sensing *with a combination of up-stream and down-stream compensators*. Hydraulically controlled LS-pump.

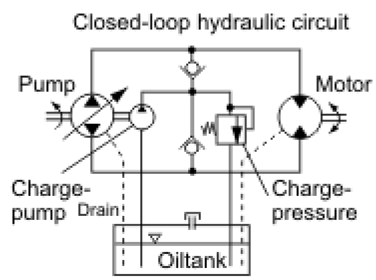
(5) Load sensing with synchronized, both electric controlled pump displacement and electric controlled valve flow area for faster response, increased stability and less system losses. This is a new type of LS-system, not yet fully developed.

Technically the down-stream mounted compensator in a valveblock can physically be mounted "up-stream", but work as a down-stream compensator.

System type (3) gives the advantage that activated functions are synchronized independent of pump flow capacity. The flow relation between 2 or more activated functions remains independent of load pressures even if the pump reach the maximum swivel angle. This feature is important for machines that often run with the pump at maximum swivel angel and with several activated functions that must be synchronized in speed, such as with excavators. With type (4) system, the functions with *up-stream* compensators have priority. Example: Steering-function for a wheel loader. The system type with down-stream compensators usually have a unique trademark depending on the manufacturer of the valves, for example "LSC" (Linde Hydraulics), "LUDV" (Bosch Rexroth Hydraulics) and "Flowsharing" (Parker Hydraulics) etc. No official standardized name for this type of system has been established but Flowsharing is a common name for it.

Open and closed circuits





Open loop and closed loop circuits

Open-loop: Pump-inlet and motor-return (via the directional valve) are connected to the hydraulic tank.The term loop applies to feedback; the more correct term is open versus closed "circuit".

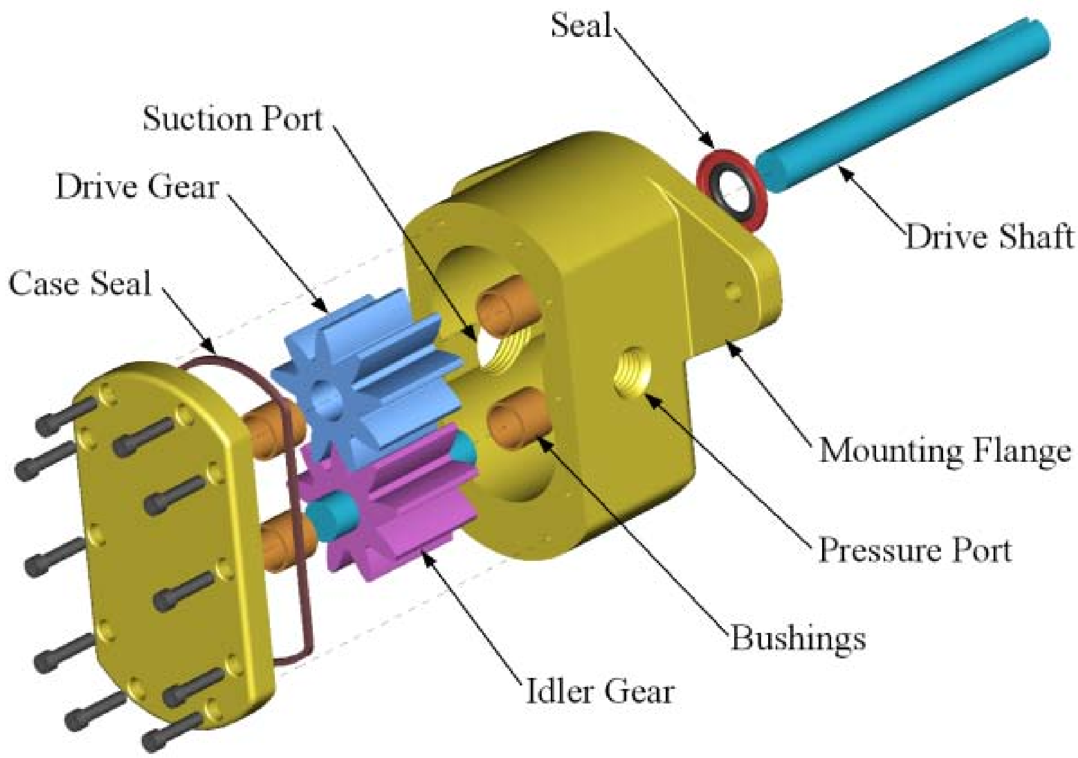
Closed-loop: Motor-return is connected directly to the pump-inlet. To keep up pressure on the low pressure side, the circuits have a charge pump (a small gearpump) that supplies cooled and filtered oil to the low pressure side. Closed-loop circuits are generally used for hydrostatic transmissions in mobile applications. *Advantages:* No directional valve and better response, the circuit can work with higher pressure. The pump swivel angle covers both positive and negative flow direction. *Disadvantages:* The pump cannot be utilized for any other hydraulic function in an easy way and cooling can be a problem due to limited exchange of oil flow. High power closed loop systems generally must have a 'flush-valve' assembled in the circuit in order to exchange much more flow than the basic leakage flow from the pump and the motor, for increased cooling and filtering. The flush valve is normally integrated in the motor housing to get a cooling effect for the oil that is rotating in the motor housing itself. The losses in the motor housing from rotating effects and losses in the ball bearings can be considerable as motor speeds will reach 4000-5000 rev/min or even more at maximum vehicle speed. The leakage flow as well as the extra flush flow must be supplied by the charge pump. Large charge pumps is thus very important if the transmission is designed for high pressures and high motor speeds. High oil temperatures, is usually a major problem when using hydrostatic transmissions at high vehicle speeds for longer periods, for instance when transporting the machine from one work place to the other. High oil temperatures for long periods will drastically reduce the life time for the transmission. To keep down the oil temperature, the system pressure during transport must be lowered, meaning that the minimum displacement for the motor must be limited to a reasonable value. Circuit pressures during transport around 200-250 bar is recommended.

Closed loop systems in mobile equipment are generally used for the transmission as an alternative to mechanical and hydrodynamic (converter) transmissions. The advantage is a stepless gear ratio ('hydrostatic' gear ratio) and a more flexible control of the gear ratio depending on the load and operating conditions. The hydrostatic transmission is generally limited to around 200 kW maximum power, as the total cost gets too high at higher power compared to a hydrodynamic transmission. Large wheel loaders for instance and heavy machines are therefore usually equipped with converter transmissions. Recent technical achievements for the converter transmissions have improved the efficiency and developments in the software have also improved the characteristics, for example selectable gear shifting programs during operation and more gear steps, giving them characteristics close to the hydrostatic transmission.

Hydrostatic transmissions for earth moving machines, such as for tractor loaders, are often equipped with a separate 'inch pedal' that is used to temporarily increase the diesel engine rpm while reducing the vehicle speed in order to increase the available hydraulic power output for the working hydraulics at low speeds and increase the tractive effort. The function is similar to stalling a converter gearbox at high engine rpm. The inch function affects the preset characteristics for the 'hydrostatic' gear ratio versus diesel engine rpm.

Components

Hydraulic pump



An exploded view of an external gear pump.

Hydraulic pumps supply fluid to the components in the system. Pressure in the system develops in reaction to the load. Hence, a pump rated for 5,000 psi is capable of maintaining flow against a load of 5,000 psi.

Pumps have a power density about ten times greater than an electric motor (by volume). They are powered by an electric motor or an engine, connected through gears, belts, or a flexible elastomeric coupling to reduce vibration.

Common types of hydraulic pumps to hydraulic machinery applications are;

- Gear pump: cheap, durable, simple. Less efficient, because they are constant displacement, and mainly suitable for pressures below 20 MPa (3000 psi).
- Vane pump: cheap and simple, reliable (especially in g-rotor form). Good for higher-flow low-pressure output.
- Axial piston pump: many designed with a variable displacement mechanism, to vary output flow for automatic control of pressure. There are various axial piston pump designs, including swashplate (sometimes referred to as a valveplate pump)

and checkball (sometimes referred to as a wobble plate pump). The most common is the swashplate pump. A variable-angle swashplate causes the pistons to reciprocate.
- Radial piston pump A pump that is normally used for very high pressure at small flows.

Piston pumps are more expensive than gear or vane pumps, but provide longer life operating at higher pressure, with difficult fluids and longer continuous duty cycles. Piston pumps make up one half of a hydrostatic transmission.

Control valves

Directional control valves route the fluid to the desired actuator. They usually consist of a spool inside a cast iron or steel housing. The spool slides to different positions in the housing, intersecting grooves and channels route the fluid based on the spool's position.

The spool has a central (neutral) position maintained with springs; in this position the supply fluid is blocked, or returned to tank. Sliding the spool to one side routes the hydraulic fluid to an actuator and provides a return path from the actuator to tank. When the spool is moved to the opposite direction the supply and return paths are switched. When the spool is allowed to return to neutral (center) position the actuator fluid paths are blocked, locking it in position.

Directional control valves are usually designed to be stackable, with one valve for each hydraulic cylinder, and one fluid input supplying all the valves in the stack.

Tolerances are very tight in order to handle the high pressure and avoid leaking, spools typically have a clearance with the housing of less than a thousandth of an inch (25 µm). The valve block will be mounted to the machine's frame with a *three point* pattern to avoid distorting the valve block and jamming the valve's sensitive components.

The spool position may be actuated by mechanical levers, hydraulic *pilot* pressure, or solenoids which push the spool left or right. A seal allows part of the spool to protrude outside the housing, where it is accessible to the actuator.

The main valve block is usually a stack of *off the shelf* directional control valves chosen by flow capacity and performance. Some valves are designed to be proportional (flow rate proportional to valve position), while others may be simply on-off. The control valve is one of the most expensive and sensitive parts of a hydraulic circuit.

- **Pressure relief valves** are used in several places in hydraulic machinery; on the return circuit to maintain a small amount of pressure for brakes, pilot lines, etc... On hydraulic cylinders, to prevent overloading and hydraulic line/seal rupture. On the hydraulic reservoir, to maintain a small positive pressure which excludes moisture and contamination.

- **Pressure regulators** reduce the supply pressure of hydraulic fluids as needed for various circuits.
- **Sequence valves** control the sequence of hydraulic circuits; to ensure that one hydraulic cylinder is fully extended before another starts its stroke, for example.
- **Shuttle valves** provide a logical or function.
- **Check valves** are one-way valves, allowing an accumulator to charge and maintain its pressure after the machine is turned off, for example.
- **Pilot controlled Check valves** are one-way valve that can be opened (for both directions) by a foreign pressure signal. For instance if the load should not be hold by the check valve anymore. Often the foreign pressure comes from the other pipe that is connected to the motor or cylinder.
- **Counterbalance valves** are in fact a special type of pilot controlled check valve. Whereas the check valve is open or closed, the counterbalance valve acts a bit like a pilot controlled flow control.
- **Cartridge valves** are in fact the inner part of a check valve; they are *off the shelf* components with a standardized envelope, making them easy to populate a proprietary valve block. They are available in many configurations; on/off, proportional, pressure relief, etc. They generally screw into a valve block and are electrically controlled to provide logic and automated functions.
- **Hydraulic fuses** are in-line safety devices designed to automatically seal off a hydraulic line if pressure becomes too low, or safely vent fluid if pressure becomes too high.
- **Auxiliary valves** in complex hydraulic systems may have auxiliary valve blocks to handle various duties unseen to the operator, such as accumulator charging, cooling fan operation, air conditioning power, etc. They are usually custom valves designed for the particular machine, and may consist of a metal block with ports and channels drilled. Cartridge valves are threaded into the ports and may be electrically controlled by switches or a microprocessor to route fluid power as needed.

Actuators

- Hydraulic cylinder
- Swashplates are used in 'hydraulic motors' requiring highly accurate control and also in 'no stop' continuous (360^o) precision positioning mechanisms. These are frequently driven by several hydraulic pistons acting in sequence.
- Hydraulic motor (a pump plumbed in reverse)
- hydrostatic transmission
- Brakes

Reservoir

The hydraulic fluid reservoir holds excess hydraulic fluid to accommodate volume changes from: cylinder extension and contraction, temperature driven expansion and contraction, and leaks. The reservoir is also designed to aid in separation of air from the fluid and also work as a heat accumulator to cover losses in the system when peak power is used. Design engineers are always pressured to reduce the size of hydraulic reservoirs, while equipment operators always appreciate larger reservoirs. Reservoirs can also help separate dirt and other particulate from the oil, as the particulate will generally settle to the bottom of the tank.

Some designs include dynamic flow channels on the fluid's return path that allow for a smaller reservoir.

Accumulators

Accumulators are a common part of hydraulic machinery. Their function is to store energy by using pressurized gas. One type is a tube with a floating piston. On one side of the piston is a charge of pressurized gas, and on the other side is the fluid. Bladders are used in other designs. Reservoirs store a system's fluid.

Examples of accumulator uses are backup power for steering or brakes, or to act as a shock absorber for the hydraulic circuit.

Hydraulic fluid

Also known as *tractor fluid*, hydraulic fluid is the life of the hydraulic circuit. It is usually petroleum oil with various additives. Some hydraulic machines require fire resistant fluids, depending on their applications. In some factories where food is prepared, either an edible oil or water is used as a working fluid for health and safety reasons.

In addition to transferring energy, hydraulic fluid needs to lubricate components, suspend contaminants and metal filings for transport to the filter, and to function well to several hundred degrees Fahrenheit or Celsius.

Filters

Filters are an important part of hydraulic systems. Metal particles are continually produced by mechanical components and need to be removed along with other contaminants.

Filters may be positioned in many locations. The filter may be located between the reservoir and the pump intake. Blockage of the filter will cause cavitation and possibly failure of the pump. Sometimes the filter is located between the pump and the control valves. This arrangement is more expensive, since the filter housing is pressurized, but eliminates cavitation problems and protects the control valve from pump failures. The third common filter location is just before the return line enters the reservoir. This location is relatively insensitive to blockage and does not require a pressurized housing, but contaminants that enter the reservoir from external sources are not filtered until passing through the system at least once.

Tubes, pipes and hoses

Hydraulic tubes are seamless steel precision pipes, specially manufactured for hydraulics. The tubes have standard sizes for different pressure ranges, with standard diameters up to 100 mm. The tubes are supplied by manufacturers in lengths of 6 m, cleaned, oiled and plugged. The tubes are interconnected by different types of flanges (especially for the larger sizes and pressures), welding cones/nipples (with o-ring seal), several types of flare connection and by cut-rings. In larger sizes, hydraulic pipes are used. Direct joining of tubes by welding is not acceptable since the interior cannot be inspected.

Hydraulic pipe is used in case standard hydraulic tubes are not available. Generally these are used for low pressure. They can be connected by threaded connections, but usually by welds. Because of the larger diameters the pipe can usually be inspected internally after welding. Black pipe is non-galvanized and suitable for welding.

Hydraulic hose is graded by pressure, temperature, and fluid compatibility. Hoses are used when pipes or tubes can not be used, usually to provide flexibility for machine operation or maintenance. The hose is built up with rubber and steel layers. A rubber interior is surrounded by multiple layers of woven wire and rubber. The exterior is designed for abrasion resistance. The bend radius of hydraulic hose is carefully designed into the machine, since hose failures can be deadly, and violating the hose's minimum bend radius will cause failure. Hydraulic hoses generally have steel fittings swaged on the ends. The weakest part of the high pressure hose is the connection of the hose to the fitting. Another disadvantage of hoses is the shorter life of rubber which requires periodic replacement, usually at five to seven year intervals.

Tubes and pipes for hydraulic applications are internally oiled before the system is commissioned. Usually steel piping is painted outside. Where flare and other couplings are used, the paint is removed under the nut, and is a location where corrosion can begin. For this reason, in marine applications most piping is stainless steel.

Seals, fittings and connections

In general, valves, cylinders and pumps have female threaded bosses for the fluid connection, and hoses have female ends with captive nuts. A male-male fitting is chosen to connect the two. Many standardized systems are in use.

Fittings serve several purposes;

1. To bridge different standards; O-ring boss to JIC, or pipe threads to face seal, for example.
2. To allow proper orientation of components, a 90°, 45°, straight, or swivel fitting is chosen as needed. They are designed to be positioned in the correct orientation and then tightened.
3. To incorporate bulkhead hardware.

4. A *quick disconnect* fitting may be added to a machine without modification of hoses or valves

A typical piece of heavy equipment may have thousands of sealed connection points and several different types:

- Pipe fittings, the fitting is screwed in until tight, difficult to orient an angled fitting correctly without over or under tightening.
- O-ring boss, the fitting is screwed into a boss and orientated as needed, an additional nut tightens the fitting, washer and o-ring in place.
- Flare fittings, are metal to metal compression seals deformed with a cone nut and pressed into a flare mating.
- Face seal, metal flanges with a groove and o-ring are fastened together.
- Beam seals are costly metal to metal seals used primarily in aircraft.
- Swaged seals, tubes are connected with fittings that are swaged permanently in place. Primarily used in aircraft.

Elastomeric seals (O-ring boss and face seal) are the most common types of seals in heavy equipment and are capable of reliably sealing 6000+ psi (40+ MPa) of fluid pressure.

Basic calculations

Hydraulic power is defined as flow times pressure. The hydraulic power supplied by a pump:

$$\text{Power} = (P \times Q) \div 600$$

where power is in kilowatts [kW], P pressure in bars, and Q is the flow in liters per minute. For example, a pump delivers 180 lit/min and the pressure equals 250 bar, therefore the power of the pump is 75 kW.

When calculating the power input to the pump, the total pump efficiency η_{total} must be included. This efficiency is the product of volumetric efficiency, η_{vol} and the hydromechanical efficiency, η_{hm}. Power input = Power output ÷ η_{total}. The average for axial piston pumps, $\eta_{total} = 0.87$. In the example the power source, for example a diesel engine or an electric motor, must be capable of delivering at least 75 ÷ 0.87 = 86 [kW]. The hydraulic motors and cylinders that the pump supplies with hydraulic power also have efficiencies and the total system efficiency (without including the pressure drop in the hydraulic pipes and valves) will end up at approx. 0.75. Cylinders normally have a total efficiency around 0.95 while hydraulic axial piston motors 0.87, the same as the pump. In general the power loss in a hydraulic energy transmission is thus around 25% or more at ideal viscosity range 25-35 [cSt].

Calculation of the required max. power output for the diesel engine, rough estimation:

(1) Check the max. powerpoint, i.e. the point where pressure times flow reach the max. value.

(2) $E_{\text{diesel}} = (P_{\max} \cdot Q_{\text{tot}}) \div \eta$.

Q_{tot} = calculate with the theoretical pump flow for the consumers not including leakages at max. power point.

$P_{\max}$ = actual pump pressure at max. power point.

Note: η is the total efficiency = (output mechanical power ÷ input mechanical power). For rough estimations, $\eta = 0.75$. Add 10-20% (depends on the application) to this power value.

(3) Calculate the required pumpdisplacement from required max. sum of flow for the consumers in worst case and the diesel engine rpm in this point. The max. flow can differ from the flow used for calculation of the diesel engine power. Pump volumetric efficiency average, piston pumps: $\eta_{\text{vol}} = 0.93$.

Pumpdisplacement $V_{\text{pump}} = Q_{\text{tot}} \div n_{\text{diesel}} \div 0.93$.

(4) Calculation of prel. cooler capacity: Heat dissipation from hydraulic oil tanks, valves, pipes and hydraulic components is less than a few percent in standard mobile equipment and the cooler capacity must include some margins. Minimum cooler capacity, $E_{\text{cooler}} = 0.25E_{\text{diesel}}$

At least 25% of the input power must be dissipated by the cooler when peak power is utilized for long periods. In normal case however, the peak power is used for only short periods, thus the actual cooler capacity required might be considerably less. The oil volume in the hydraulic tank is also acting as a heat accumulator when peak power is used. The system efficiency is very much dependent on the type of hydraulic work tool equipment, the hydraulic pumps and motors used and power input to the hydraulics may vary a lot. Each circuit must be evaluated and the load cycle estimated. New or modified systems must always be tested in practical work, covering all possible load cycles. An easy way of measuring the actual average power loss in the system is to equip the machine with a test cooler and measure the oil temperature at cooler inlet, oil temperature at cooler outlet and the oil flow through the cooler, when the machine is in normal operating mode. From these figures the test cooler power dissipation can be calculated and this is equal to the power loss when temperatures are stabilized. From this test the actual required cooler can be calculated to reach specified oil temperature in the oil tank. One problem can be to assemble the measuring equipment inline, especially the oil flow meter.

Chapter 2

Hydraulic Jump

A **hydraulic jump** is a phenomenon in the science of hydraulics which is frequently observed in open channel flow such as rivers and spillways. When liquid at high velocity discharges into a zone of lower velocity, a rather abrupt rise occurs in the liquid surface. The rapidly flowing liquid is abruptly slowed and increases in height, converting some of the flow's initial kinetic energy into an increase in potential energy, with some energy irreversibly lost through turbulence to heat. In an open channel flow, this manifests as the fast flow rapidly slowing and piling up on top of itself similar to how a shockwave forms.

The phenomenon is dependent upon the initial fluid speed. If the initial speed of the fluid is below the critical speed, then no jump is possible. For initial flow speeds which are not significantly above the critical speed, the transition appears as an undulating wave. As the initial flow speed increases further, the transition becomes more abrupt, until at high enough speeds, the transition front will break and curl back upon itself. When this happens, the jump can be accompanied by violent turbulence, eddying, air entrainment, and surface undulations, or waves.

