Hydraulic
Mechanics and Engineering

Yadira Ferrer

Lashawna Rupp

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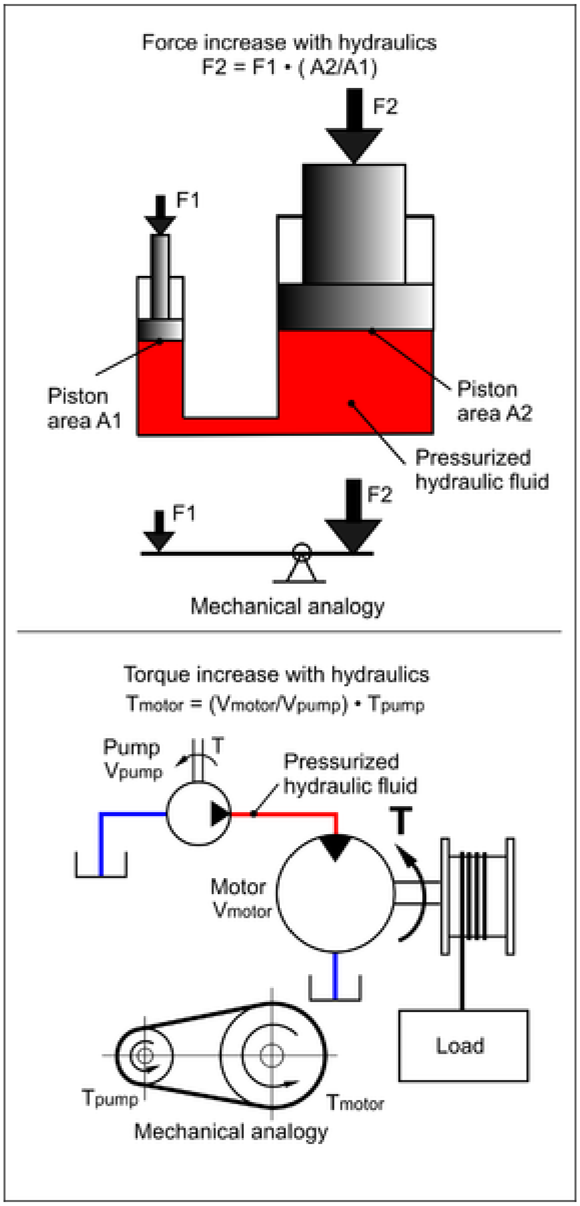
Chapter 1

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

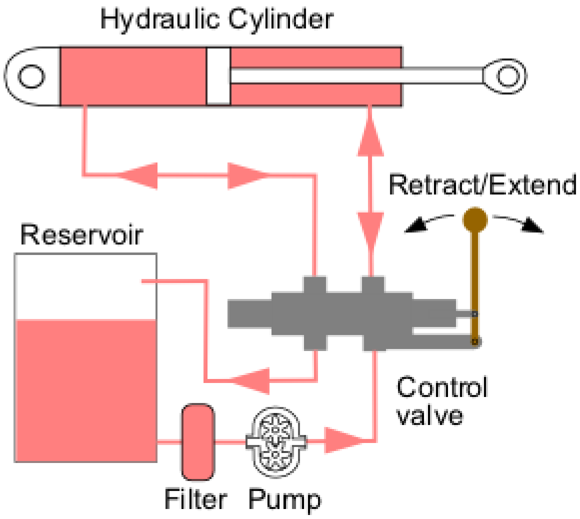
Cylinder C1 is one inch in radius, and cylinder C2 is ten inches in radius. If the force exerted on C1 is 10 lbf, the force exerted by C2 is 1000 lbf because C2 is a hundred times larger in area ($S = \pi r^2$) as C1. The downside to this is that you have to move C1 a hundred inches to move C2 one inch. 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