There are two main manifestations of hydraulic jumps and historically different terminology has been used for each. However, the mechanisms behind them are similar because they are simply variations of each other seen from different frames of reference, and so the physics and analysis techniques can be used for both types.

The different manifestations are:

- The stationary hydraulic jump – rapidly flowing water transitions in a stationary jump to slowly moving water as shown in Figures 1 and 2.
- The tidal bore – a wall or undulating wave of water moves upstream against water flowing downstream as shown in Figures 3 and 4. If considered from a frame of reference which moves with the wave front, you can see that this case is physically similar to a stationary jump.

A related case is a cascade – a wall or undulating wave of water moves downstream overtaking a shallower downstream flow of water as shown in Figure 5. If considered from a frame of reference which moves with the wave front, this is amenable to the same analysis as a stationary jump.

Figure 2: A common example of a hydraulic jump is the roughly circular stationary wave that forms around the central stream of water. The jump is at the transition between the point where the circle appears still and where the turbulence is visible.

These phenomena are addressed in an extensive literature from a number of technical viewpoints.

Classes of hydraulic jumps

Figure 3: A tidal bore in Alaska showing a turbulent shock-wave-like front. At this point the water is relatively shallow and the fractional change in elevation is large.

Hydraulic jumps can be seen in both a stationary form, called a hydraulic jump, and a dynamic or moving form, called a positive surge or "hydraulic jump in translation". They can be described using the same analytic approaches and are simply variants of a single phenomenon.

Moving hydraulic jump

Figure 4: An undular front on a tidal bore. At this point the water is relatively deep and the fractional change in elevation is small.

A tidal bore is a hydraulic jump which occurs when the incoming tide forms a wave (or waves) of water that travel up a river or narrow bay against the direction of the current. As is true for hydraulic jumps in general, bores take on various forms depending upon the difference in the waterlevel upstream and down, ranging from an undular wavefront to a shock-wave-like wall of water. Figure 3 shows a tidal bore with the characteristics common to shallow upstream water – a large elevation difference is observed. Figure 4 shows a tidal bore with the characteristics common to deep upstream water – a small elevation difference is observed and the wavefront undulates. In both cases the tidal wave moves at the speed characteristic of waves in water of the depth found immediately behind the wave front. A key feature of tidal bores and positive surges is the intense turbulent mixing induced by the passage of the bore front and by the following wave motion.

Figure 5: Series of roll waves moving down a spillway, where they terminate in a stationary hydraulic jump.

Another variation of the moving hydraulic jump is the cascade. In the cascade, a series of roll waves or undulating waves of water moves downstream overtaking a shallower downstream flow of water.

Stationary hydraulic jump

The stationary hydraulic jump is most frequently seen on rivers and on engineered features such as outfalls of dams and irrigation works. They occur when a flow of liquid at high velocity discharges into a zone of the river or engineered structure which can only sustain a lower velocity. When this occurs, the water slows in a rather abrupt rise (a step or standing wave) on the liquid surface.

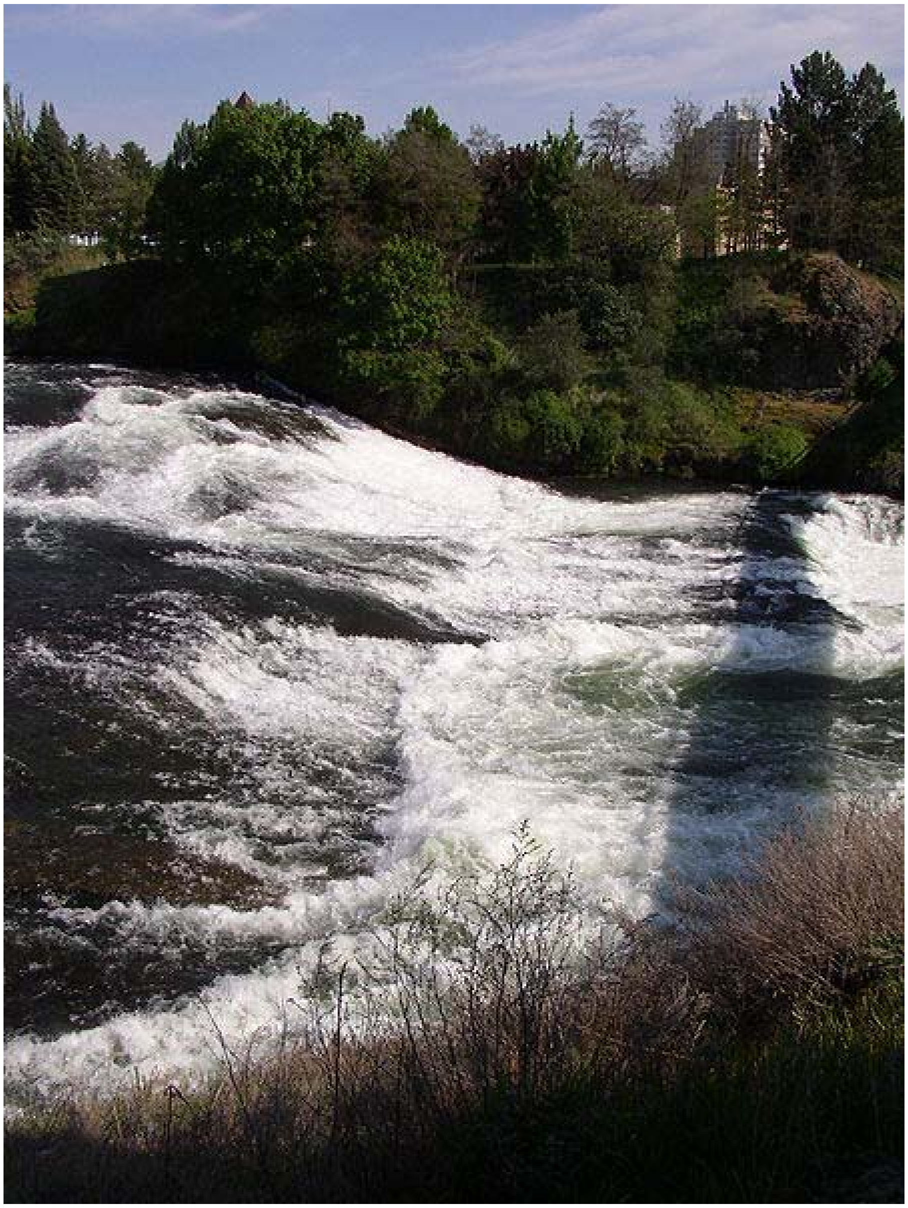
Comparing the characteristics before and after, one finds:

Descriptive Hydraulic Jump Characteristics

Characteristic	Before the jump	After the jump
fluid speed	supercritical (faster than the wave speed) also known as shooting or superundal	subcritical also known as tranquil or subundal
fluid height	low	high
flow	typically smooth turbulent	typically turbulent flow (rough and choppy)

The other stationary hydraulic jump occurs when a rapid flow encounters a submerged object which throws the water upwards. The mathematics behind this form is more complex and will need to take into account the shape of the object and the flow characteristics of the fluid around it.

Analysis of the hydraulic jump on a liquid surface



Naturally occurring hydraulic jump observed on the Upper Spokane Falls north channel.

In spite of the apparent complexity of the flow transition, application of simple analytic tools to a two dimensional analysis are effective in providing analytic results which closely parallel both field and laboratory results. Analysis shows:

- Height of the jump: the relationship between the depths before and after the jump as a function of flow rate.
- Energy loss in the jump
- Location of the jump on a natural or an engineered structure
- Character of the jump: undular or abrupt

Height of the jump

There are several methods of predicting the height of a hydraulic jump.

They all reach common conclusions that:

- The ratio of the water depth before and after the jump depend solely on the ratio of velocity of the water entering the jump to the speed of the wave over-running the moving water.
- The height of the jump can be many times the initial depth of the water.

Applying the energy principle

Assuming a two-dimensional situation with flow rate, (q) as shown by Figure 7 below, the energy principle yields an expression of the energy loss in the hydraulic jump. Hydraulic jumps are commonly used as energy dissipaters downstream of dam spillways.

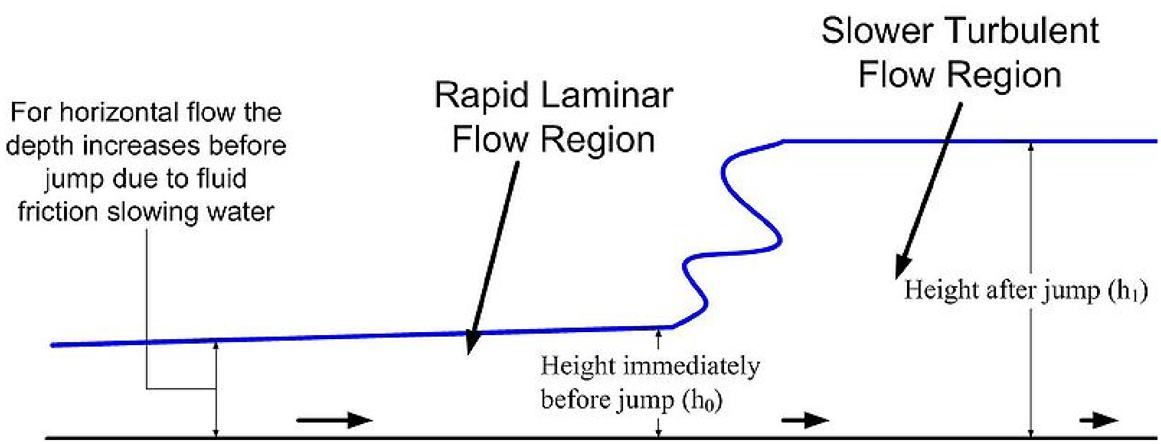


Figure 7: Illustration of behaviour in a hydraulic jump.
Applying the continuity principle

In fluid dynamics, the equation of continuity is effectively an equation of conservation of mass. Considering any fixed closed surface within an incompressible moving fluid, the fluid flows into a given volume at some points and flows out at other points along the surface with no net change in mass within the space since the density is constant. We will assume a rectangular channel. The differential continuity equation, in Cartesian coordinates:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

where ρ is density, t is time, and $\boldsymbol{v}$ is fluid velocity.

Since the density is constant and we are considering only a 2-dimensional case, this integrates to:

$$v_0 \times h_0 = v_1 \times h_1$$

or $v_1 = v_0 \times \frac{h_0}{h_1}$

Substituting yields a cubic equation which can be solved using Cardano's method to determine that:

$$\frac{h_1}{h_0} = \frac{-1 \pm \sqrt{1 + \frac{8v_0^2}{gh_0}}}{2}$$

The conservation of momentum across the jump, assuming constant density, can be expressed as:

$$\frac{d}{dt}\int_{z_0}^{z_1} \rho\langle\mathbf{v}\rangle A\, ds = \rho\langle\mathbf{v}v\rangle_0 A_0 - \rho\langle\mathbf{v}v\rangle_1 A_1 + p_0\mathbf{A}_0 - p_1\mathbf{A}_1 - \mathbf{F} + \rho\mathbf{g}\int_{z_0}^{z_1} A\, dz = 0$$

Where $\mathbf{v}$is the velocity field, and v is the component of velocity perpendicular to the control volume surface.

Essentially, the time variation of momentum in the control volume bounded by z_0 and z_1 can be expressed as the difference of momentum fluxes entering and leaving the control volume. For a flow field that is everywhere parallel to z, $\mathbf{v}$has the same direction and magnitude as v. Thus, $\langle\mathbf{v}v\rangle = \langle v^2\rangle$. Also, for turbulent flow, $\beta = \frac{\langle v^2\rangle}{\langle v\rangle^2} = 1$. Additionally, we will only consider changes in x-momentum, so the last integral, which has only a z-component, need not be included in subsequent equations. With these simplifications, the expression for momentum conservation becomes:

$$\rho\langle v\rangle_0^2 A_0 - \rho\langle v\rangle_1^2 A_1 + p_0\mathbf{A}_0 - p_1\mathbf{A}_1 = 0$$

Assuming a uniform velocity over the flow at z_0 and z_1, which implies a surface normal vector $\mathbf{A}$, parallel to the flow,

$$\rho v_0^2 A_0 - \rho v_1^2 A_1 + p_0 A_0 - p_1 A_1 = 0$$

The static pressure in the flow is simply the hydrostatic pressure, $p = p_a + \rho g h$, where p_a is the atmospheric pressure. The force caused by the atmospheric pressure will cancel across any boundary, so it need not be considered. The net force caused by the pressure acting on the control volume before and after the jump is:

$$pA = \int_0^h \rho g h' \, dh' = \frac{1}{2}\rho g h^2$$

The expression for conservation of momentum can now be written as:

$$\rho v_0^2 h_0 - \rho v_1^2 h_1 + \frac{1}{2}\rho g h_0^2 - \frac{1}{2}\rho g h_1^2 = 0$$

Dividing by constant ρ and introducing the result from continuity gives

$$v_0^2 \left(h_0 - \frac{h_0^2}{h_1} \right) + \frac{g}{2}(h_0^2 - h_1^2) = 0$$

Which, after some algebra, simplifies to:

$$\frac{1}{2}\frac{h_1}{h_0}\left(\frac{h_1}{h_0} + 1\right) - Fr^2 = 0$$

Where $Fr^2 = \frac{v_0^2}{gh_0}$. Fr is the dimensionless Froude number, and relates inertial to gravitational forces in the flow. Solving this quadratic yields the same equation for $\frac{h_1}{h_0}$ as stated above.

Negative answers do not yield meaningful physical solutions, so this reduces to:

$$\frac{h_1}{h_0} = \frac{-1 + \sqrt{1 + \frac{8v_0^2}{gh_0}}}{2}$$

Burdekin Dam on the Burdekin River in Queensland, Australia showing pronounced hydraulic jump induced by down-stream obstructions and a grade change.

This produces three solutions:

- When $\frac{v_0^2}{gh_0} = 1$, then $\frac{h_1}{h_0} = 1$ (i.e., there is no jump)
- When $\frac{v_0^2}{gh_0} < 1$, then $\frac{h_1}{h_0} < 1$ (i.e., there is a negative jump – this can be shown as not conserving energy and is only physically possible if some force were to accelerate the fluid at that point)
- When $\frac{v_0^2}{gh_0} > 1$ or $\frac{v_0^2}{gh_0} > 1$, then $\frac{h_1}{h_0} > 1$ (i.e., there is a positive jump)

This is equivalent to the condition that $Fr > 1$. Since the $\sqrt{gh_0}$ is the speed of a shallow gravity wave, the condition that *Fr* > 1 is equivalent to stating that the initial velocity represents supercritical flow (Froude number > 1) while the final velocity represents subcritical flow (Froude number < 1).

Jump height in terms of flow

The ratio of the flow height before the jump and after the jump can be simply expressed in terms of the Froude number of the incoming flow. The greater that the flow is supercritical, the more pronounced the jump will be.

$$\frac{h_1}{h_0} = \frac{\sqrt{1+8Fr^2}-1}{2}$$

known as Bélanger equation.

Practically this means that water accelerated by large drops can create stronger standing waves in the form of hydraulic jumps as it decelerates at the base of the drop. Such standing waves, when found downstream of a weir or natural rock ledge, can form an extremely dangerous "keeper" with a water wall that "keeps" floating objects (e.g., logs, kayaks, or kayakers) recirculating in the standing wave for extended periods.

Alternate but equivalent approach applying the impulse–momentum principle

A similar analysis, reaching exactly the same results, derives the same results starting with the impulse–momentum principle.

Net impulse = change in momentum

$$\rho(gh_0 - gh_1)t = \rho\left(\frac{v_1^2}{2} - \frac{v_0^2}{2}\right)t$$

$$\frac{v_0^2}{2} + gh_0 = \frac{v_1^2}{2} + gh_1$$

This equation yields the same overall relationship between jump height and Froude number.

Energy dissipation by a hydraulic jump

Saint Anthony Falls on the Mississippi River showing a pronounced hydraulic jump.

One of the most important engineering applications of the hydraulic jump is to dissipate energy in channels, dam spillways, and similar structures so that the excess kinetic energy does not damage these structures. The rate of energy dissipation or head loss across a hydraulic jump is a function of the hydraulic jump inflow Froude number. The larger the jump, as expressed in terms of its inflow Froude number, the greater the head loss.

Analytically, the fractional energy loss (FEL) can be expressed in terms of the Froude number (Fr_0) for the incident flow as:

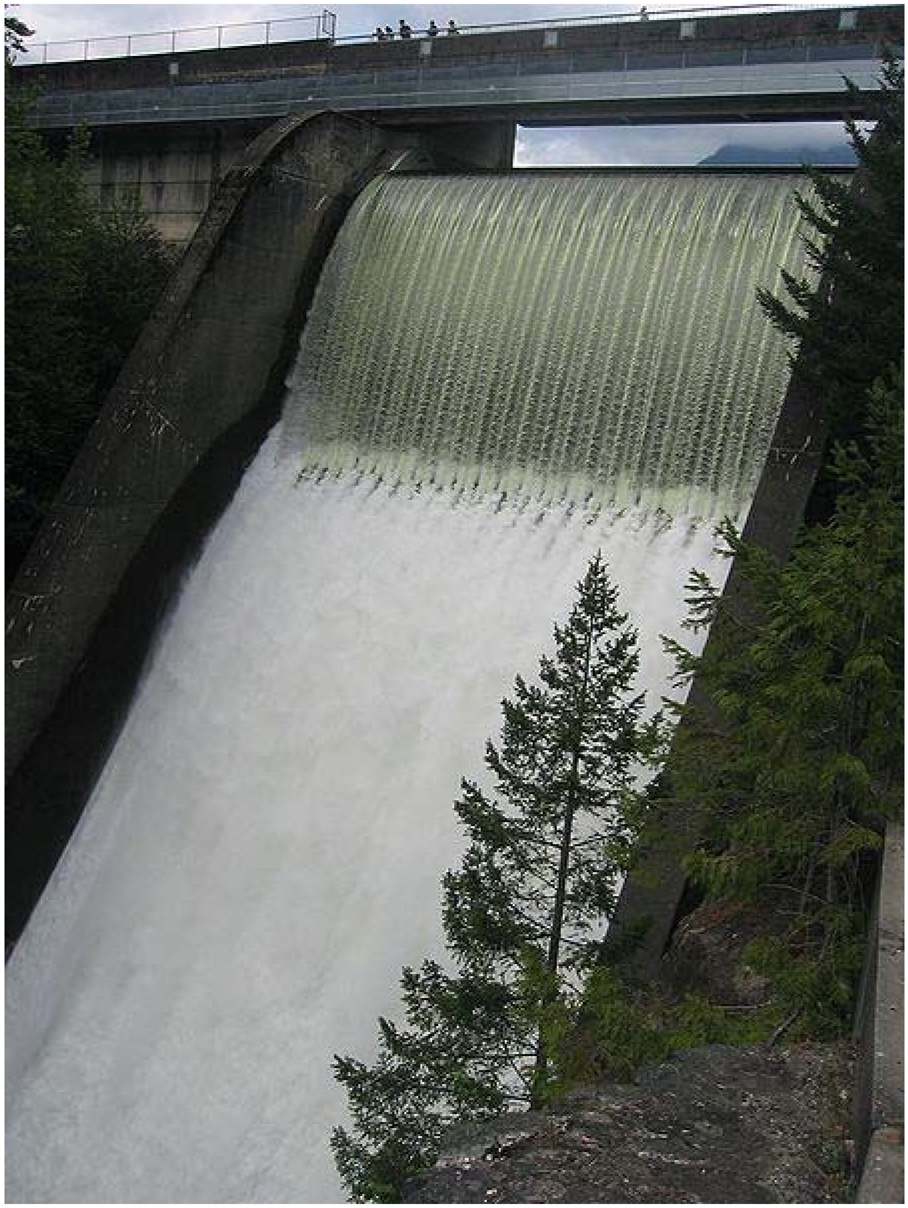
$$FEL = \frac{\left(\sqrt{1+8Fr_0^2}-3\right)^3}{8\left(\sqrt{1+8Fr_0^2}-1\right)\left(\sqrt{Fr_0^2+2}\right)}$$

Since $Fr_0 = \sqrt{\frac{v_0^2}{gh_0}}$ this is equivalent to concluding the energy loss can be predicted by predicting or measuring the speed and depth of the entering water.

Location of hydraulic jump in a streambed or an engineered structure

In the design of a dam the energy of the fast-flowing stream over a spillway must be partially dissipated to prevent erosion of the streambed downstream of the spillway, which could ultimately lead to failure of the dam. This can be done by arranging for the formation of a hydraulic jump to dissipate energy. To limit damage, this hydraulic jump normally occurs on an apron engineered to withstand hydraulic forces and to prevent local cavitation and other phenomena which accelerate erosion.

In the design of a spillway and apron, the engineers select the point at which a hydraulic jump will occur. Obstructions or slope changes are routinely designed into the apron to force a jump at a specific location. Obstructions are unnecessary, as the slope change alone is normally sufficient. To trigger the hydraulic jump without obstacles, an apron is designed such that the flat slope of the apron retards the rapidly flowing water from the spillway. If the apron slope is insufficient to maintain the original high velocity, a jump will occur.



Supercritical flow down the Cleveland Dam spillway at the head of the Capilano River in North Vancouver, British Columbia, Canada.

Two methods of designing an induced jump are common:

- If the downstream flow is restricted by the down-stream channel such that water backs up onto the foot of the spillway, that downstream water level can be used to identify the location of the jump.

- If the spillway continues to drop for some distance, but the slope changes such that it will no longer support supercritical flow, the depth in the lower subcritical flow region is sufficient to determine the location of the jump.

In both cases, the final depth of the water is determined by the downstream characteristics. The jump will occur if and only if the level of inflowing (supercritical) water level (h_0) satisfies the condition:

$$h_0 = \frac{h_1}{2}\left(-1 + \sqrt{1 + 8Fr^2 h_1/g}\right)$$

Fr = Upstream Froude Number
g = acceleration due to gravity (essentially constant for this case)
h = height of the fluid (h_0 = initial height while h_1 = final downstream height)

Air entrainment in hydraulic jumps

The hydraulic jump is characterised by a highly turbulent flow. Macro-scale vortices develop in the jump roller and interact with the free surface leading to air bubble entrainment, splashes and droplets formation in the two-phase flow region. The air–water flow is associated with turbulence, which can also lead to sediment transport. The turbulence may be strongly affected by the bubble dynamics. Physically, the mechanisms involved in these processes are complex.

The air entrainment occurs in the form of air bubbles and air packets entrapped at the impingement of the upstream jet flow with the roller. The air packets are broken up in very small air bubbles as they are entrained in the shear region, characterised by large air contents and maximum bubble count rates. Once the entrained bubbles are advected into regions of lesser shear, bubble collisions and coalescence lead to larger air entities that are driven towards the free-surface by a combination of buoyancy and turbulent advection.

Applying wave theory to the hydraulic jump

In fluid dynamics, gravity waves are waves generated in a fluid which has as the restoring force, gravity. Gravity waves on an air-water interface are called surface gravity waves or surface waves. Hydraulic jumps, ocean waves and tsunamis can all be treated as examples of gravity waves.

The wave speed or celerity (speed of individual waves, as opposed to the speed of a group of waves) of gravity waves in shallow water is given by:

- $v = \sqrt{gh}\sqrt{\frac{\tanh(kh)}{kh}}$ which approaches $\sqrt{gh}$ for small h;

In which:

- v = wave speed or celerity (m/s)
- g = gravitational acceleration (9.8 m/s² on Earth)
- h = water depth (m)

- $k = \frac{2\pi}{\lambda}$ wave number where λ is the wavelength.

The constraints on the approximation for the speed of a gravity wave as $\sqrt{gh}$ for shallow depths are:

- For wavelengths close to or less than 1.7 cm the surface tension cannot be neglected so that this approximation is invalid.
- For depths significantly greater than the wavelength, λ, of the wave the speed c of the wave is governed only by the wavelength following the equation $c = \frac{g\lambda}{2\pi}$ where g is the acceleration of gravity.

A hydraulic jump can be viewed as discontinuous waves of all frequencies, which are generated and propagate from a point near the jump. The waves propagate both upstream and downstream. Since a large fraction of the waves fall in a wavelength range where they are shallow water gravity waves that move at the same speed for a given depth, they move upstream at the same rate; however, as the water shallows upstream, their speed drops quickly, limiting the rate at which they can propagate upstream to $\sqrt{gh}$. Shorter wavelengths, which propagate more slowly than the speed of the wave in the deeper downstream water, are swept away downstream. A fairly wide range of wavelengths and frequencies are still present, so Fourier analysis would suggest that a relatively abrupt wave front can be formed.

Viewing the hydraulic jump from a wave perspective provides another insight into the phenomena. When the incoming water speed is slow enough, a number of the longer wavelength waves propagate faster than the incoming flow, and can disperse upstream as well as downstream. The deeper the incoming water is, the more pronounced the dispersion effect will be. Only a small subset of frequencies will match the speed of the flow. This truncation of the Fourier spectrum results in a hydraulic jump characterized by undulating waves rather than an abrupt jump. When visible undulations are present, the wavelength of the visible undulations provide a direct indication of the speed of the water upstream of the hydraulic jump.

This characteristic behavior allows one to estimate the pre-jump water depth and water speed simply by observing the height of the jump, the characteristics of the jump, and correlating them as tabulated below. Such an “eyeball” estimate is routinely used by river runners while judging rapids; their conclusions are generally based on an intuitive sense rather than an analytic approach.

Tabular summary of the analytic conclusions

Hydraulic Jump Characteristics

Amount upstream flow is supercritical (i.e., prejump Froude Number)	Ratio of height after to height before jump	Descriptive characteristics of jump	Fraction of energy dissipated by jump
≤ 1.0	1.0	No jump; flow must be supercritical for jump to occur	none
1.0–1.7	1.0–2.0	Standing or undulating wave	< 5%
1.7–2.5	2.0–3.1	Weak jump (series of small rollers)	5% – 15%
2.5–4.5	3.1–5.9	Oscillating jump	15% – 45%
4.5–9.0	5.9–12.0	Stable clearly defined well-balanced jump	45% – 70%
> 9.0	> 12.0	Clearly defined, turbulent, strong jump	70% – 85%

NB: the above classification is very rough. Undular hydraulic jumps have been observed with inflow/prejump Froude numbers up to 3.5 to 4.

Hydraulic jump variations

A number of variations are amenable to similar analysis:

Shallow fluid hydraulic jumps

The hydraulic jump in your sink

Figure 2 above illustrates a daily example of a hydraulic jump can be seen in the sink. Around the place where the tap water hits the sink, you will see a smooth-looking flow pattern. A little further away, you will see a sudden "jump" in the water level. This is a hydraulic jump.

The nature of this jump differs from those previously discussed in the following ways:

- The water is flowing radially. As a result it continuously grows shallower and slows due to friction (the Froude number drops) up to the point where the jump occurs.
- The flow depth is thin enough that the surface tension can no longer be neglected, changing the wave solution conclusions. The higher speed of the surface tension waves bleed off the high frequency component, making an undular jump the dominant form.

Changes in the behavior of the jump can be observed by changing the flow rate.

Internal wave hydraulic jumps

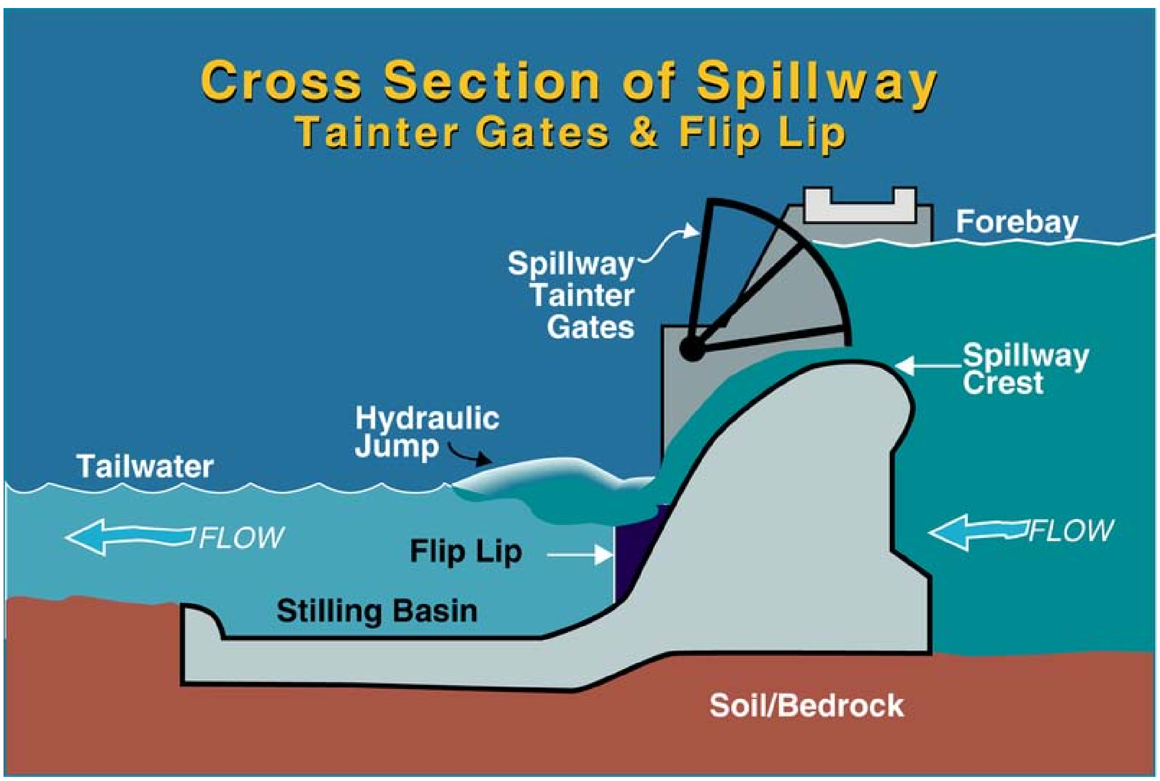
Hydraulic jumps in abyssal fan formation

Turbidity currents can result in internal hydraulic jumps (i.e., hydraulic jumps as internal waves in fluids of different density) in abyssal fan formation. The internal hydraulic jumps have been associated with salinity or temperature induced stratification as well as with density differences due to suspended materials. When the bed slope over which the turbidity current flattens, the slower rate of flow is mirrored by increased sediment deposition below the flow, producing a gradual backward slope. Where a hydraulic jump occurs, the signature is an abrupt backward slope, corresponding to the rapid reduction in the flow rate at the point of the jump.

Atmospheric hydraulic jumps

A related situation is the Morning Glory cloud observed, for example, in Northern Australia, sometimes called an undular jump.

Industrial and recreational applications for hydraulic jumps



Energy dissipation using hydraulic jump.

Industrial

The hydraulic jump is the most commonly used choice of design engineers for energy dissipation below spillways and outlets. A properly designed hydraulic jump can provide for 60-70% energy dissipation of the energy in the basin itself, limiting the damage to structures and the streambed. Even with such efficient energy dissipation, stilling basins must be carefully designed to avoid serious damage due to uplift, vibration, cavitation, and abrasion. An extensive literature has been developed for this type of engineering.

Recreational

Kayak playing on the transition between the turbulent flow and the recirculation region in the pier wake.

While travelling down river, kayaking and canoeing paddlers will often stop and playboat in standing waves and hydraulic jumps. The standing waves and shock fronts of hydraulic jumps make for popular locations for such recreation.

Similarly, kayakers and surfers have been known to ride tidal bores up rivers.

Chapter 3

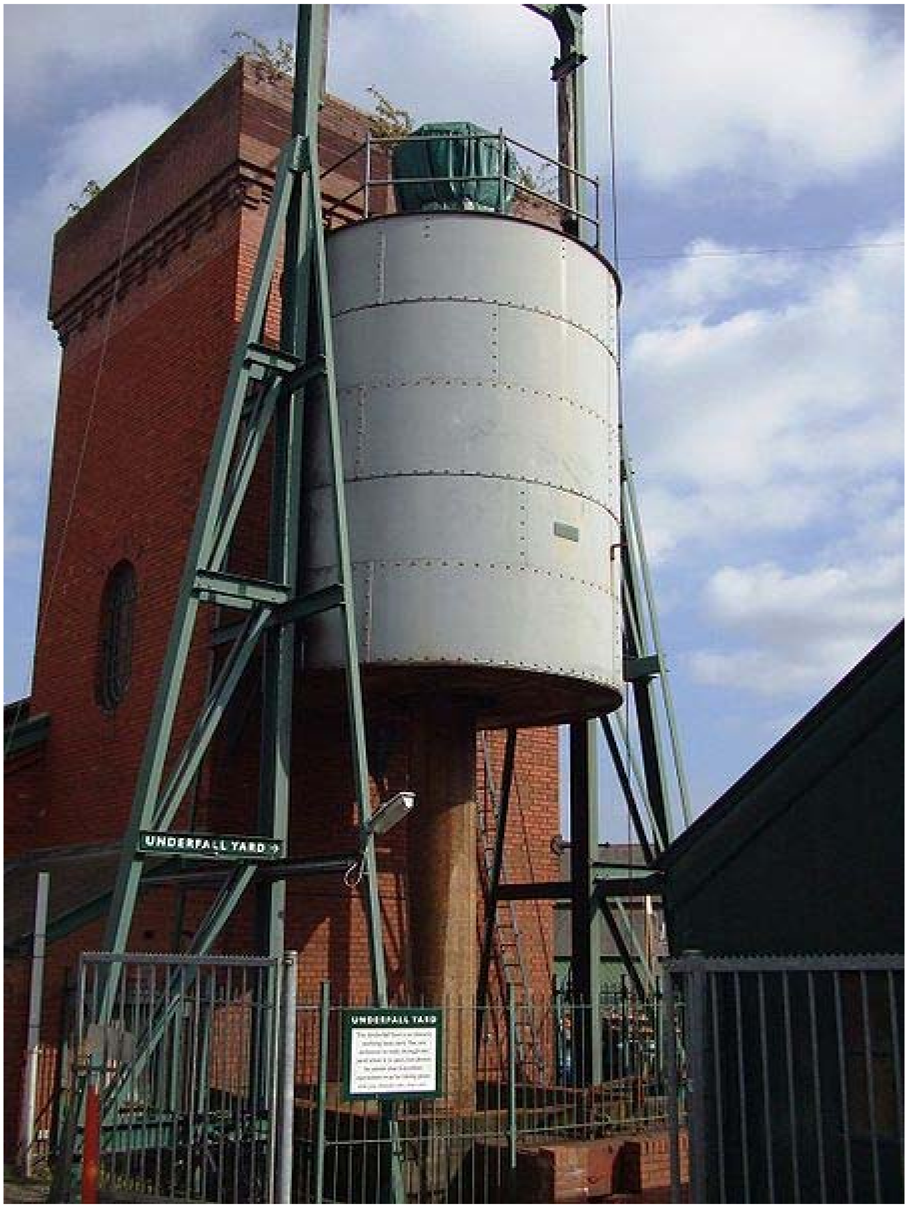
Hydraulic Accumulator

A **hydraulic accumulator** is an energy storage device. It is a pressure storage reservoir in which a non-compressible hydraulic fluid is held under pressure by an external source. That external source can be a spring, a raised weight, or a compressed gas. The main reasons that an *accumulator* is used in a hydraulic system are so that the pump doesn't need to be so large to cope with extremes of demand, so that the supply circuit can respond more quickly to any temporary demand and to smooth pulsations.

Compressed gas accumulators are by far the most common type. These are also called hydro-pneumatic accumulators.

Types of accumulator

Raised weight



Hydraulic engine house, Bristol Harbour

A raised weight accumulator consists of a vertical cylinder containing fluid connected to the hydraulic line. The cylinder is closed by a piston on which a series of weights are placed that exert a downward force on the piston and thereby energizes the fluid in the cylinder. In contrast to compressed gas and spring accumulators, this type delivers a nearly constant pressure, regardless of the volume of fluid in the cylinder, until it is empty. (The pressure will decline somewhat as the cylinder is emptied due to the decline in weight of the remaining fluid.)

A working example of this type of accumulator may be found at the hydraulic engine house, Bristol Harbour. The external accumulator was added around 1920. The water is pumped from the harbour into a header tank and then fed by gravity to the pumps. The working pressure is 750 psi (5.2 MPa, or 52 bar) which is used to power the cranes, bridges and locks of Bristol Harbour.

The original operating mechanism of Tower Bridge, London, also used this type of accumulator. Although no longer in use, two of the six accumulators may still be seen *in situ* in the bridge's museum.

London had an extensive public hydraulic power system from the mid-nineteenth century finally closing in the 1970s with 5 hydraulic power stations, operated by the London Hydraulic Power Company. Railway goods yards and docks often had their own separate system, a notable example of an early accumulator, dating from 1869 being at the Regent's Canal Dock of the Regent's Canal Company at Limehouse, London. The artifact has been converted into a visitor attraction which is open yearly during London Open House weekend, usually the third weekend in September.

Compressed gas (or gas-charged) accumulator

A compressed gas accumulator consists of a cylinder with two chambers that are separated by an elastic diaphragm, a totally enclosed bladder, or a floating piston. One chamber contains hydraulic fluid and is connected to the hydraulic line. The other chamber contains an inert gas under pressure (typically nitrogen) that provides the compressive force on the hydraulic fluid. Inert gas is used because oxygen and oil can form an explosive mixture when combined under high pressure. As the volume of the compressed gas changes the pressure of the gas, and the pressure on the fluid, changes inversely.

The compressed gas accumulator was invented by Jean Mercier, for use in variable pitch propellers.

Spring type

A spring type accumulator is similar in operation to the gas-charged accumulator above, except that a heavy spring (or springs) is used to provide the compressive force. According to Hooke's law the magnitude of the force exerted by a spring is linearly proportional to its extension. Therefore as the spring compresses, the force it exerts on the fluid is increased linearly.

Metal bellows type

The metal bellows accumulators function similarly to the compressed gas type, except the elastic diaphragm or floating piston is replaced by a hermetically sealed welded metal bellows. Fluid may be internal or external to the bellows. The advantages to the metal bellows type include exceptionally low spring rate, allowing the gas charge to do all the work with little change in pressure from full to empty, and a long stroke relative to solid (empty) height, which gives maximum storage volume for a given container size. The welded metal bellows accumulator provides an exceptionally high level of accumulator performance, and can be produced with a broad spectrum of alloys resulting in a broad range of fluid compatibility. Another advantage to this type is that it does not face issues with high pressure operation, thus allowing more energy storage capacity.

Functioning of an accumulator

In modern, often mobile, hydraulic systems the preferred item is a gas charged accumulator, but simple systems may be spring-loaded. There may be more than one accumulator in a system. The exact type and placement of each may be a compromise due to its effects and the costs of manufacture.

An accumulator is placed close to the pump with a non-return valve preventing flow back to it. In the case of piston-type pumps this accumulator is placed in the best place to absorb pulsations of energy from the multi-piston pump. It also helps protect the system from fluid hammer. This protects system components, particularly pipework, from both potentially destructive forces.

An additional benefit is the additional energy that can be stored while the pump is subject to low demand. The designer can use a smaller-capacity pump. The large excursions of system components, such as landing gear on a large aircraft, that require a considerable volume of fluid can also benefit from one or more accumulators. These are often placed close to the demand to help overcome restrictions and drag from long pipework runs. The outflow of energy from a discharging accumulator is much greater, for a short time, than even large pumps could generate.

An accumulator can maintain the pressure in a system for periods when there are slight leaks without the pump being cycled on and off constantly. When temperature changes cause pressure excursions the accumulator helps absorb them. Its size helps absorb fluid that might otherwise be locked in a small fixed system with no room for expansion due to valve arrangement.

The gas precharge in an accumulator is set so that the separating bladder, diaphragm or piston does not reach or strike either end of the operating cylinder. The design precharge normally ensures that the moving parts do not foul the ends or block fluid passages. Poor maintenance of precharge can destroy an operating accumulator. A properly designed and maintained accumulator should operate trouble-free for years.

Chapter 4

Hydraulic Cylinder

The hydraulic cylinders on this excavator control the machine's linkages.

A **Hydraulic cylinder** (also called a linear hydraulic motor) is a mechanical actuator that is used to give a unidirectional force through a unidirectional stroke. It has many applications, notably in engineering vehicles.

Operation

Hydraulic cylinders get their power from pressurized hydraulic fluid, which is typically oil. The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on each end by the cylinder bottom (also called the cap end) and by the cylinder head where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder in two chambers, the bottom chamber (cap end) and the piston rod side chamber (rod end). The hydraulic pressure acts on the piston to do linear work and motion.

Flanges, trunnions, and/or clevisses are mounted to the cylinder body. The piston rod also has mounting attachments to connect the cylinder to the object or machine component that it is pushing.

A hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings in a fixed or regulated flow of oil to the bottom side of the hydraulic cylinder, to move the piston rod upwards. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil pressure in the piston rod chamber is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A:

$$F = P \cdot A.$$

The piston moves instead downwards if oil is pumped into the piston rod side chamber and the oil from the piston area flows back to the reservoir without pressure. The pressure in the piston rod area chamber is (Pull Force) / (piston area - piston rod area).

Parts of a hydraulic cylinder

A hydraulic cylinder consists of the following parts:

Cylinder barrel

The cylinder barrel is mostly a seamless thick walled forged pipe that must be machined internally. The cylinder barrel is ground and/or honed internally.

Cylinder Bottom or Cap

In most hydraulic cylinders, the barrel and the bottom portion are welded together. This can damage the inside of the barrel if done poorly. Therefore some cylinder designs have a screwed or flanged connection from the cylinder end cap to the barrel. In this type the barrel can be disassembled and repaired in future.

Cylinder Head

The cylinder head is sometimes connected to the barrel with a sort of a simple lock (for simple cylinders). In general however the connection is screwed or flanged. Flange connections are the best, but also the most expensive. A flange has to be welded to the pipe before machining. The advantage is that the connection is bolted and always simple to remove. For larger cylinder sizes, the disconnection of a screw with a diameter of 300 to 600 mm is a huge problem as well as the alignment during mounting.

Piston

The piston is a short, cylinder-shaped metal component that separates the two sides of the cylinder barrel internally. The piston is usually machined with grooves to fit elastomeric or metal seals. These seals are often O-rings, U-cups or cast iron rings. They prevent the pressurized hydraulic oil from passing by the piston to the chamber on the opposite side. This difference in pressure between the two sides of the piston causes the cylinder to extend and retract. Piston seals vary in design and material according to the pressure and temperature requirements that the cylinder will see in service. Generally speaking, elastomeric seals made from nitrile rubber or other materials are best in lower temperature environments while seals made of Viton are better for higher temperatures. The best seals for high temperature are cast iron piston rings.