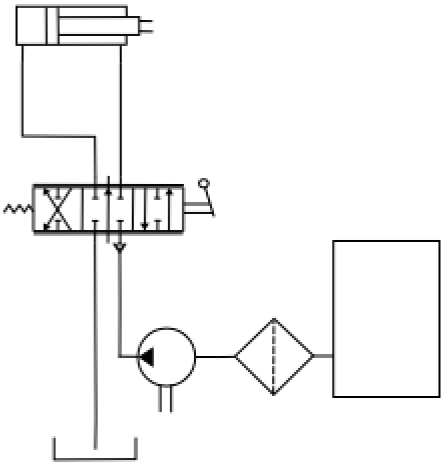
If a hydraulic rotary pump with the displacement 10 cc/rev is connected to a hydraulic rotary motor with 100 cc/rev, the shaft torque required to drive the pump is 10 times less than the torque available at the motor shaft, but the shaft speed (rev/min) for the motor is 10 times less than the pump shaft 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.

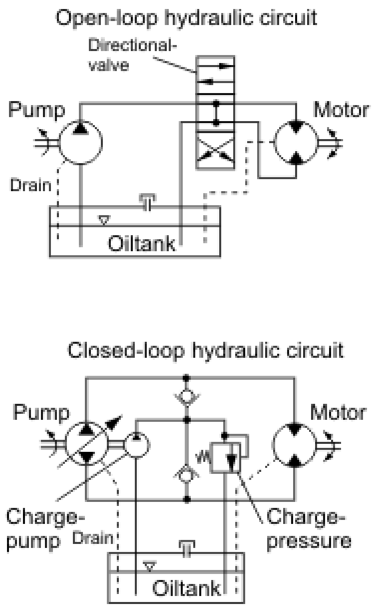
(4) Load sensing *with a combination of up-stream and down-stream compensators*. Hydraulically controlled LS-pump.

(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".

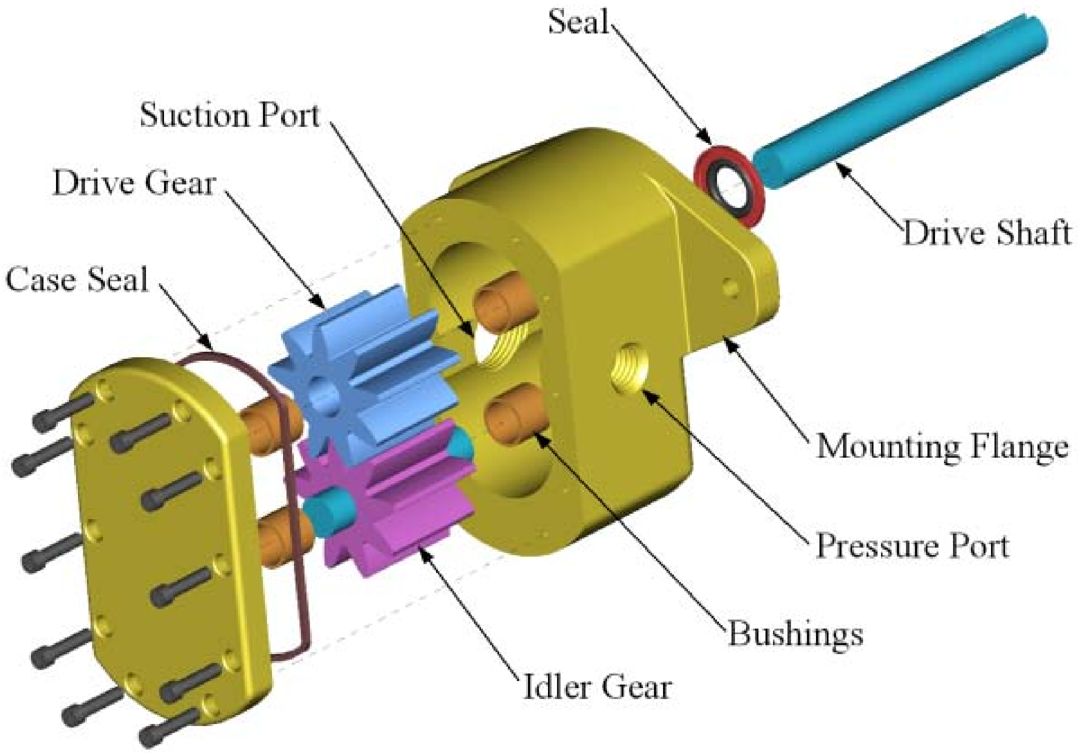
Closed-loop: Motor-return is connected directly to the pump-inlet. To keep up pressure on the low pressure side, the circuits have a charge pump (a small gearpump) that supplies cooled and filtered oil to the low pressure side. Closed-loop circuits are generally used for hydrostatic transmissions in 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, $\eta_{\text{total}} = 0.87$. 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) $E_{\text{diesel}} = (P_{\text{max}} \cdot Q_{\text{tot}}) \div \eta$.