Piston Rod

The piston rod is typically a hard chrome-plated piece of cold-rolled steel which attaches to the piston and extends from the cylinder through the rod-end head. In double rod-end cylinders, the actuator has a rod extending from both sides of the piston and out both ends of the barrel. The piston rod connects the hydraulic actuator to the machine component doing the work. This connection can be in the form of a machine thread or a mounting attachment such as a rod-clevis or rod-eye. These mounting attachments can be threaded or welded to the piston rod or, in some cases, they are a machined part of the rod-end.

Rod gland

The cylinder head is fitted with seals to prevent the pressurized oil from leaking past the interface between the rod and the head. This area is called the rod gland. It often has another seal called a rod wiper which prevents contaminants from entering the cylinder when the extended rod retracts back into the cylinder. The rod gland also has a rod wear ring. This wear ring acts as a linear bearing to support the weight of the piston rod and guides it as it passes back and forth through the rod gland. In some cases, especially in small hydraulic cylinders, the rod gland and the rod wear ring are made from a single integral machined part.

Other parts

- Cylinder bottom connection
- Seals
- Cushions

A hydraulic cylinder should be used for pushing and pulling only. No bending moments or side loads should be transmitted to the piston rod or the cylinder. For this reason, the ideal connection of a hydraulic cylinder is a single clevis with a spherical ball bearing.

This allows the hydraulic actuator to move and allow for any misalignment between the actuator and the load it is pushing.

Hydraulic Cylinder Designs

There are primarily two styles of hydraulic cylinder construction used in industry: tie rod style cylinders and welded body style cylinders.

Tie Rod Cylinders

Tie rod style hydraulic cylinders use high strength threaded steel rods to hold the two end caps to the cylinder barrel. This method of construction is most often seen in industrial factory applications. Small bore cylinders usually have 4 tie rods, while large bore cylinders may require as many as 16 or 20 tie rods in order to retain the end caps under the tremendous forces produced. Tie rod style cylinders can be completely disassembled for service and repair.

The National Fluid Power Association (NFPA) has standardized the dimensions of hydraulic tie rod cylinders. This enables cylinders from different manufacturers to interchange within the same mountings.

Welded Body Cylinders

Welded body cylinders have no tie rods. The barrel is welded directly to the end caps. The ports are welded to the barrel. The front rod gland is usually threaded into or bolted to the cylinder barrel. This allows the piston rod assembly and the rod seals to be removed for service.

A Cut Away of a Welded Body Hydraulic Cylinder showing the internal components

Welded body cylinders have a number of advantages over tie rod style cylinders. Welded cylinders have a narrower body and often a shorter overall length enabling them to fit better into the tight confines of machinery. Welded cylinders do not suffer from failure due to tie rod stretch at high pressures and long strokes. The welded design also lends itself to customization. Special features are easily added to the cylinder body. These may include special ports, custom mounts, valve manifolds, and so on.

The smooth outer body of welded cylinders also enables the design of multi-stage telescopic cylinders.

Welded body hydraulic cylinders dominate the mobile hydraulic equipment market such as construction equipment (excavators, bulldozers, and road graders) and material handling equipment (forklift trucks, telehandlers, and lift-gates). They are also used in heavy industry such as cranes, oil rigs, and large off-road vehicles in above-ground mining.

Piston Rod construction

The piston rod of a hydraulic cylinder operates both inside and outside the barrel, and consequently both in and out of the hydraulic fluid and surrounding atmosphere.

Metallic coatings

Smooth and hard surfaces are desirable on the outer diameter of the piston rod and slide rings for proper sealing. Corrosion resistance is also advantageous. A chromium layer may often be applied on the outer surfaces of these parts. However, chromium layers may be porous, thereby attracting moisture and eventually causing oxidation. In harsh marine environments, the steel is often treated with both a nickel layer and a chromium layer. Often 40 to 150 micrometer thick layers are applied. Sometimes solid stainless steel rods are used. High quality stainless steel such as AISI 316 may be used for low stress applications. Other stainless steels such as AISI 431 may also be used where there are higher stresses, but lower corrosion concerns.

Ceramic coatings

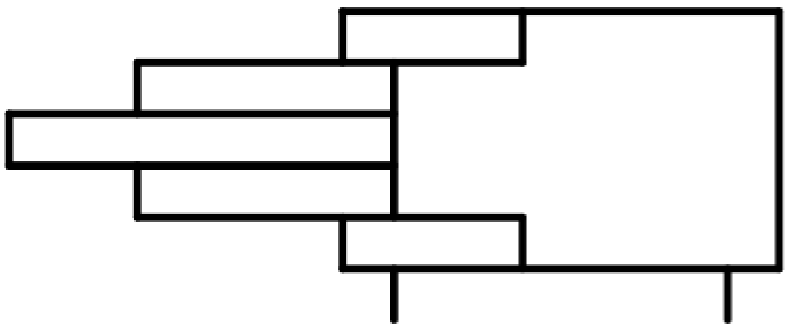
Due to shortcomings of metallic materials, ceramic coatings were developed. Initially ceramic protection schemes seemed ideal, but porosity was higher than projected. Recently the corrosion resistant semi ceramic Lunac 2+ coatings were introduced. These hard coatings are non porous and do not suffer from high brittleness.

Lengths

Piston rods are generally available in lengths which are cut to suit the application. As the common rods have a soft or mild steel core, their ends can be welded or machined for a screw thread.

Special hydraulic cylinders

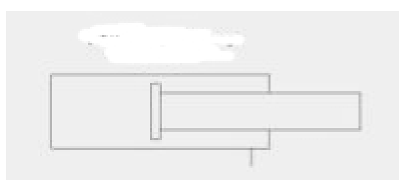
Telescopic cylinder



Telescopic cylinder (ISO 1219 symbol)

The length of a hydraulic cylinder is the total of the stroke, the thickness of the piston, the thickness of bottom and head and the length of the connections. Often this length does not fit in the machine. In that case the piston rod is also used as a piston barrel and a second piston rod is used. These kind of cylinders are called telescopic cylinders. If we call a normal rod cylinder single stage, telescopic cylinders are multi-stage units of two, three, four, five and even six stages. In general telescopic cylinders are much more expensive than normal cylinders. Most telescopic cylinders are single acting (push). Double acting telescopic cylinders must be specially designed and manufactured.

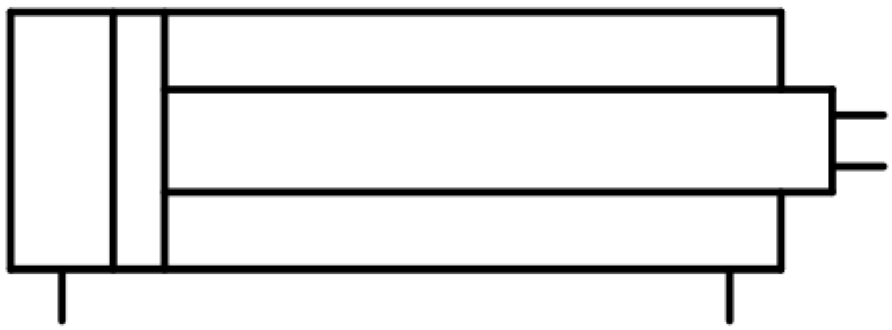
Plunger cylinder



Plunger cylinder

A hydraulic cylinder without a piston or with a piston without seals is called a plunger cylinder. A plunger cylinder can only be used as a pushing cylinder; the maximum force is piston rod area multiplied by pressure. This means that a plunger cylinder in general has a relatively thick piston rod.

Differential cylinder



Differential cylinder (ISO 1219 symbol)

A differential cylinder acts like a normal cylinder when pulling. If the cylinder however has to push, the oil from the piston rod side of the cylinder is not returned to the reservoir, but goes to the bottom side of the cylinder. In such a way, the cylinder goes much faster, but the maximum force the cylinder can give is like a plunger cylinder. A differential cylinder can be manufactured like a normal cylinder, and only a special control is added.

Rephasing cylinder

Rephasing cylinders are two or more cylinders plumbed in series or parallel, with the bores and rods sized such that all rods extend and/or retract equally when flow is directed to the first, or last, cylinder within the system.

In "parallel" applications, the bore and rod sizes are always the same, and the cylinders are always used in pairs. In "series" applications, the bore and rod sizes are always different, and two or more cylinders may be used. In these applications, the bores and rods are sized such that all rods extend or retract equally when flow is applied to the first or last cylinder within the system.

This hydraulic synchronization of rod positions eliminates the need for a flow divider in the hydraulic system, or any type of mechanical connection between the cylinder rods to achieve synchronization.

Position sensing "smart" hydraulic cylinder

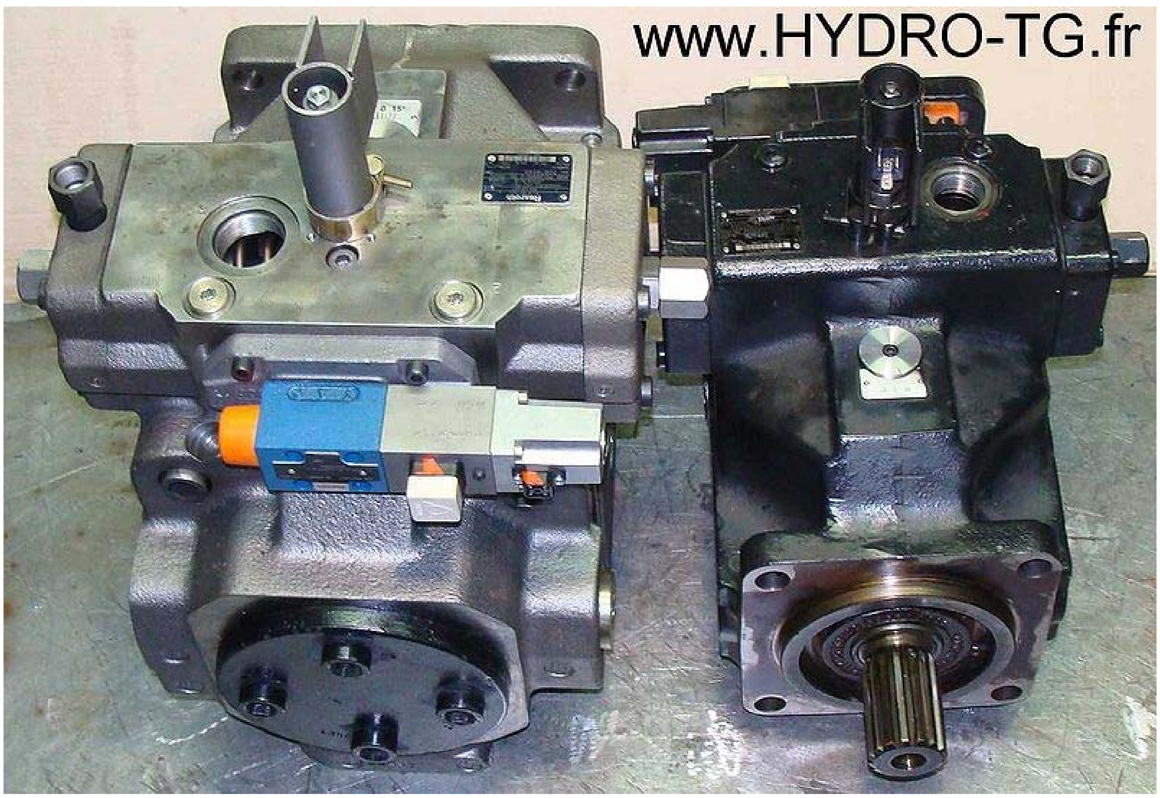
Position sensing hydraulic cylinders eliminate the need for a hollow cylinder rod. Instead, an external sensing “bar” utilizing Hall-Effect technology senses the position of the cylinder’s piston. This is accomplished by the placement of a permanent magnet within the piston. The magnet propagates a magnetic field through the steel wall of the cylinder, providing a locating signal to the sensor.

A note about popular terminology

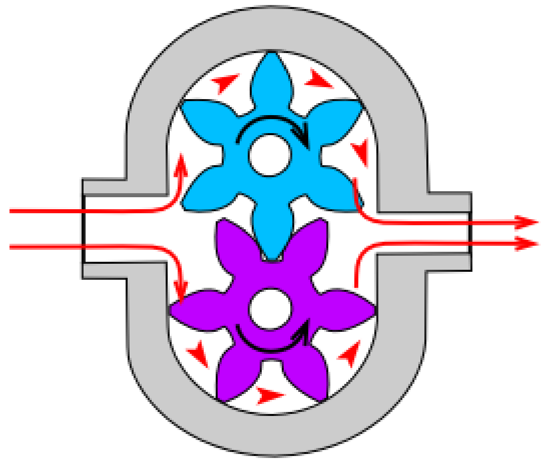
At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

Chapter 5

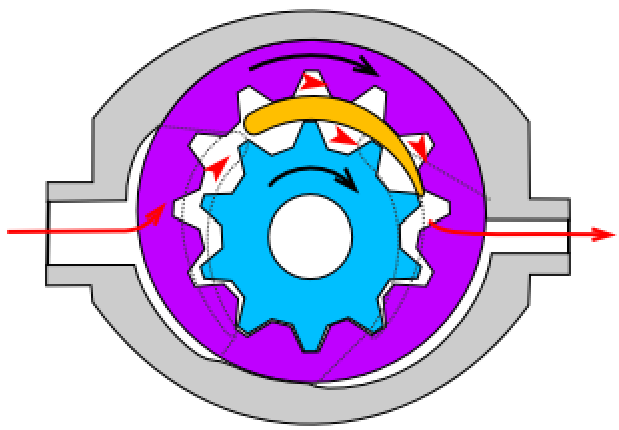
Hydraulic Pump



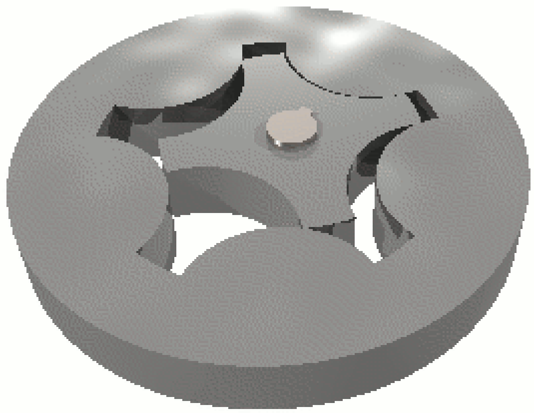
Hydraulic pump Rexroth A4VSO250



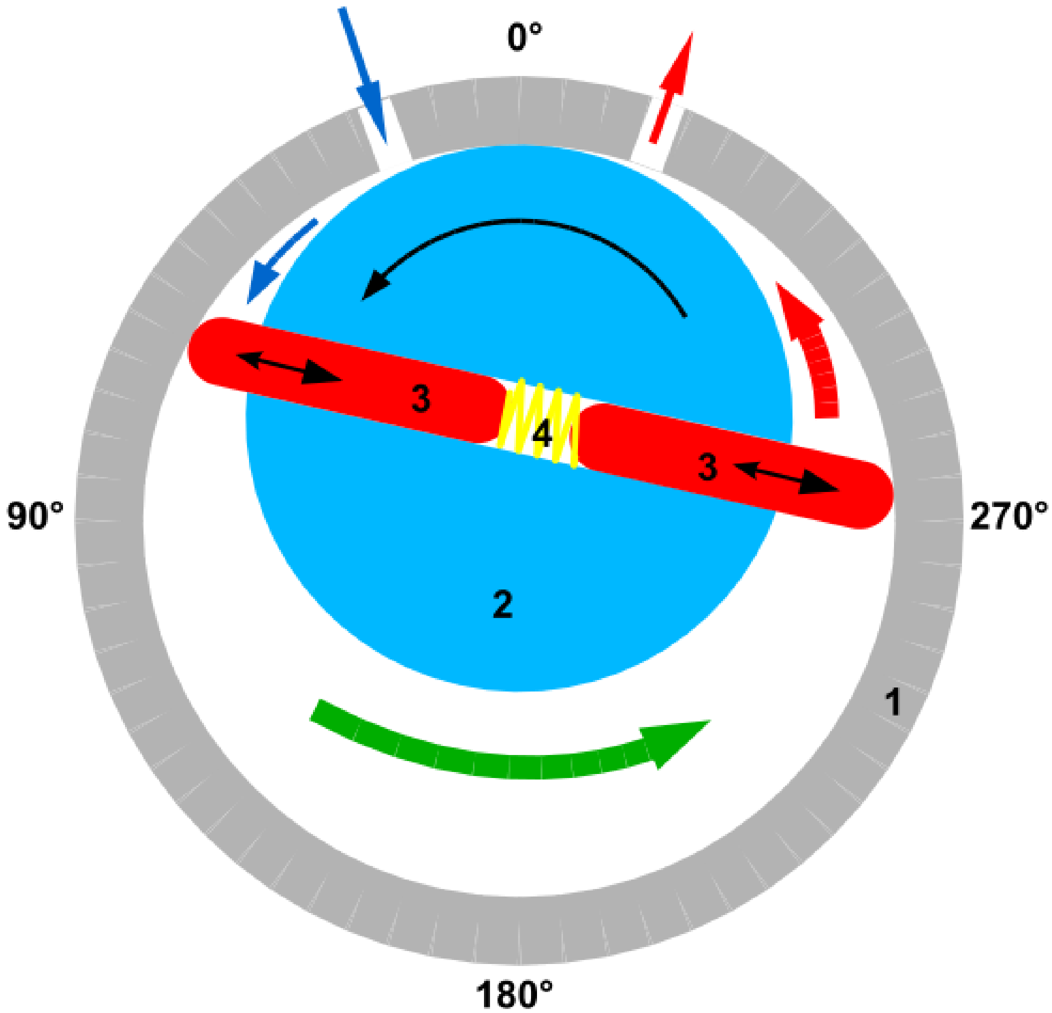
Gearpump with external teeth



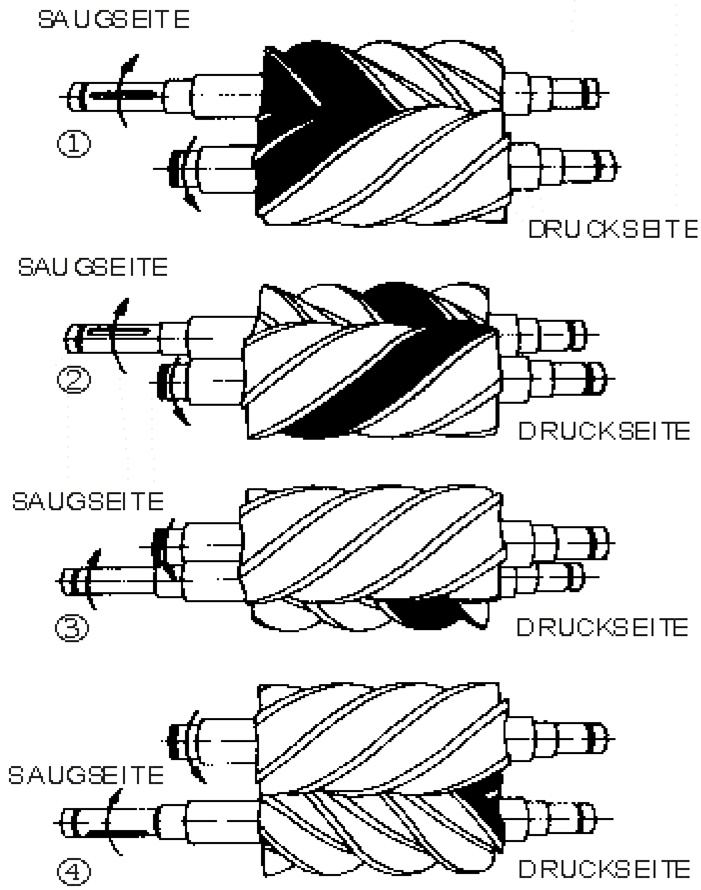
Gearpump with internal teeth



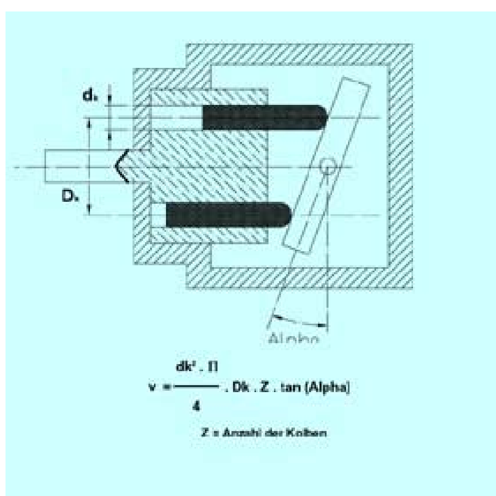
A gerotor (image does not show intake or exhaust)



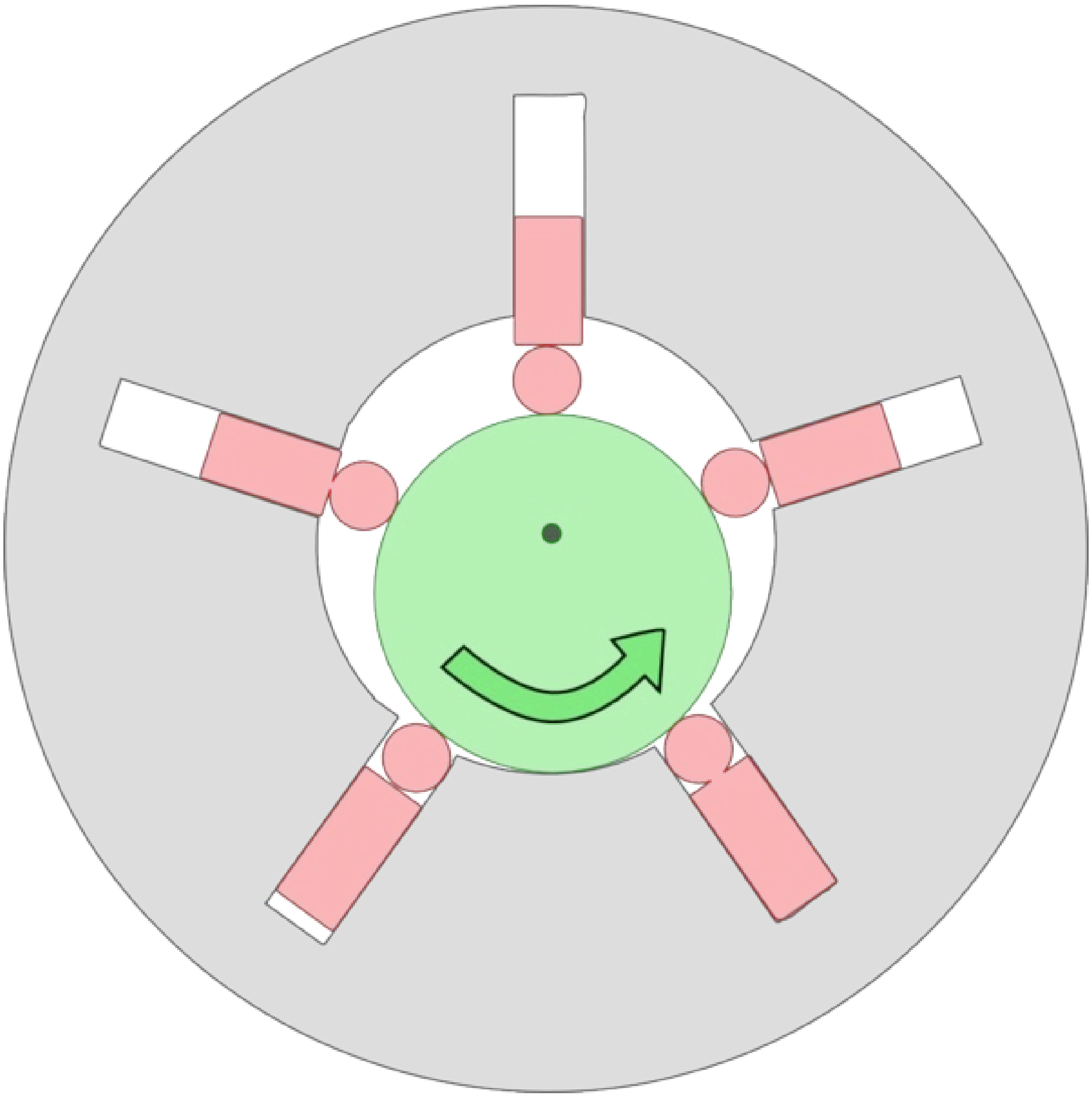
Fixed displacement vane pump



Principle of screw pump



Axial piston pump, swashplate principle



Radial piston pump

Hydraulic pumps are used in hydraulic drive systems and can be hydrostatic or hydrodynamic.

Hydrostatic pumps are positive displacement pumps while hydrodynamic pumps can be fixed displacement pumps, in which the displacement (flow through the pump per rotation of the pump) cannot be adjusted, or variable displacement pumps, which have a more complicated construction that allows the displacement to be adjusted.

Hydraulic pump types

Gear pumps

Gear pumps (with external teeth) (fixed displacement) are simple and economical pumps. The swept volume or displacement of gear pumps for hydraulics will be between about 1 cm^3 (0.001 litre) and 200 cm^3 (0.2 litre). These pumps create pressure through the meshing of the gear teeth, which forces fluid around the gears to pressurize the outlet side. Some gear pumps can be quite noisy, compared to other types, but modern gear pumps are highly reliable and much quieter than older models.

Rotary vane pumps

Rotary vane pumps (fixed and simple adjustable displacement) have higher efficiencies than gear pumps, but are also used for mid pressures up to 180 bars in general. Some types of vane pumps can change the centre of the vane body, so that a simple adjustable pump is obtained. These adjustable vane pumps are in general constant pressure or constant power pumps: the displacement is increased until the required pressure or power is reached and subsequently the displacement or swept volume is decreased until an equilibrium is reached.

Screw pumps

Screw pumps (fixed displacement) are a double Archimedes' screw, but closed. This means that two screws are used in one body. The pumps are used for high flows and relatively low pressure (max 100 bar). They were used on board ships where the constant pressure hydraulic system was going through the whole ship, especially for the control of ball valves, but also for the steering gear and help drive systems. The advantage of the screw pumps is the low sound level of these pumps; the efficiency is not that high.

Bent axis pumps

Bent axis pumps, axial piston pumps and motors using the bent axis principle, fixed or adjustable displacement, exists in two different basic designs. The Thoma-principle (engineer Hans Thoma, Germany, patent 1935) with max 25 degrees angle and the Wahlmark-principle (Gunnar Axel Wahlmark, patent 1960) with spherical-shaped pistons in one piece with the piston rod, piston rings, and maximum 40 degrees between the driveshaft centerline and pistons (Volvo Hydraulics Co.). These have the best efficiency of all pumps. Although in general the largest displacements are approximately one litre per revolution, if necessary a two-liter swept volume pump can be built. Often variable-displacement pumps are used, so that the oil flow can be adjusted carefully. These pumps can in general work with a working pressure of up to 350–420 bars in continuous work.

Axial piston pumps swashplate principle

Axial piston pumps using the swashplate principle (fixed and adjustable displacement) have a quality that is almost the same as the bent axis model. They have the advantage of being more compact in design. The pumps are easier and more economical to manufacture; the disadvantage is that they are more sensitive to oil contamination.

Radial piston pumps

Radial piston pumps (fixed displacement) are used especially for high pressure and relatively small flows. Pressures of up to 650 bar are normal. In fact variable displacement is not possible, but sometimes the pump is designed in such a way that the plungers can be switched off one by one, so that a sort of variable displacement pump is obtained.

Peristaltic pumps

Peristaltic pumps are not generally used for high pressures.

Pumps for open and closed systems

Most pumps are working in open systems. The pump draws oil from a reservoir at atmospheric pressure. It is very important that there is no cavitation at the suction side of the pump. For this reason the connection of the suction side of the pump is larger in diameter than the connection of the pressure side. In case of the use of multi-pump assemblies, the suction connection of the pump is often combined. It is preferred to have free flow to the pump (pressure at inlet of pump at least 0.8 bars). The body of the pump is often in open connection with the suction side of the pump.

In case of a closed system, both sides of the pump can be at high pressure. The reservoir is often pressurized with 6-20 bars boost pressure. For closed loop systems, normally axial piston pumps are used. Because both sides are pressurized, the body of the pump needs a separate leakage connection.

Multi pump assembly

In a hydraulic installation, one pump can serve more cylinders and motors. The problem however is that in that case a constant pressure system is required and the system always needs the full power. It is more economic to give each cylinder and motor its own pump. In that case multi pump assemblies can be used. Gearpumps can often be obtained as multi pumps. The different chambers (sometimes of different size) are mounted in one body or built together. Also vane pumps can often be obtained as a multi pump. Gerotor pumps are often supplied as multi pumps. Screw pumps can be built together with a gear pump or a vane pump. Axial piston swashplate pumps can be built together with a second pump of the same or smaller size, or can be built together with one or more gear pumps or vane pumps (depending on the supplier). Axial plunger pumps of the bent axis design can not be built together with other pumps.

Hydraulic pumps, calculation formulas

Flow

Q = n * Vstroke *η vol
Q = Flow in m^3/s
n = revs per second
Vstroke = swept volume in m3
η volume is volumetric efficiency

Power

P = n * Vstroke * Δp / ηmech,hydr
P = Power in Watt (Nm/s)
n = revs per second.
Vstroke = swept volume in m^3
Δp = pressure difference over pump in N/m^2
ηmech,hydr = mechanical/hydraulic efficiency

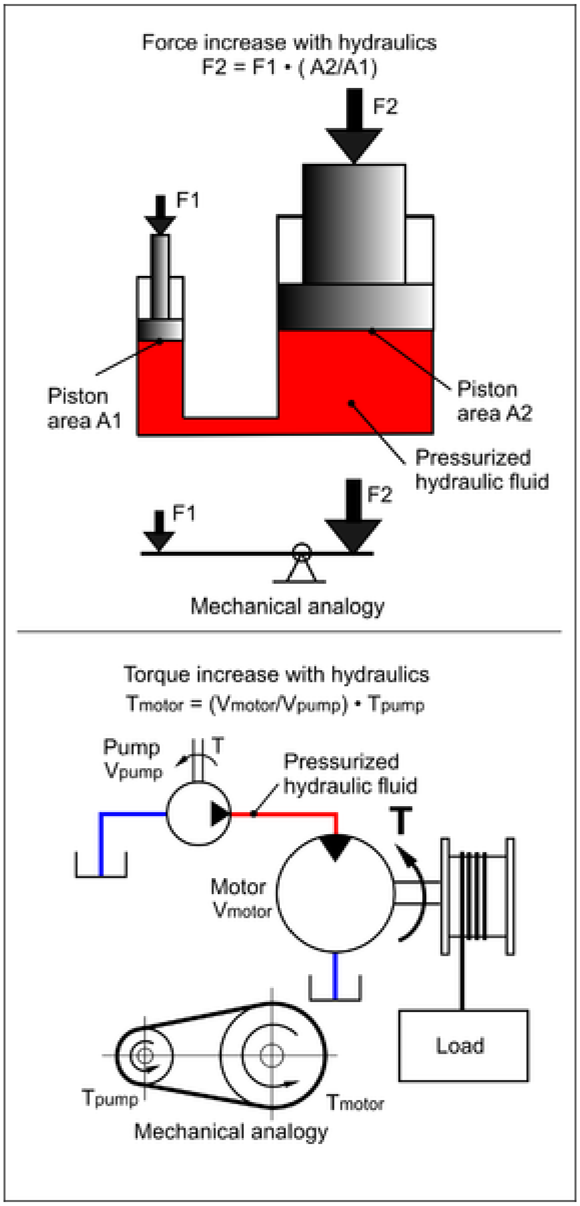
Chapter 6

Hydraulic Drive System

A **hydraulic drive system** is a drive or transmission system that uses pressurized hydraulic fluid to drive hydraulic machinery. The term hydrostatic refers to the transfer of energy from flow and pressure, not from the kinetic energy of the flow.

A hydraulic drive system consists of three parts: The generator (e.g. a hydraulic pump), driven by an electric motor, a combustion engine or a windmill; valves, filters, piping etc. (to guide and control the system); the motor (e.g. a hydraulic motor or hydraulic cylinder) to drive the machinery.

Principle of a hydraulic drive



Principle of hydraulic drive system

Pascal law is the basis of hydraulic drive systems. As the pressure in the system is the same, the force that the fluid gives to the surroundings is therefore equal to pressure x area. In such a way, a small piston feels a small force and a large piston feels a large force.

The same principle applies for a hydraulic pump with a small swept volume that asks for a small torque, combined with a hydraulic motor with a large swept volume that gives a large torque. In such a way a transmission with a certain ratio can be built.

Most hydraulic drive systems make use of hydraulic cylinders. Here the same principle is used- a small torque can be transmitted in to a large force.

By throttling the fluid between the generator part and the motor part, or by using hydraulic pumps and/or motors with adjustable swept volume, the ratio of the transmission can be changed easily. In case throttling is used, the efficiency of the transmission is limited. In case adjustable pumps and motors are used, the efficiency, however, is very large. In fact, up to around 1980, a hydraulic drive system had hardly any competition from other adjustable drive systems.

Nowadays, electric drive systems using electric servo-motors can be controlled in an excellent way and can easily compete with rotating hydraulic drive systems. Hydraulic cylinders are, in fact, without competition for linear forces. For these cylinders, hydraulic systems will remain of interest and if such a system is available, it is easy and logical to use this system for the rotating drives of the cooling systems, also.

Hydraulic cylinder

Hydraulic cylinders (also called linear hydraulic motors) are mechanical actuators that are used to Maintaining a Hydraulic System give a linear force through a linear stroke. Hydraulic cylinders are able to give pushing and pulling forces of millions of metric tons with only a simple hydraulic system. Very simple hydraulic cylinders are used in presses; here, the cylinder consists of a volume in a piece of iron with a plunger pushed in it and sealed with a cover. By pumping hydraulic fluid in the volume, the plunger is pushed out with a force of plunger-area pressure.

More sophisticated cylinders have a body with end cover, a piston rod, and a cylinder head. At one side the bottom is, for instance, connected to a single clevis, whereas at the other side, the piston rod is also foreseen with a single clevis. The cylinder shell normally has hydraulic connections at both sides; that is, a connection at the bottom side and a connection at the cylinder head side. If oil is pushed under the piston, the piston rod is pushed out and oil that was between the piston and the cylinder head is pushed back to the oil tank.

The pushing or pulling force of a hydraulic cylinder is as follows:

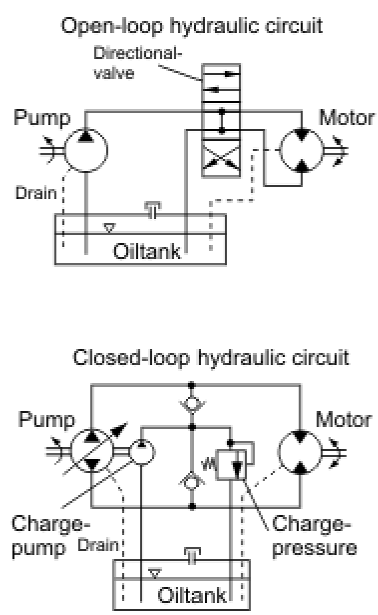
$F = Ab * pb - Ah * ph$
F = Pushing Force in N
$Ab = (\pi/4) * (\text{Bottom-diameter})^2$ [in m2]
$Ah = (\pi/4) * ((\text{Bottom-diameter})^2-(\text{Piston-rod-diameter})^2))$ [in m2]
pb = pressure at bottom side in [N/m2]
ph = pressure at cylinder head side in [N/m2]

Apart from miniature cylinders, in general, the smallest cylinder diameter is 32 mm and the smallest piston rod diameter is 16 mm.

Simple hydraulic cylinders have a maximum working pressure of about 70 bar. The next step is 140 bar, 210 bar, 320/350 bar and further. In general, the cylinders are custom built. The stroke of a hydraulic cylinder is limited by the manufacturing process. The majority of hydraulic cylinders have a stroke between 0, 3, and 5 meters, whereas 12-15 meter stroke is also possible, but for this length only a limited number of suppliers are on the market.

In case the retracted length of the cylinder is too long for the cylinder to be built in the structure, telescopic cylinders can be used. One has to realize that for simple pushing applications telescopic cylinders might be easily available; for higher forces and/or double acting cylinders, they must be designed especially and are very expensive. If hydraulic cylinders are only used for pushing and the piston rod is brought in again by other means, one can also use plunger cylinders. Plunger cylinders have no sealing over the piston, if the cylinder even exists. This means that only one oil connection is necessary. In general the diameter of the plunger is rather large compared with a normal piston cylinder, whereas a hydraulic motor will always leak oil. A hydraulic cylinder does not have a leakage over the piston nor over the cylinder head sealing so that there is no need for a mechanical brake.

Hydraulic motor



Principal circuit diagram for **open loop** and **closed loop** system.

The hydraulic motor is the rotary counterpart of the hydraulic cylinder. Conceptually, a hydraulic motor should be interchangeable with the hydraulic pump, due to the fact it performs the opposite function. However, most hydraulic pumps cannot be used as hydraulic motors because they cannot be backdriven. Also, a hydraulic motor is usually designed for the working pressure at both sides of the motor. Another difference is that a motor can be reversed by a reversing valve.

Another factor affecting the operation of hydraulic motors is fluid flow rate. Pressure in a hydraulic system is like the voltage in an electrical system and fluid flow rate is the equivalent of current. Pressure provides the force and flow rate of the speed. The size of the pump decides the flow rate, not just the pressure.

Hydraulic valves

These valves are usually very heavy duty to stand up to high pressures. Some special valves can control the direction of the flow of fluid and act as a control unit for a system.

Open and closed systems

An open system is one where the hydraulic fluid is returned into a large, unpressurized tank at the end of a cycle through the system. In contrast, a closed system is where the hydraulic fluid stays in one closed pressurized loop without returning to a main tank after each cycle.

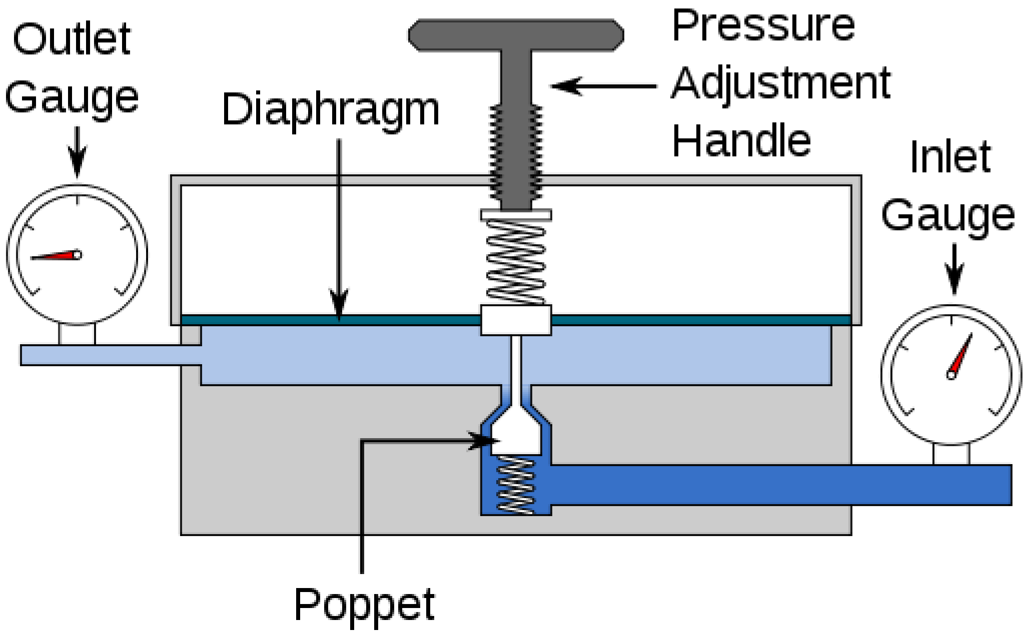
Chapter 7

Pressure Regulator

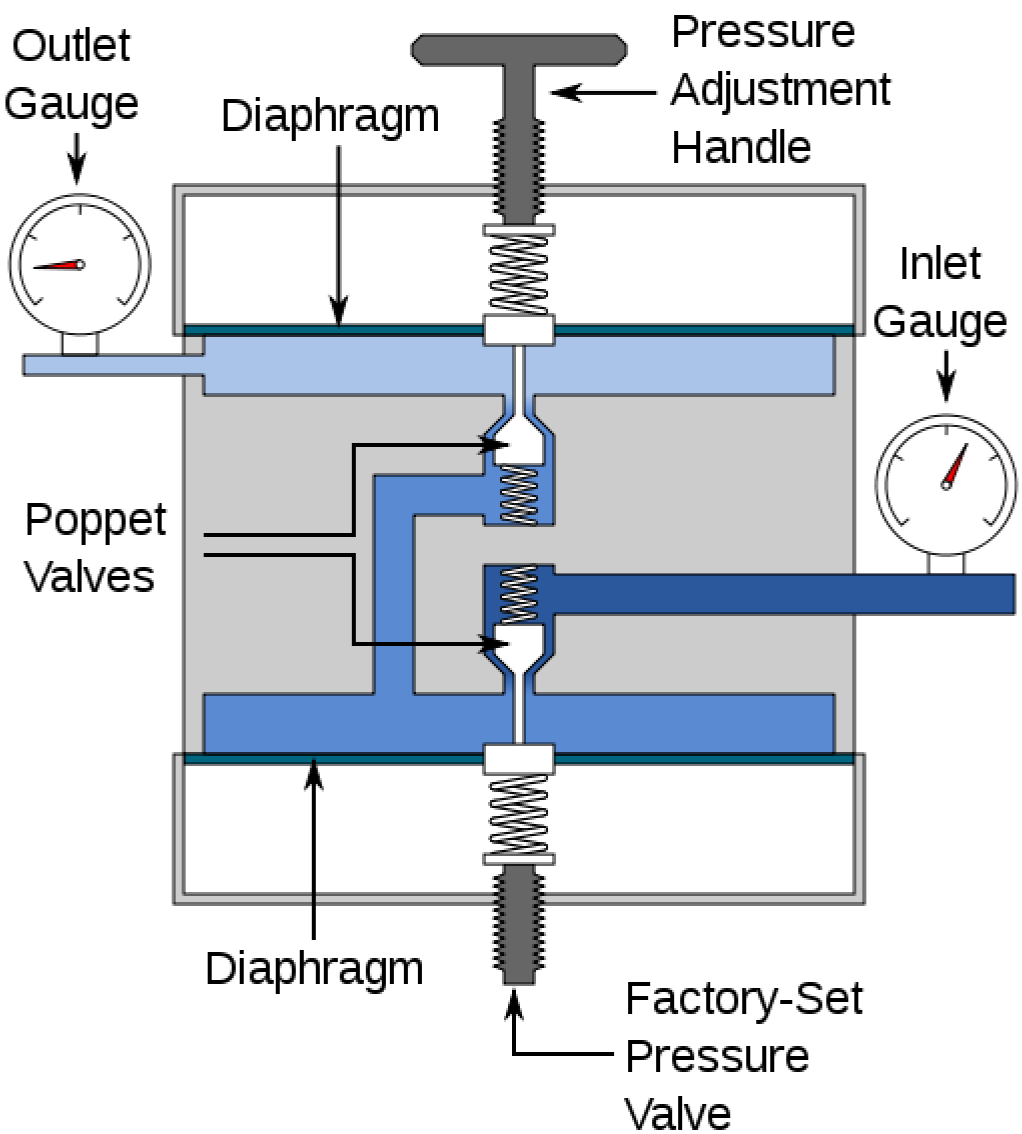
Oxygen and MAPP gas cylinders with two-stage pressure regulators

A **pressure regulator** is a valve that automatically cuts off the flow of a liquid or gas at a certain pressure. Regulators are used to allow high-pressure fluid supply lines or tanks to be reduced to safe and/or usable pressures for various applications.