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, $E_{\text{cooler}} = 0.25 E_{\text{diesel}}$

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.

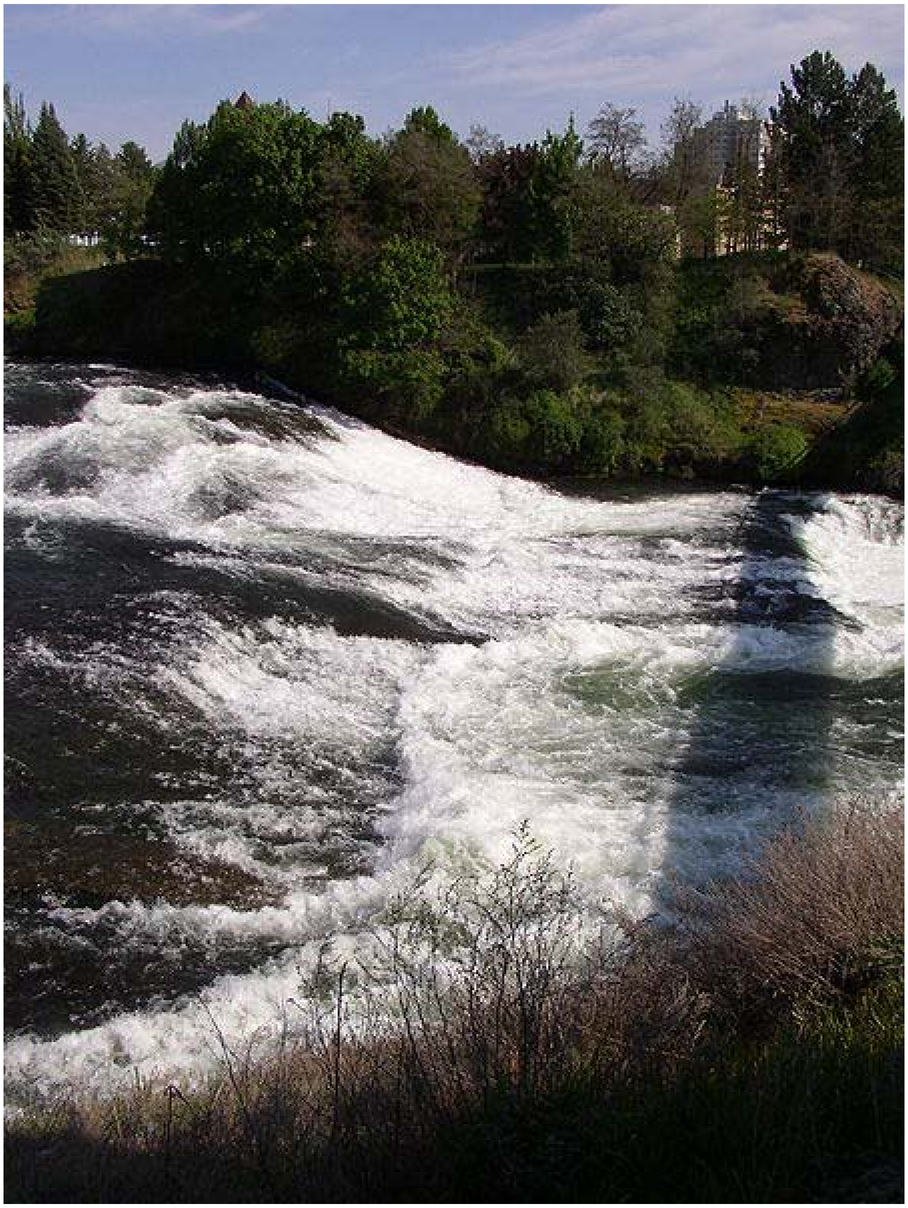
Comparing the characteristics before and after, one finds:

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.

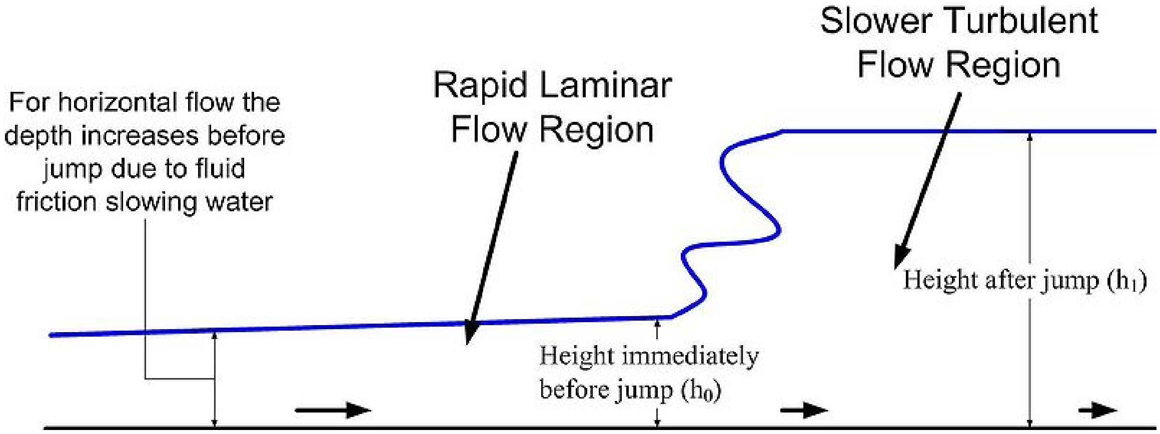


Figure 7: Illustration of behaviour in a hydraulic jump.
Applying the continuity principle

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 $\mathbf{v}$ 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:

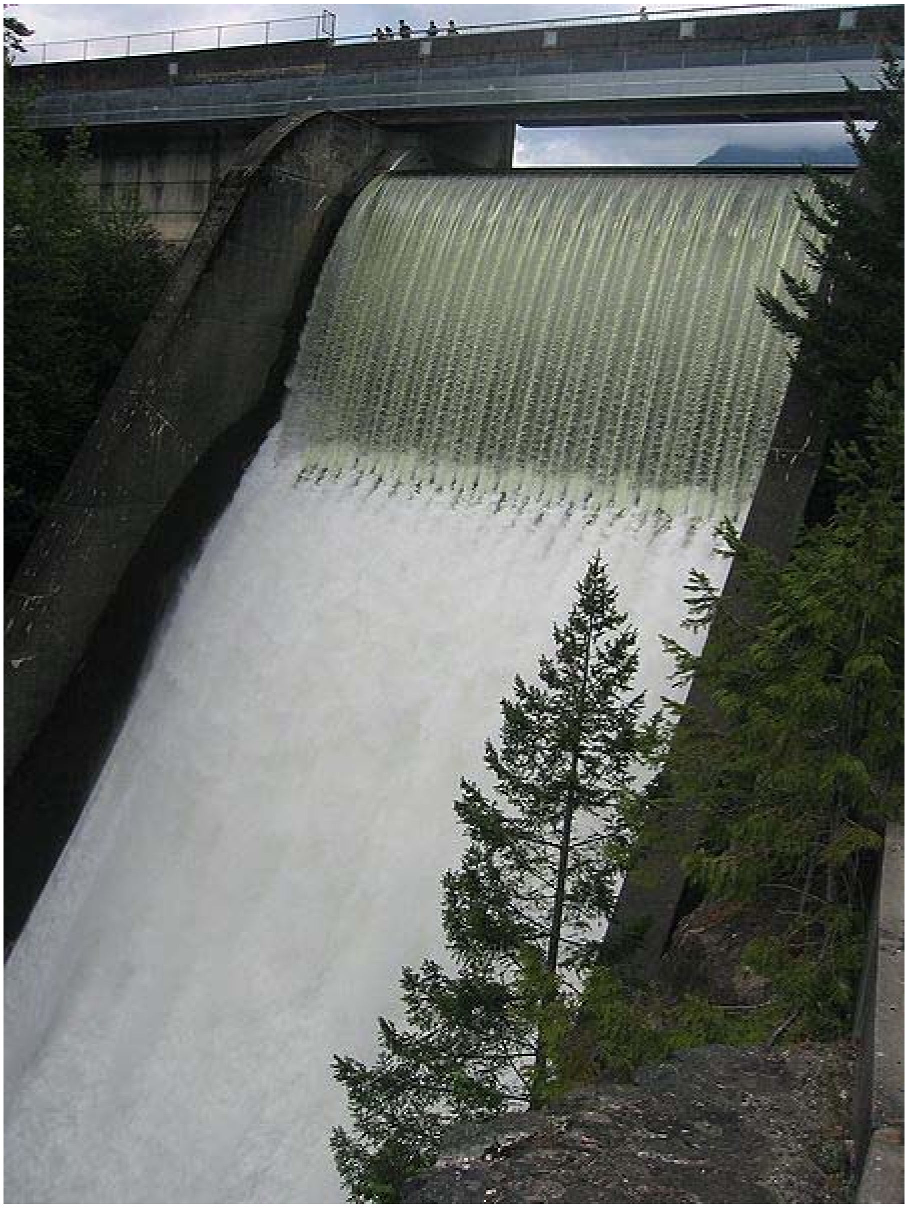
$$FEL = \frac{\left(\sqrt{1+8Fr_0^2}-3\right)^3}{8\left(\sqrt{1+8Fr_0^2}-1\right)\left(\sqrt{Fr_0^2+2}\right)}$$

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:

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

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

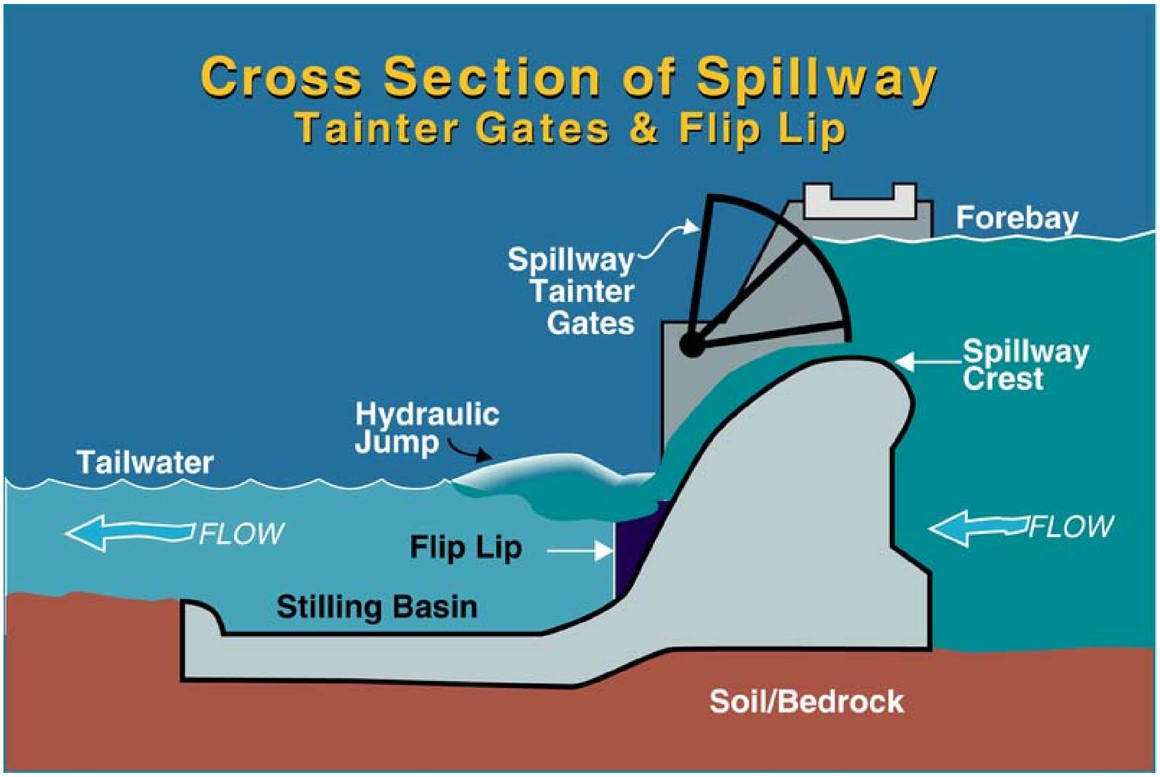
Hydraulic jumps in abyssal fan formation