Operation



Single-stage pressure regulator



Two-stage pressure regulator

A pressure regulator's primary function is to match the flow of gas through the regulator to the demand for gas placed upon the system. If the load flow decreases, then the regulator flow must decrease also. If the load flow increases, then the regulator flow must increase in order to keep the controlled pressure from decreasing due to a shortage of gas in the pressure system.

A pressure regulator includes a *restricting element*, a *loading element*, and a *measuring element*:

- The restricting element is a type of valve. It can be a globe valve, butterfly valve, poppet valve, or any other type of valve that is capable of operating as a variable restriction to the flow.

- The loading element applies the needed force to the restricting element. It can be any number of things such as a weight, a spring, a piston actuator, or more commonly the diaphragm actuator in combination with a spring.
- When the actuator is forced against an expansion disk, the force is distributed among the pressure walls. This allows the gas to flow at the proper rate and not to be continually vaporized and diluted.
- The measuring element determines when the inlet flow is equal to the outlet flow. The diaphragm is often used as a measuring element because it can also serve as a combine element.

In the pictured single-stage regulator, a diaphragm is used with a poppet valve to regulate pressure. As pressure in the upper chamber increases, the diaphragm is pushed upward, causing the poppet to reduce flow, bringing the pressure back down. By adjusting the top screw, the downward pressure on the diaphragm can be increased, requiring more pressure in the upper chamber to maintain equilibrium. In this way, the outlet pressure of the regulator is controlled.

Applications

Water pressure reduction

Often, water enters water-using appliances at fluctuating pressures, especially in remote locations, and industrial settings. This pressure often needs to be kept within a range to avoid damage to appliances, or accidents involving burst pipes/conduits. A single-stage regulator is sufficient in accuracy due to the high error tolerance of most such appliances.

Oxy-fuel welding and cutting

Oxy-fuel welding and cutting processes require gases at specific pressures, and regulators will generally be used to reduce the high pressures of storage cylinders to those usable for cutting and welding. Oxy-gas regulators usually have two stages: The first stage of the regulator releases the gas at a constant rate from the cylinder despite the pressure in the cylinder becoming less as the gas in the cylinder is used, as in the first stage of a scuba-diving regulator. The second stage of the regulator controls the pressure reduction from the intermediate pressure to low pressure. It is constant flow. The valve assembly has two pressure gauges, one indicating cylinder pressure, the other indicating hose pressure.

Propane/LP Gas

All propane and LP Gas applications require the use of a regulator. Because pressures in propane tanks can fluctuate significantly, regulators must be present to deliver a steady flow pressure to downstream appliances. These regulators normally compensate for tank pressures in from as little as 30psig to in excess of 200psig and commonly deliver 11 inches water column for residential applications and 35 inches of water column, (27.7 inches of water column equals 1 pound per square inch), for industrial applications. Propane regulators differ in size and shape, delivery pressure and adjust-ability but are uniform in their purpose to deliver a constant outlet pressure for downstream requirements. As is the case in all regulators, outlet pressure is lower than inlet pressure.

Recreational vehicles

For recreational vehicles with plumbing, a pressure regulator is a necessity. When camping, a source of water may have an enormous pressure level, particularly if it comes from a tank that is at a much higher elevation than the campground. Water pressure is dependent on how far the water must fall. Without a pressure regulator, the intense pressure encountered at some campgrounds in mountainous areas may be enough to burst the camper's water pipes or unseat the plumbing joints, causing flooding. Pressure regulators for this purpose are typically sold as small screw-on accessories that fit inline with the hoses used to connect an RV to the water supply, which are almost always screw-thread-compatible with the common garden hose.

Breathable air supply

Pressure regulators are used with air tanks used for breathing during SCUBA diving. The tank may contain pressures well in excess of 2000 PSI, which could cause a fatal barotrauma injury to a person breathing it directly. A regulator allows only a sustained flow of air at the ambient pressure (which varies by depth in the water).

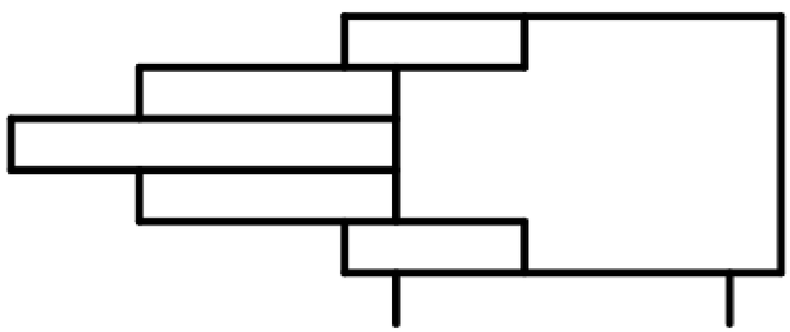
Mining Industry

As the pressure builds rapidly in relation to depth, underground mining operations require a fairly complex water system with pressure reducing valves. These devices must be installed at a certain distance interval, usually 600 feet. Without such valves, pipes would easily burst and pressure would be too great for equipment operation.

Chapter 8

Telescopic Cylinder

Telescopic cylinders are a special design of hydraulic cylinder that provide an exceptionally long output travel from a very compact retracted length. Typically the collapsed length of a telescopic cylinder is 20 to 40% of the fully extended length depending on the number of stages. This feature is very attractive to machine design engineers when a conventional single stage rod style actuator will not fit in an application to produce the required output stroke.



Telescopic cylinder (ISO 1219 symbol)

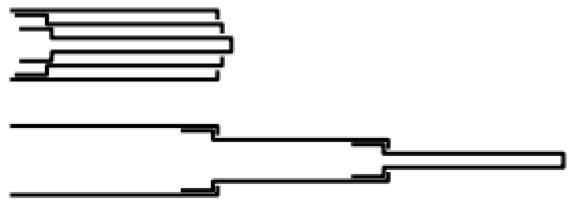
Telescopic cylinders are usually powered by hydraulics but some special light duty designs are powered by compressed air.

Telescopic cylinders are also referred to as telescoping cylinders and multi-stage telescopic cylinders.

An application for telescopic cylinders commonly seen is that of the dump body on a dump truck used in a construction site. In order to empty the load of gravel completely, the dump body must be raised to an angle of about 60 degrees. To accomplish this long travel with a conventional hydraulic cylinder is very difficult considering that the collapsed length of a single stage rod cylinder is approximately 110% of its output stroke.

It would be very challenging for the design engineer to fit the single stage cylinder into the chassis of the dump truck with the dump body in the horizontal rest position. This task is easily accomplished, however, using a telescopic style multi-stage cylinder.

Design and Technical Terminology



Showing the telescopic principle, an object collapsed (top) and extended (bottom), providing more reach.

Telescopic cylinders are designed with a series of steel tubes of progressively smaller diameters nested within each other. The largest diameter sleeve is called the main or barrel. The smaller inner sleeves are called the stages. The smallest stage is often called the plunger.

The cylinders are usually mounted in machinery by pivot mounts welded to the end or outer body of the barrel as well as on the end of the plunger.

Telescopic cylinders can be built with as many as 6 stages. Six stages seems to be the practical design limit as stability problems become more difficult with larger numbers of stages. Telescopic cylinders require careful design as they are subjected to large side forces especially at full extension. The weight of the steel bodies and the hydraulic oil contained within the actuator create moment loads on the bearing surfaces between stages. These forces, combined with the load being pushed, threaten to bind or even buckle the telescopic assembly. Sufficient bearing surfaces must therefore be incorporated in the design of the actuator to prevent failure in service due to side forces. Telescopic cylinders must only be used in machinery as a device for providing force and travel. Side forces and moment loads must be minimized. Telescopic cylinders should not be used to stabilize a structural component.

Telescopic cylinders are often limited to a maximum hydraulic pressure of 2000 psi. This is because the outward forces produced by internal hydraulic pressure tends to expand the steel sleeve sections. Too much pressure will cause the nested sleeves to balloon outward, bind the mechanism and stop moving. The danger exists that a permanent deformation of the outer diameter of a sleeve could occur, thus ruining a telescopic actuator. For this reason, care must be taken to avoid shock pressures in a hydraulic system using telescopic cylinders. Often such hydraulic systems are equipped with shock suppressing components, such as hydraulic accumulators, to absorb pressure spikes.

Basic Design Types of Telescopic Cylinders

Telescopic cylinders can usually be classified into two basic designs: single acting and double acting. A number of other special designs also exist including a hybrid single/double acting design, and a constant speed, constant thrust design.

Single Acting

Single acting telescopic cylinders are the simplest and most common design. As with a single acting rod style cylinder, the single acting telescopic cylinder is extended using hydraulic pressure but retracts using external forces when the hydraulic pressure is removed and relieved to the reservoir. This external retraction force is usually gravity acting on the weight of the load. This external weight must obviously be sufficient to overcome the friction and mechanical losses within the machine design even after the work portion of the machine cycle has been accomplished. In the example above of the dump truck, the weight of the dump body, now raised at an angle of 60 degrees but empty of the load, must be enough to force the unpressurized hydraulic fluid out of the cylinder and cause it to retract to the fully collapsed position.

'Spider' set up outside a building. This aerial platform vehicle uses a telescopic hydraulic cylinder to extend the platform

Double Acting

A double acting cylinder is extended and retracted using hydraulic pressure in both directions. Double acting telescopic cylinders are thus much more complex in design than the single acting type. This additional complexity is due to the requirement of adding retracting piston faces to all of the cylinder stages and the difficulty in supplying pressurized fluid to the retraction pistons of the intermediate stages.

To accomplish the double acting feature, additional hydraulic seals are added to internally seal off the individual stages. In addition, internal oil passageways are machined so that as each stage completes retracting, an oil passage is open to supply the next stage with pressurized fluid to retract. Thus a double acting telescopic actuator usually retracts starting from the smallest diameter stage to finish with the largest stage retracting lastly. Because the seals used to accomplish this must pass over these internally machined fluid transfer holes, the seals are usually made from hard materials to resist wear and abrasion. They are often iron rings or glass reinforced nylon seals.

The extension and retraction fluid supply ports on double acting telescopic cylinders are usually located at opposite ends of the cylinder assembly. The extension port is mounted at the base of the outer barrel and the retraction port is mounted in the end of the plunger section. This can, in some applications, prove to be very difficult to connect with hydraulic hoses due to the distance between these ports at full extension. In such a circumstance, both ports can be located in the barrel. An internal passageway must be fitted, however, so that the retracting fluid is supplied to the plunger section at full extension. This special passageway is in itself a telescopic assembly that extends with the cylinder and is outfitted with seals on the various stages.

This additional complexity makes double acting telescopic cylinders very expensive. They are usually custom designed for each application.

Typical applications for double acting telescopic cylinders include the packer-ejector cylinders in garbage trucks and transfer trailers, horizontal compactors, telescopic excavator shovels, and roll-on/roll-off trucks. In all of these applications, the cylinder operates near horizontally and thus gravity is not available to retract the actuator. A double acting design is therefore required to both push and pull the telescoping mechanism.

Care must be taken when controlling most double acting telescopic design cylinders. The effective retraction area is often much less than the extension area. Thus if the hydraulic fluid return line is blocked during extension a pressure intensifying effect can occur causing seal failure or even causing the metal sleeve to balloon outward. The cylinder could thus be rendered unable to retract because of failed seals or jam in position due to binding.

Another problem can occur if a double acting telescopic cylinder encounters a load that pulls on the actuator during extension such as when a tilting load goes over center and opens the cylinder beyond the internal volume of the hydraulic oil. When the piston face catches up again and strikes the oil column a pressure spike occurs which can damage the actuator.

Single/Double Acting Combination

In some unique applications, a single acting telescopic cylinder is adequate to accomplish the work except for one stage that is required to be double acting.

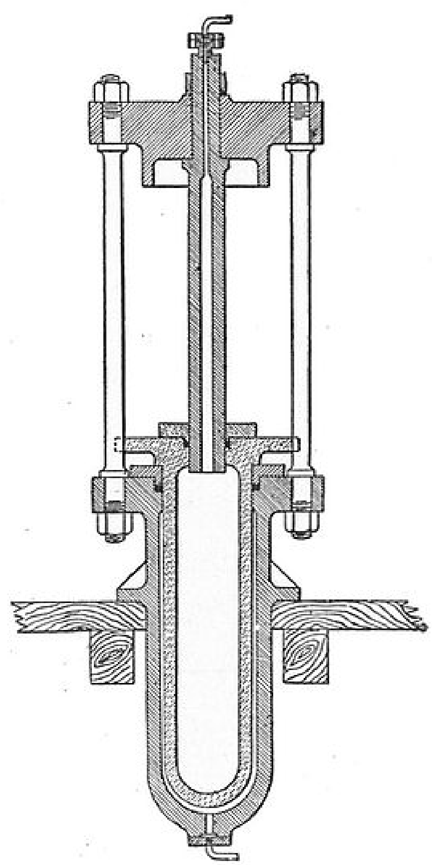
An example of this is erecting the mast of a large mobile drilling rig. The mast is erected to the vertical position using a telescopic cylinder. However, to lower the mast, gravity is not available for the initial tilt back from the vertical position. Thus, the plunger stage only of the telescopic actuator is equipped as a double acting cylinder to provide the initial force to pull the mast back from vertical. Once the tilt back has been initiated, then gravity takes over and supplies the force to complete the full cylinder retraction. The remaining stages, therefore, are single acting. This special combination is much less complex and much less costly than using an entirely double acting design.

Constant Thrust, Constant Speed

In some special applications, a telescopic cylinder is required to extend with a constant force or constant speed. To accomplish this the cylinder is designed so that all the stages extend at the same time. This can also be accomplished in a double acting design by matching the extension and retraction areas of the pistons on all the stages.

Chapter 9

Hydraulic Intensifier



Concentric cylinder hydraulic intensifier, from Kennedy, *Modern Engines*

A **hydraulic intensifier** is a hydraulic machine for transforming hydraulic power at low pressure into a reduced volume at higher pressure.

Such a machine may be constructed by mechanically connecting two pistons, each working in a separate cylinder of a different diameter. As the pistons are mechanically linked, their force and stroke length are the same. If the diameters are different, the hydraulic pressure in each cylinder will vary in the same ratio as their areas: the smaller piston giving rise to a higher pressure. As the pressure is inversely proportional to the area, it will be inversely proportional to the *square* of the diameter.

The working volume of the intensifier is limited by the stroke of the piston. This in turn limits the amount of work that may be done by one stroke of the intensifier. These are not reciprocating machines (i.e. continually running multi-stroke machines) and so their entire work must be carried out by a single stroke. This limits their usefulness somewhat, to machines that can accomplish their task within a single stroke. They are often used where a powerful hydraulic jack is required, but there is insufficient space to fit the cylinder size that would normally be required, for the lifting force necessary and with the available system pressure. Using an intensifier, mounted outside the jack, allows a higher pressure to be obtained and thus a smaller cylinder used for the same lift force. Intensifiers are also used as part of machines such as hydraulic presses, where a higher pressure is required and a suitable supply is already available.

Some small intensifiers have been constructed with a stepped piston. This is a double-ended piston, of two different diameters, each end working in a different cylinder. This construction is simple and compact, requiring an overall length little more than twice the stroke. It is also still necessary to provide two seals, one for each piston, and to vent the area between them. A leak of pressure into the volume between the pistons would transform the machine into an effective single piston with equal area on each side, thus defeating the intensifier effect.

A mechanically compact and popular form of intensifier is the concentric cylinder form, as illustrated. In this design, one piston and cylinder are reversed: instead of the large diameter piston driving a smaller piston, it instead drives a smaller moving cylinder that fits over a fixed piston. This design is compact, and again may be made in little over twice the stroke. It has the great advantage though that there is no "piston rod" and the effective distance between the two pistons is short, thus permitting a much lighter construction without risk of bending or jamming.

In the example illustrated, the two pistons are approximately 1:2 ratio in diameter, giving a 1:4 increase in pressure. Note that it is the diameter of the effective piston, i.e. the seal diameter that matters. The cylinders here are relieved beyond the seal and are of greater diameter, for easy running. Although the moving cylinder's bore is around ¾ of the outer diameter, not ½, it is its seal diameter that matters, not its internal clearance bore.

The celebrated mechanical engineer Harry Ricardo began his career by working in his grandfather, Alexander Rendel's, civil engineering practice. At the time they were involved in the construction of bridges in India, which required hydraulic lifting, hoisting and riveting equipment. As the existing transport infrastructure was poor, all plant used on site needed to be lightweight and easily portable. Machines also needed to be connected to their hydraulic power source by flexible tubing, which limited their working pressure to around 500 psi. At this time, modern shipyard equipment was using pressures of up to 2000 psi. This high-pressure equipment was smaller and lighter than the bulkier low-pressure variety, a desirable feature for this construction work. Ricardo's innovation was to specify the use of portable hydraulic intensifiers for these tools, permitting the use of the improved high-pressure form, even where their supply was at low-pressure, through flexible hose. These intensifiers were so successful that eventually several hundred were supplied and used.

Chapter 10

Water Hammer

Water hammer (or, more generally, **fluid hammer**) is a pressure surge or wave resulting when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). Water hammer commonly occurs when a valve is closed suddenly at an end of a pipeline system, and a pressure wave propagates in the pipe. It may also be known as *hydraulic shock*.

This pressure wave can cause major problems, from noise and vibration to pipe collapse. It is possible to reduce the effects of the water hammer pulses with accumulators and other features.

Rough calculations can be made either using the Joukowsky equation, or more accurate ones using the method of characteristics.

Cause and effect

If the pipe is suddenly closed at the outlet (downstream), the mass of water before the closure is still moving forward with some velocity, building up a high pressure and shock waves. In domestic plumbing this is experienced as a loud banging resembling a hammering noise. Water hammer can cause pipelines to break if the pressure is high enough. Air traps or stand pipes (open at the top) are sometimes added as dampers to water systems to provide a cushion to absorb the force of moving water in order to prevent damage to the system. (At some hydroelectric generating stations what appears to be a water tower is actually one of these devices, known as a surge drum).

In the home, water hammer may occur when a dishwasher, washing machine, or toilet shuts off water flow. The result may be heard as a loud bang, repetitive banging (as the shock wave travels back and forth in the plumbing system), or as some shuddering.

On the other hand, when an upstream valve in a pipe is closed, the water downstream of the valve will attempt to continue flowing, creating a vacuum that may cause the pipe to collapse or implode. This problem can be particularly acute if the pipe is on a downhill slope. To prevent this, air and vacuum relief valves, or air vents, are installed just downstream of the valve to allow air to enter the line and prevent this vacuum from occurring.

Other causes of water hammer are pump failure, and check valve slam (due to sudden deceleration, a check valve may slam shut rapidly, depending on the dynamic characteristic of the check valve and the mass of the water between a check valve and tank).

Related phenomena

Expansion joints on a steam line that have been destroyed by steam hammer

Steam distribution systems may also be vulnerable to a situation similar to water hammer, known as *steam hammer*. In a steam system, water hammer most often occurs when some of the steam condenses into water in a horizontal section of the steam piping. Subsequently, steam picks up the water, forms a "slug" and hurls it at high velocity into a pipe fitting, creating a loud hammering noise and greatly stressing the pipe. This condition is usually caused by a poor condensate drainage strategy.

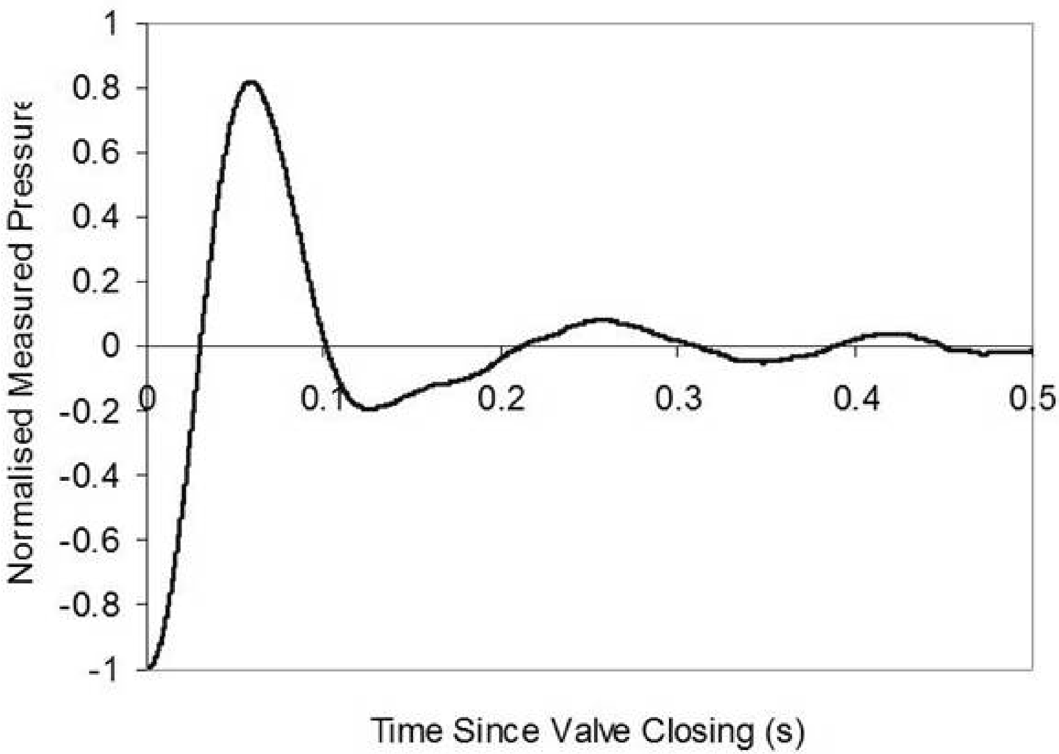
Where air filled traps are used, these eventually become depleted of their trapped air over a long period of time through absorption into the water. This can be cured by shutting off the supply, opening taps at the highest and lowest locations to drain the system (thereby restoring air to the traps), and then closing the taps and re-opening the supply.

Mitigating measures

Water hammer has caused accidents and fatalities, but usually damage is limited to breakage of pipes or appendages. An engineer should always assess (at least qualitatively) risk of a pipeline burst. Pipelines with hazardous goods should always receive special attention and should be thoroughly investigated.

The following characteristics may reduce or eliminate water hammer:

- Reduce pressure at rising main stopcock.
- Lower fluid velocities. To keep water hammer low, pipe-sizing charts for some applications recommend flow velocity at or below 5 ft/s (1.5 m/s).
- Fit slowly-closing valves. Toilet flush valves are available in a quiet flush type that closes quietly.
- High pipeline pressure rating (expensive).
- Good pipeline control (start-up and shut-down procedures).
- Water towers (used in many drinking water systems) help maintain steady flow rates and trap large pressure fluctuations.
- Air vessels work in much the same way as water towers, but are pressurized. They typically have an air cushion above the fluid level in the vessel, which may be regulated or separated by a bladder. Sizes of air vessels may be up to hundreds of cubic meters on large pipelines. They come in many shapes, sizes and configurations. Such vessels often are called accumulators or expansion tanks.
- A hydropneumatic device similar in principle to a shock absorber called a 'Water Hammer Arrestor' can be installed between the water pipe and the machine which will absorb the shock and stop the banging.
- Air valves are often used to remediate low pressures at high points in the pipeline. Though effective, sometimes large numbers of air valves need be installed. These valves also allow air into the system, which is often unwanted.
- Shorter branch pipe lengths.
- Shorter lengths of straight pipe, i.e. add elbows, expansion loops. Water hammer is related to the speed of sound in the fluid, and elbows reduce the influences of pressure waves.
- Arranging the larger piping in loops that supply shorter smaller run-out pipe branches. With looped piping, lower velocity flows from both sides of a loop can serve a branch.
- Flywheel on pump.
- Pumping station bypass.
- Hydroelectric power plants must be carefully designed and maintained because the water hammer can cause water pipes to fail catastrophically.



Typical pressure wave caused by closing a valve in a pipeline

The magnitude of the pulse

One of the first to successfully investigate the water hammer problem was the Italian engineer Lorenzo Allievi.

Water hammer can be analyzed by two different approaches, *rigid column theory* which ignores compressibility of the fluid and elasticity of the walls of the pipe, or by a full analysis including elasticity. When the time it takes a valve to close is long compared to the propagation time for a pressure wave to travel the length of the pipe, then rigid column theory is appropriate; otherwise considering elasticity may be necessary. Below are two approximations for the peak pressure, one that considers elasticity, but assumes the valve closes instantaneously, and a second that neglects elasticity but includes a finite time for the valve to close.

Instant valve closure; compressible fluid

The pressure profile of the water hammer pulse can be calculated from the Joukowsky equation

$$\frac{\delta P}{\delta t} = \rho a \frac{\delta v}{\delta t}$$

So for a valve closing instaneously, the maximum magnitude of the water hammer pulse is:

$$\Delta P = \rho a \Delta v$$

where ΔP is the magnitude of the pressure wave (Pa), ρ is the density of the fluid (kgm^{-3}), a is the speed of sound in the fluid (ms^{-1}), and Δv is the change in the fluid's velocity (ms^{-1}). The pulse comes about due to Newton's laws of motion and the continuity equation applied to the deceleration of a fluid element .

Equation for wave speed

As the speed of sound in a fluid is the $\sqrt{\frac{\text{effective bulk modulus}}{\text{density}}}$, the peak pressure will depend on the fluid compressibility if the valve is closed abruptly.

$$a = \sqrt{\frac{K/\rho}{(1 + V/a)[1 + (K/E)(D/t)c)]}}$$

,

where

- a = wave speed
- K = bulk modulus of elasticity of the fluid
- ρ = density of the fluid
- E = elastic modulus of the pipe
- D = internal pipe diameter
- t = pipe wall thickness
- c = dimensionless parameter due to system pipe-constraint condition on wave speed

Slow valve closure; incompressible fluid

When the valve is closed slowly compared to the transit time for a pressure wave to travel the length of the pipe, the elasticity can be neglected, and the phenomenon can be described in terms of inertance or rigid column theory. For this case, one approximation to the maximum pressure (using Imperial units), P, produced in a water filled line is:

$P = 0.07VL / t + P_1$

where P_1 is the inlet pressure, V is the flow velocity in ft/sec, t is the valve closing time in seconds and L is the upstream pipe length in feet

Expression for the excess pressure due to water hammer

When a valve with a volumetric flow rate Q is closed, an excess pressure δP is created upstream of the valve, whose value is given by the Joukowsky equation:

$$\delta P = Z_h\, Q$$

In this expression:

- overpressurization δP is expressed in Pa;
- Q is the volumetric flow in m^3/s;
- Z_h is the hydraulic impedance, expressed in $kg/m^4/s$.

The hydraulic impedance Z_h of the pipeline determines the magnitude of the water hammer pulse. It is itself defined by:

$$Z_h = \frac{\sqrt{\rho\, B_{eff}}}{A}$$

with:

- ρ the density of the liquid, expressed in kg/m^3;
- A cross sectional area of the pipe, m^2;
- B_{eff} effective modulus of compressibility of the liquid in the pipe, expressed in Pa.

The latter follows from a series of hydraulic concepts:

- compressibility of the liquid, defined by its adiabatic compressibility modulus B_l, resulting from the equation of state of the liquid generally available from thermodynamic tables;
- the elasticity of the walls of the pipe, which defines a modulus of equivalent compressibility B_{eq}. In the case of a pipe of circular cross section whose thickness e is small compared to the diameter D, the equivalent modulus of compressibility is given by the following formula: $B_{eq} = \frac{e\, E}{D}$; in which E is the Young's modulus (in Pa) of the material of the pipe;
- possibly compressibility B_g of gas dissolved in the liquid, defined by: $B_g = \frac{\gamma\, P}{\alpha}$
    - γ being the ratio of specific heats of the gas
    - α the rate of ventilation (the volume fraction of undissolved gas)
    - and P the pressure (in Pa).

Thus, the effective compressibility modulus is:

$$\frac{1}{B_{eff}} = \frac{1}{B_l} + \frac{1}{B_{eq}} + \frac{1}{B_g}$$

As a result, we see that we can reduce the water hammer by:

- increasing the pipe diameter at constant flow, which reduces the inertia of the liquid column;
- choosing to use a material with a reduced Young's modulus;
- introducing a device that increases the flexibility of the entire hydraulic system, such as a hydraulic accumulator;
- where possible, increasing the percentage of undissolved air in the liquid.

Dynamic equations

The water hammer effect can be simulated by solving the following partial differential equations.

$$\frac{\partial V}{\partial x} + \frac{1}{B_m}\frac{\partial P}{\partial t} = 0$$
$$\frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{f}{2D}V|V| = 0$$

where V is the fluid velocity inside pipe, ρ is the fluid density and B_m is the equivalent bulk modulus, f is the friction factor.

Column separation

Column separation refers to the breaking of liquid columns in fully filled pipelines. This may occur in a water-hammer event when the pressure in a pipeline drops to the vapor pressure at specific locations such as closed ends, high points or knees (changes in pipe slope). The liquid columns are separated by a vapor cavity that grows and diminishes according to the dynamics of the system. The collision of two liquid columns, or of one liquid column with a closed end, may cause a large and nearly instantaneous rise in pressure. This pressure rise travels through the entire pipeline and forms a severe load for hydraulic machinery, individual pipes and supporting structures. The situation is even worse: in one water-hammer event many repetitions of cavity formation and collapse may occur.

Simulation software

Most water hammer software packages use the method of characteristics to solve the differential equations involved. This method works well if the wave speed does not vary in time due to either air or gas entrainment in a pipeline. The Wave Method (WM) is also used in various software packages. WM allows large networks to be analyzed efficiently. Many commercial and non commercial packages exist today.

Software packages vary in complexity, dependent on the processes modeled. The more sophisticated packages may have any of the following features:

- Multiphase flow capabilities
- An algorithm for cavitation growth and collapse
- Unsteady friction - the pressure waves will dampen as turbulence is generated and due to variations in the flow velocity distribution
- Varying bulk modulus for higher pressures (water will become less compressible)
- Fluid structure interaction - the pipeline will react on the varying pressures and will cause pressure waves itself

Applications

- The water hammer principle can be used to create a simple water pump called a hydraulic ram.
- Leaks can sometimes be detected using water hammer.
- Enclosed air pockets can be detected in pipelines.
- The US Navy is conducting field trials for mine clearing using water hammer.

Chapter 11

Specific Speed

Specific speed N_s is a quasi non-dimensional number used to classify pump impellers as to their type and proportions. In Imperial units it is defined as the speed in revolutions per minute at which a geometrically similar impeller would operate if it were of such a size as to deliver one gallon per minute against one foot of hydraulic head. In metric units flow may be in l/s or m^3/s and head in m, and care must be taken to state the units used.

Performance is defined as the ratio of the pump or turbine against a reference pump or turbine, which divides the actual performance figure to provide a unitless figure of merit. The resulting figure would more descriptively be called the "ideal-reference-device-specific performance." This resulting unitless ratio may loosely be expressed as a "speed," only because the performance of the reference ideal pump is linearly dependent on its speed, so that the ratio of [device-performance to reference-device-performance] is *also* the increased speed the reference device would need to turn, in order to produce the performance, instead of its reference speed of "1 unit."

Specific speed is used in engineering design where it is thought of as an index used to predict desired pump or turbine characteristics; e.g., the general shape of a pump's impeller. Often it is used to predict the type of pump or turbine required for a design flow rate and head. Once the desired specific speed is known, basic dimensions of the unit's components can be easily calculated.

Several mathematical definitions of specific speed (all of them actually ideal-device-specific) have been created for different devices and applications.

Pump specific speed

Low-specific speed radial flow impellers develop hydraulic head principally through centrifugal force. Pumps of higher specific speeds develop head partly by centrifugal force and partly by axial force. An axial flow or propeller pump with a specific speed of 10,000 or greater generates its head exclusively through axial forces. Radial impellers are generally low flow/high head designs whereas axial flow impellers are high flow/low head designs.

Centrifugal pump impellers have specific speed values ranging from 500 to 10,000 (English units), with radial flow pumps at 500-4000, mixed flow at 2000-8000 and axial flow pumps at 7000-20,000. Values of specific speed less than 500 are associated with positive displacement pumps.

As the specific speed increases, the ratio of the impeller outlet diameter to the inlet or eye diameter decreases. This ratio becomes 1.0 for a true axial flow impeller.

$$N_s = \frac{n\sqrt{Q}}{(gH)^{3/4}}$$

where:

N_s is specific speed (unitless)
n is pump rotational speed (revolutions per seconds)
Q is flowrate (m^3/s) at the point of best efficiency
H is total head (m) per stage at the point of best efficiency
g is acceleration due to gravity (m/s^2)

Note that the units used affect the specific speed value and consistent units should be used for comparisons. Pump specific speed can be calculated using British gallons or using Metric units (m^3/s or L/s and metres head), changing the values listed above.

Net suction specific speed

The net suction specific speed is mainly used to see if there will be problems with cavitation during the pump's operation on the suction side . It is defined by centrifugal and axial pumps' inherent physical characteristics and operating point . The net suction specific speed of a pump will define the range of operation in which a pump will experience stable operation . The higher the net suction specific speed, then the smaller the range of stable operation. The envelope of stable operation is defined in terms of the best efficiency point of the pump.

The net suction specific speed is defined as:

$$N_{ss} = \frac{N\sqrt{Q}}{NPSH_R^{0.75}}$$

where:

N_{ss} = net suction specific speed
N = rotational speed of pump in rpm

Q = flow of pump in US gallons per minute
$NPSH_R$ = Net positive suction head (NPSH) required in feet at pump's best efficiency point

Turbine specific speed

The specific speed value (radians/second) for a turbine is the speed of a geometrically similar turbine which would produce one unit of he specific speed of a turbine is given by the manufacturer (along with other ratings) and will always refer to the point of maximum efficiency. This allows accurate calculations to be made of the turbine's performance for a range of heads.

Well-designed efficient machines typically use the following values: Impulse turbines have the lowest n_s values, typically ranging from 1 to 10, a Pelton wheel is typically around 4, Francis turbines fall in the range of 10 to 100, while Kaplan turbines are at least 100 or more, all in imperial units.

$n_s = n\sqrt{P}/H^{5/4}$ (dimensioned parameter), n = rpm

where:

Ω = angular velocity (radians per second)
H_n = Net head after turbine and waterway loss (m)
Q = water flow (m^3/s)

English units

Expressed in English units, the "specific speed" is defined as $n_s = n\sqrt{(P)}/h^{5/4}$

- where n is the wheel speed in rpm
- P is the power in horsepower
- h is the water head in feet

Metric units

Expressed in metric units, the "specific speed" is $n_s = 0.2626\ n\sqrt{(P)}/h^{5/4}$

- where n is the wheel speed in rpm
- P is the power in kilowatts
- h is the water head in meters

The factor 0.2626 is only required when the specific speed is to be adjusted to English units. In countries which use the metric system, the factor is omitted, and quoted specific speeds are correspondingly larger.

Example

Given a flow and head for a specific hydro site, and the RPM requirement of the generator, calculate the specific speed. The result is the main criteria for turbine selection or the starting point for analytical design of a new turbine. Once the desired specific speed is known, basic dimensions of the turbine parts can be easily calculated.

Turbine calculations:

$$N_s = \frac{2.294}{H_n^{0.486}}$$

$$D_e = 84.5(0.79 + 1.602N_s)\frac{\sqrt{H_n}}{60 * \Omega}$$

D_e = Runner diameter (m)

Chapter 12

Darcy–Weisbach Equation

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 form

Head loss can be calculated with

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

where

- h_f is the head loss due to friction;
- L is the length of the pipe;
- D is the hydraulic diameter of the pipe (for a pipe of circular section, this equals the internal diameter of the pipe);
- V is the average velocity of the fluid flow, equal to the volumetric flow rate per unit cross-sectional wetted area;
- g is the local acceleration due to gravity;
- f is a dimensionless coefficient called the Darcy friction factor. It can be found from a Moody diagram or more precisely by solving Colebrook equation.

Pressure loss form

Given that the head loss h_f expresses the pressure loss Δp as the height of a column of fluid,

$$\Delta p = \rho \cdot g \cdot h_f$$

where ρ is the density of the fluid, the Darcy–Weisbach equation can also be written in terms of pressure loss:

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2}$$

where the pressure loss due to friction Δp is a function of:

- the ratio of the length to diameter of the pipe, L/D;
- the density of the fluid, ρ;
- the mean velocity of the flow, V, as defined above;
- a (dimensionless) coefficient of laminar, or turbulent flow, f.

Since the pressure loss equation can be derived from the head loss equation by multiplying each side by ρ and g.

Darcy friction factor

The friction factor f or flow coefficient λ is not a constant and depends on the parameters of the pipe and the velocity of the fluid flow, but it is known to high accuracy within certain flow regimes. It may be evaluated for given conditions by the use of various empirical or theoretical relations, or it may be obtained from published charts. These charts are often referred to as Moody diagrams, after L. F. Moody, and hence the factor itself is sometimes called the *Moody friction factor*. It is also sometimes called the Blasius friction factor, after the approximate formula he proposed.

For laminar (slow) flows, it is a consequence of Poiseuille's law that $\lambda=64/Re$, where Re is the Reynolds number calculated substituting for the characteristic length the hydraulic diameter of the pipe, which equals the inside diameter for circular pipe geometries.

For turbulent flow, methods for finding the friction factor f include using a diagram such as the Moody chart; or solving equations such as the Colebrook-White equation, or the Swamee-Jain equation. While the diagram and Colebrook-White equation are iterative methods, the Swamee-Jain equation allows f to be found directly for full flow in a circular pipe.

Confusion with the Fanning friction factor

The Darcy–Weisbach friction factor is 4 times larger than the Fanning friction factor, so attention must be paid to note which one of these is meant in any "friction factor" chart or equation being used. Of the two, the Darcy–Weisbach factor is more commonly used by civil and mechanical engineers, and the Fanning factor by chemical engineers, but care should be taken to identify the correct factor regardless of the source of the chart or formula.

Most charts or tables indicate the type of friction factor, or at least provide the formula for the friction factor with laminar flow. If the formula for laminar flow is $f = 16/Re$, it's the Fanning factor, and if the formula for laminar flow is $f = 64/Re$, it's the Darcy–Weisbach factor.

Which friction factor is plotted in a Moody diagram may be determined by inspection if the publisher did not include the formula described above:

1. Observe the value of the friction factor for laminar flow at a Reynolds number of 1000.
2. If the value of the friction factor is 0.064, then the Darcy friction factor is plotted in the Moody diagram. Note that the nonzero digits in 0.064 are the numerator in the formula for the laminar Darcy friction factor: $f = 64/Re$.
3. If the value of the friction factor is 0.016, then the Fanning friction factor is plotted in the Moody diagram. Note that the nonzero digits in 0.016 are the numerator in the formula for the laminar Fanning friction factor: $f = 16/Re$.

The procedure above is similar for any available Reynolds number that is an integral power of ten. It is not necessary to remember the value 1000 for this procedure – only that an integral power of ten is of interest for this purpose.

History

Historically this equation arose as a variant on the Prony equation; this variant was developed by Henry Darcy of France, and further refined into the form used today by Julius Weisbach of Saxony in 1845. Initially, data on the variation of *f* with velocity was lacking, so the Darcy–Weisbach equation was outperformed at first by the empirical Prony equation in many cases. In later years it was eschewed in many special-case situations in favor of a variety of empirical equations valid only for certain flow regimes, notably the Hazen-Williams equation or the Manning equation, most of which were significantly easier to use in calculations. However, since the advent of the calculator, ease of calculation is no longer a major issue, and so the Darcy–Weisbach equation's generality has made it the preferred one.

Derivation

The Darcy–Weisbach equation is a phenomenological formula obtainable by dimensional analysis.

Away from the ends of the pipe, the characteristics of the flow are independent of the position along the pipe. The key quantities are then the pressure drop along the pipe per unit length, $\Delta p/L$, and the volumetric flow rate. The flow rate can be converted to an average velocity V by dividing by the wetted area of the flow (which equals the cross-sectional area of the pipe if the pipe is full of fluid).

Pressure has dimensions of energy per unit volume. Therefore, the pressure drop between two points must be proportional to $(1/2)\rho V^2$, which has the same dimensions as it resembles the expression for the kinetic energy per unit volume. We also know that pressure must be proportional to the length of the pipe between the two points L as the pressure drop per unit length is a constant. To turn the relationship into a proportionality coefficient of dimensionless quantity we can divide by the hydraulic diameter of the pipe, D, which is also constant along the pipe. Therefore,

$$\Delta p \propto \frac{L}{D} \cdot \frac{1}{2}\rho V^2.$$

The proportionality coefficient is the dimensionless "Darcy friction factor" or "flow coefficient". This dimensionless coefficient will be a combination of geometric factors such as π, the Reynolds number and (outside the laminar regime) the relative roughness of the pipe (the ratio of the roughness height to the hydraulic diameter).

Note that $(1/2)\rho V^2$ is not the kinetic energy of the fluid per unit volume, for the following reasons. Even in the case of laminar flow, where all the flow lines are parallel to the length of the pipe, the velocity of the fluid on the inner surface of the pipe is zero due to viscosity, and the velocity in the center of the pipe must therefore be larger than the average velocity obtained by dividing the volumetric flow rate by the wet area. The average kinetic energy then involves the mean-square velocity, which always exceeds the square of the mean velocity. In the case of turbulent flow, the fluid acquires random velocity components in all directions, including perpendicular to the length of the pipe, and thus turbulence contributes to the kinetic energy per unit volume but not to the average lengthwise velocity of the fluid.

Practical applications

In hydraulic engineering applications, it is often desirable to express the head loss in terms of volumetric flow rate in the pipe. For this, it is necessary to substitute the following into the original head loss form of the Darcy-Weisbach equation

$$V^2 = \frac{Q^2}{A_w^2}$$

where

- V is, as above, the average velocity of the fluid flow, equal to the volumetric flow rate per unit cross-sectional wetted area;
- Q is the volumetric flow rate;
- A_w is the cross-sectional wetted area;

For the general case of an arbitrarily-full pipe, the value of A_w will not be immediately known, being an implicit function of pipe slope, cross-sectional shape, flow rate and other variables. If, however, the pipe is assumed to be full flowing and of circular cross-section, as is common in practical scenarios, then

$$A_w^2 = \left(\frac{\pi D^2}{4}\right)^2 = \frac{\pi^2 D^4}{16}$$

where D is the diameter of the pipe

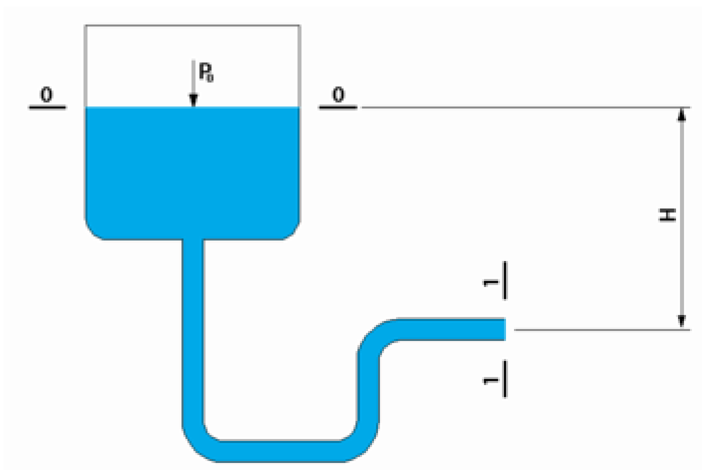
Substuting these results into the original formulation yields the final equation for head loss in terms of volumetic flow rate in a full-flowing circular pipe

$$h_f = \frac{8 f L Q^2}{g \pi^2 D^5}$$

where all symbols are defined as above.

Chapter 13

Net Positive Suction Head



Hydraulic circuit

NPSH is an acronym 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 nearing the 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 that is most often described as "pumping gravel". Additionally, the inevitable increase in vibration can cause other mechanical faults in the pump and associated equipment.

Considering the circuit shown in the picture, in 1-1 NPSH is :

$$NPSH = \frac{p_0 - p_v}{\rho g} + \Delta z - h_L$$

where h_L is the head loss between 0 and 1, p_0 is the pressure at the water surface, p_v is the vapour pressure (saturation pressure) for the fluid at the temperature T_1 at 1, Δz is the difference in height $z_1 - z_0$ (shown as H on the diagram) from the water surface to the location 1, and ρ is the fluid density, assumed constant, and g is gravitational acceleration.

In pump operation, two aspects of this parameter are called respectively **NPSHA** or NPSH (a) *Net Positive Suction Head (available)* and **NPSHR** or NPSH(r) or NPSH-3 *Net Positive Suction Head (required)*, where NPSH(a) is the suction pressure presented at the pump inlet port, and NPSH(r) is the suction pressure limit at which the pump's total differential head performance is reduced by 3% due to cavitation. Cavitation occurs at suction pressure levels below the NPSH-3 level and pump damage can occur from cavitation even though the pump may continue to provide the expected hydraulic performance.

A somewhat simpler informal way to understand NPSH…

Fluid can be pushed very hard down a pipe. The only limit is the ability of the pipe to handle the pressure. However, a liquid cannot be pulled very hard up a pipe because bubbles are created as the liquid evaporates into a gas. The lower the vacuum pressure created, the bigger 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, plus, if the pump is below the tank, the weight of the fluid from gravity above the pump inlet also helps. Until the fluid gets to the pump, these are the only two forces providing the push. Friction losses and vapor pressure must also be considered. Friction losses limit the ability of gravity and air pressure to push the water towards 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 push you have before the bubbles form.

NPSH is widely misunderstood, and is a fairly difficult concept to grasp. 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 headpressure 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 into 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 into the intake port and the impeller is then pushing the liquid out at the discharge, 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 vapour. 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 earlier, hence a high NPSH requirement.

Water will boil at lower temperatures under lower pressures. Conversely the boiling-point is raised 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 start to cavitate when pumping hot water.

Some general NPSH Examples

(based on sea level).

Example 1: A tank with a liquid level 2 metres above the pump intake, plus the atmospheric pressure of 10 metres, minus a 2 metre friction loss into the pump (say for pipe & valve loss), minus the NPSHR curve (say 2.5 metres) of the pre-designed pump = an NPSHA (available) of 7.5 metres. (not forgetting the flow duty). This equates to 3 times the NPSH required. This pump will operate well so long as all other parameters are correct.

Remember that (+ or -) flow duty will change the reading on the pump manufacture NPSHR curve. The lower the flow, the lower the NPSHR, and vice versa.

Lifting out of a well will also create negative NPSH; however remember that atmospheric pressure at sea level is 10 metres! This helps us, as it gives us a bonus boost or “push” into the pump intake. (Remember that you only have 10 metres of atmospheric pressure as a bonus and nothing more!).

Example 2: A well or bore with an operating level of 5 metres below the intake, minus a 2 metre friction loss into pump (pipe loss), minus the NPSHR curve (say 2.4 metres) of the pre-designed pump = an NPSHA (available) of (negative) -9.4 metres. NOW we add the atmospheric pressure of 10 metres. We have a positive NPSHA of 0.6 metres. (minimum requirement is 0.6 metres above NPSHR), so the pump should lift from the well.

Now we will try the situation from example 2 above, but will pump 70 degrees Celsius (158F) water from a hot spring, creating negative NPSH.

Example 3: A well or bore running at 70 degrees Celsius (158F) with an operating level of 5 metres below the intake, minus a 2 metre friction loss into pump (pipe loss), minus the NPSHR curve (say 2.4 metres) of the pre-designed pump, minus a temperature loss of 3 metres/10 feet = an NPSHA (available) of (negative) -12.4 metres. NOW we add the atmospheric pressure of 10 metres and we have a negative NPSHA of -2.4 metres remaining.

Remembering that the minimum requirement is 600 mm above the NPSHR therefore this pump will not be able to pump the 70 degree Celsius liquid and will cavitate and lose performance and cause damage. To work efficiently, this pump requires that it be buried into the ground in a pit next to the hot spring well to a depth of 2.4 metres plus the required 600 mm minimum, totalling a total depth of 3 metres into the pit. (3.5 metres to be completely safe).

A minimum of 600 mm (0.06 bar) and a recommended 1.5 metre (0.15 bar) head pressure “higher” than the NPSHR pressure value required by the manufacturer is required to allow the pump to operate properly.

Serious damage may occur if a large pump has been sited incorrectly with an incorrect NPSHR value and this may result in a very expensive pump or installation repair.

NPSH problems may be able to be solved by changing the NPSHR or by re-siting the pump.

If an NPSHA is say 10 bar then the pump you are using will deliver exactly 10 bar more over the entire operational curve of a pump than its listed operational curve.

Example: A pump with a max. pressure head of 8 bar (80 metres) will actually run at 18 bar if the NPSHA is 10 bar.

i.e.: 8 bar (pump curve) plus 10 bar NPSHA = 18 bar.

This phenomenon is what manufacturers use when they design multistage pumps, (Pumps with more than one impeller). Each multi stacked impeller boosts the previous impeller to raise the pressure head. Some pumps can have up to 40 stages or more, in order to boost heads up to hundreds of metres.

Chapter 14

Water Supply Network

A **water supply system** or **water supply network** is a system of engineered hydrologic and hydraulic components which provide water supply. A water supply system typically includes:

1. A watershed (water purification - sources of drinking water);
2. A raw (untreated) water collection point (above or below ground) where the water accumulates, such as a lake, a river, or groundwater from an underground aquifer. Untreated drinking water (usually water being transferred to the water purification facilities) may be transferred using uncovered ground-level aqueducts, covered tunnels or underground water pipes.
3. Water purification facilities. Treated water is transferred using water pipes (usually underground).
4. Water storage facilities such as reservoirs, water tanks, or watertowers. Smaller water systems may store the water in cisterns or pressure vessels. (Tall buildings may also need to store water locally in pressure vessels in order for the water to reach the upper floors.)
5. Additional water pressurizing components such as pumping stations may need to be situated at the outlet of underground or above ground reservoirs or cisterns (if gravity flow is unfeasible)
6. A pipe network for distribution of water to the consumers (which may be private houses or industrial, commercial or institution establishments) and other usage points (such as fire hydrants)
7. Connections to the sewers (underground pipes, or aboveground ditches in some developing countries) are generally found downstream of the water consumers, but the sewer system is considered to be a separate system, rather than part of the water supply system

Water abstraction and raw water transfer

Raw water (untreated) is collected from a surface water source (such as an intake on a lake or a river) or from a groundwater source (such as a water well drawing from an underground aquifer) within the watershed that provides the water resource.

Shallow dams and reservoirs are susceptible to outbreaks of toxic algae, especially if the water is warmed by a hot sun. The bacteria grow from stormwater runoff carrying fertilizer into the river where it acts as a nutrient for the algae. Such outbreaks render the water unfit for human consumption.

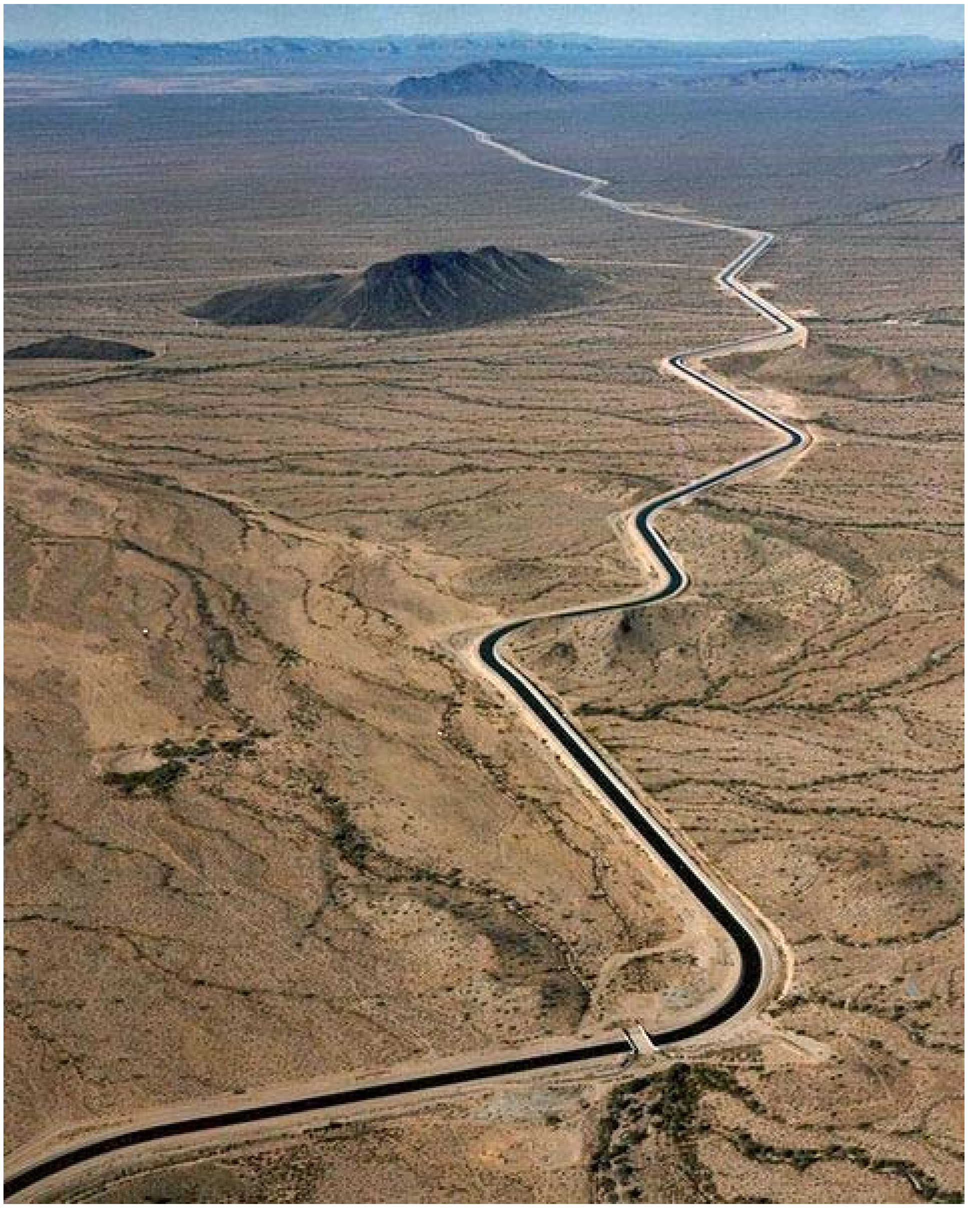
The raw water is transferred to the water purification facilities using uncovered aqueducts, covered tunnels or underground water pipes.

Water treatment

Virtually all large systems must treat the water; a fact that is tightly regulated by global, state and federal agencies, such as the World Health Organization (WHO) or the United States Environmental Protection Agency (EPA). Water treatment must occur before the product reaches the consumer and afterwards (when it is discharged again). Water purification usually occurs close to the final delivery points to reduce pumping costs and the chances of the water becoming contaminated after treatment.

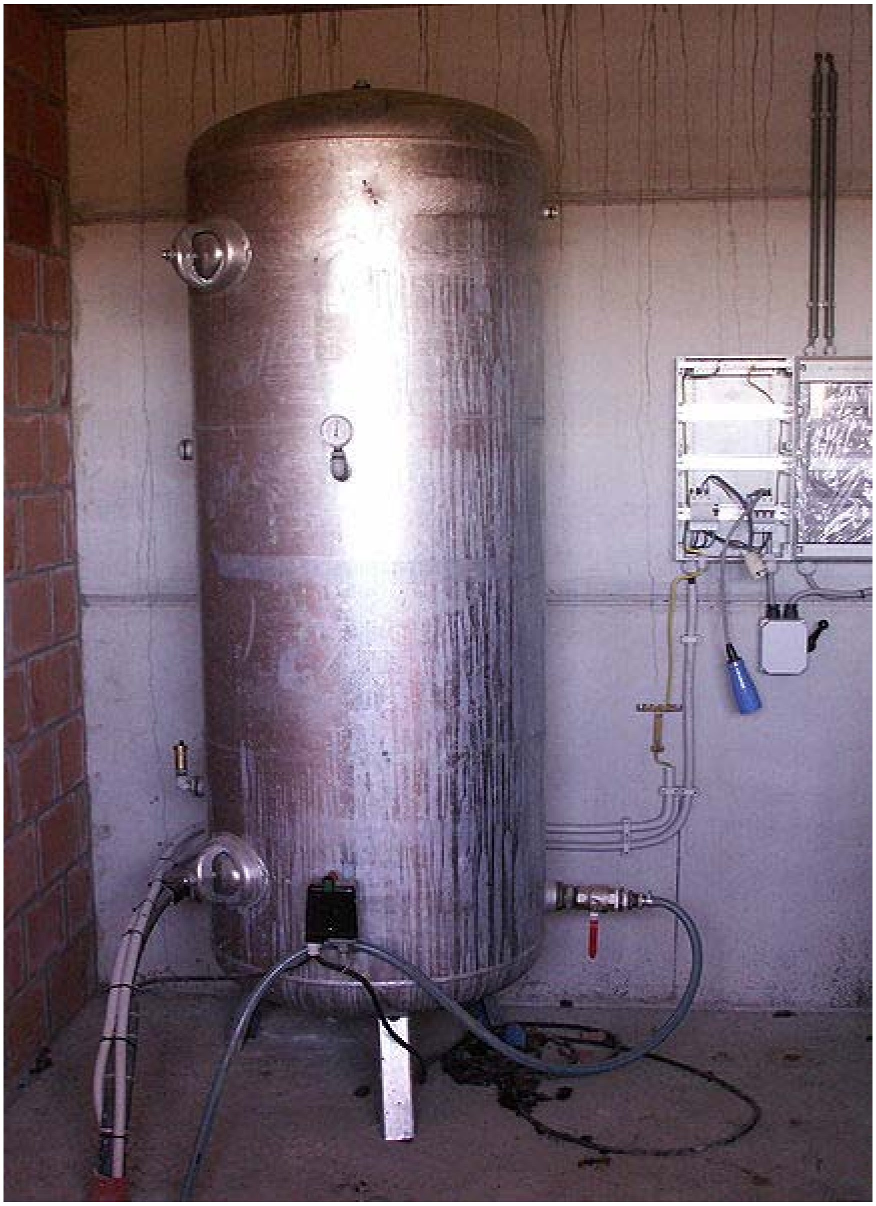
Traditional surface water treatment plants generally consists of three steps: clarification, filtration and disinfection. Clarification refers to the separation of particles (dirt, organic matter, etc.) from the water stream. Chemical addition (i.e. alum, ferric chloride) destabilizes the particle charges and prepares them for clarification either by settling or floating out of the water stream. Sand, anthracite or activated carbon filters refine the water stream, removing smaller particulate matter. While other methods of disinfection exist, the preferred method is via chlorine addition. Chlorine effectively kills bacteria and most viruses and maintains a residual to protect the water supply through the supply network.

Water distribution network



The Central Arizona Project Aqueduct transfers untreated water

Most (treated) water distribution happens through underground pipes



Pressurizing the water is required between the small water reserve and the end-user

The product, delivered to the point of consumption, is called fresh water if it receives little or no treatment, or drinking water if the treatment achieves the water quality standards required for human consumption.

Once treated, chlorine is added to the water and it is distributed by the local supply network. Today, water supply systems are typically constructed of plastic, ferrous, or concrete circular pipe. However, other "pipe" shapes and material may be used, such as square or rectangular concrete boxes, arched brick pipe, or wood. Near the end point, the network of pipes through which the water is delivered is often referred to as the *water mains*.

The energy that the system needs to deliver the water is called pressure. That energy is transferred to the water, therefore becoming water pressure, in a number of ways: by a pump, by gravity feed from a water source (such as a water tower) at a higher elevation, or by compressed air.

The water is often transferred from a water reserve such as a large communal reservoir before being transported to a more pressurised reserve as a watertower.

In small domestic systems, the water may be pressurised by a pressure vessel or even by an underground cistern (the latter however does need additional pressurizing). This eliminates the need of a watertower or any other heightened water reserve to supply the water pressure.

These systems are usually owned and maintained by local governments, such as cities, or other public entities, but are occasionally operated by a commercial enterprise. Water supply networks are part of the master planning of communities, counties, and municipalities. Their planning and design requires the expertise of city planners and civil engineers, who must consider many factors, such as location, current demand, future growth, leakage, pressure, pipe size, pressure loss, fire fighting flows, etc. — using pipe network analysis and other tools. Constructioncomparable sewage systems, was one of the great engineering advances that made urbanization possible. Improvement in the quality of the water has been one of the great advances in public health.

As water passes through the distribution system, the water quality can degrade by chemical reactions and biological processes. Corrosion of metal pipe materials in the distribution system can cause the release of metals into the water with undesirable aesthetic and health effects. Release of iron from unlined iron pipes can result in customer reports of "red water" at the tap . Release of copper from copper pipes can result in customer reports of "blue water" and/or a metallic taste. Release of lead can occur from the solder used to join copper pipe together or from brass fixtures. Copper and lead levels at the consumer's tap are regulated to protect consumer health.

Utilities will often adjust the chemistry of the water before distribution to minimize its corrosiveness. The simplest adjustment involves control of pH and alkalinity to produce a water that tends to passivate corrosion by depositing a layer of calcium carbonate. Corrosion inhibitors are often added to reduce release of metals into the water. Common corrosion inhibitors added to the water are phosphates and silicates.

Maintenance of a biologically safe drinking water is another goal in water distribution. Typically, a chlorine based disinfectant, such as sodium hypochlorite or monochloramine is added to the water as it leaves the treatment plant. Booster stations can be placed within the distribution system to ensure that all areas of the distribution system have adequate sustained levels of disinfection.

Topologies of water distribution networks

Like electric power lines, roads, and microwave radio networks, water systems may have a loop or branch network topology, or a combination of both. The piping networks are circular or rectangular. If any one section of water distribution main fails or needs repair, that section can be isolated without disrupting all users on the network.

Most systems are divided into zones. Factors determining the extent or size of a zone can include hydraulics, telemetry systems, history, and population density. Sometimes systems are designed for a specific area then are modified to accommodate development. Terrain affects hydraulics and some forms of telemetry. While each zone may operate as a stand-alone system, there is usually some arrangement to interconnect zones in order to manage equipment failures or system failures.

Water network maintenance

Water supply networks usually represent the majority of assets of a water utility. Systematic documentation of maintenance works using a Computerized Maintenance Management System is a key to a successful operation of a water utility.