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

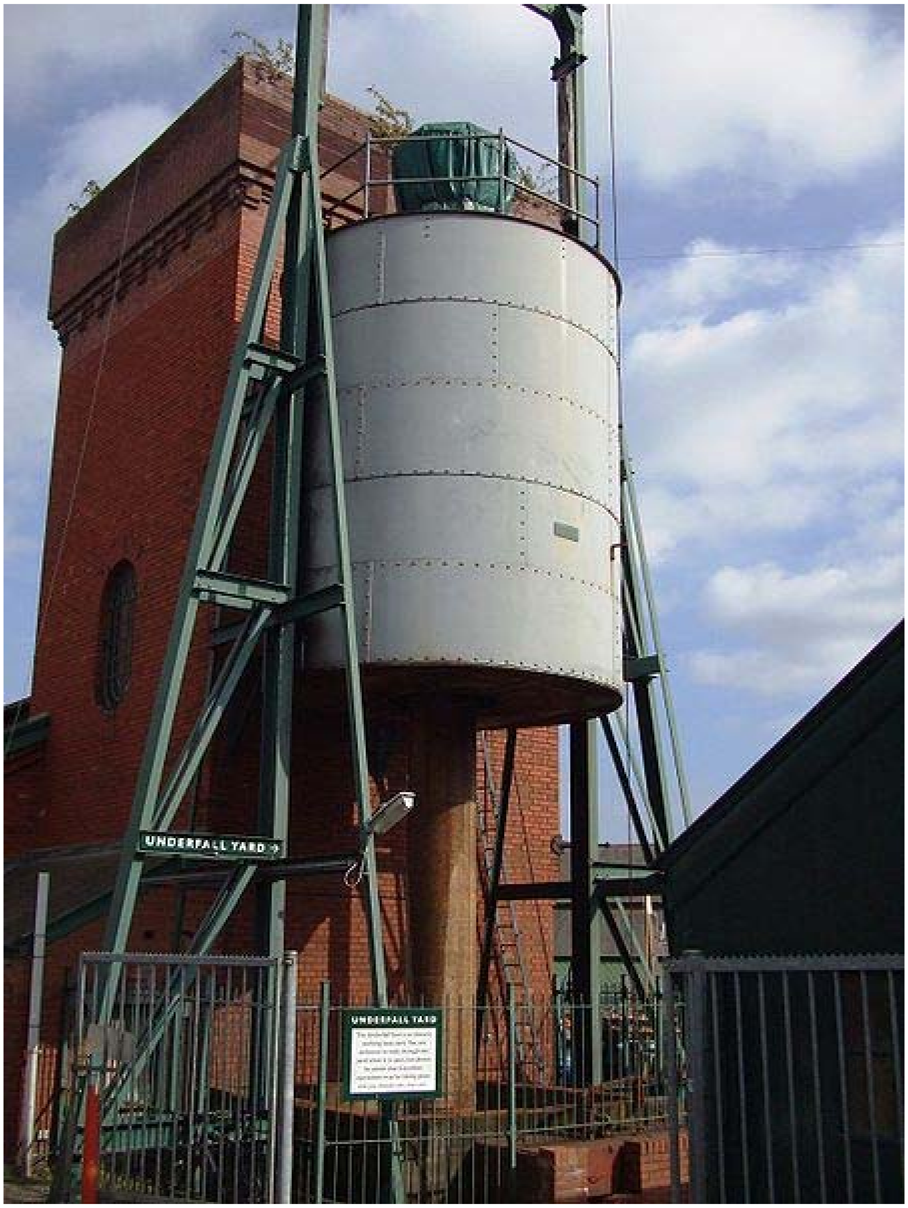
Hydraulic Accumulator

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.

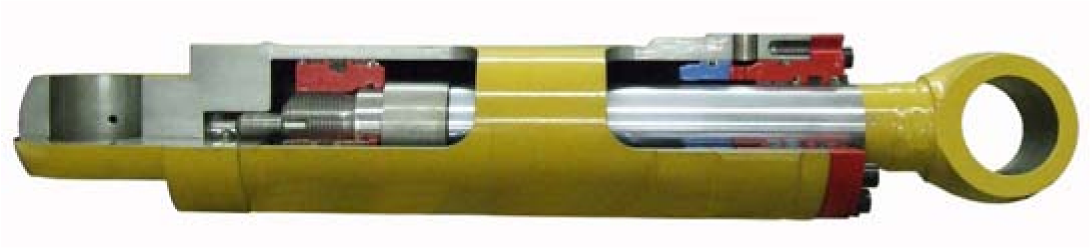
Tie Rod Cylinders

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

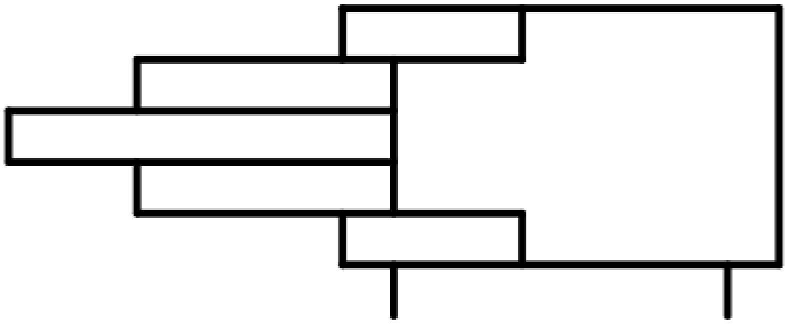
Due to shortcomings of metallic materials, ceramic coatings were developed. Initially ceramic protection schemes seemed ideal, but porosity was higher than projected. Recently the corrosion resistant semi ceramic Lunac 2+ coatings were introduced. These hard coatings are non porous and do not suffer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

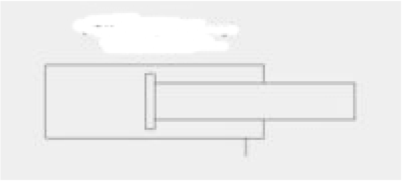
Telescopic cylinder



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

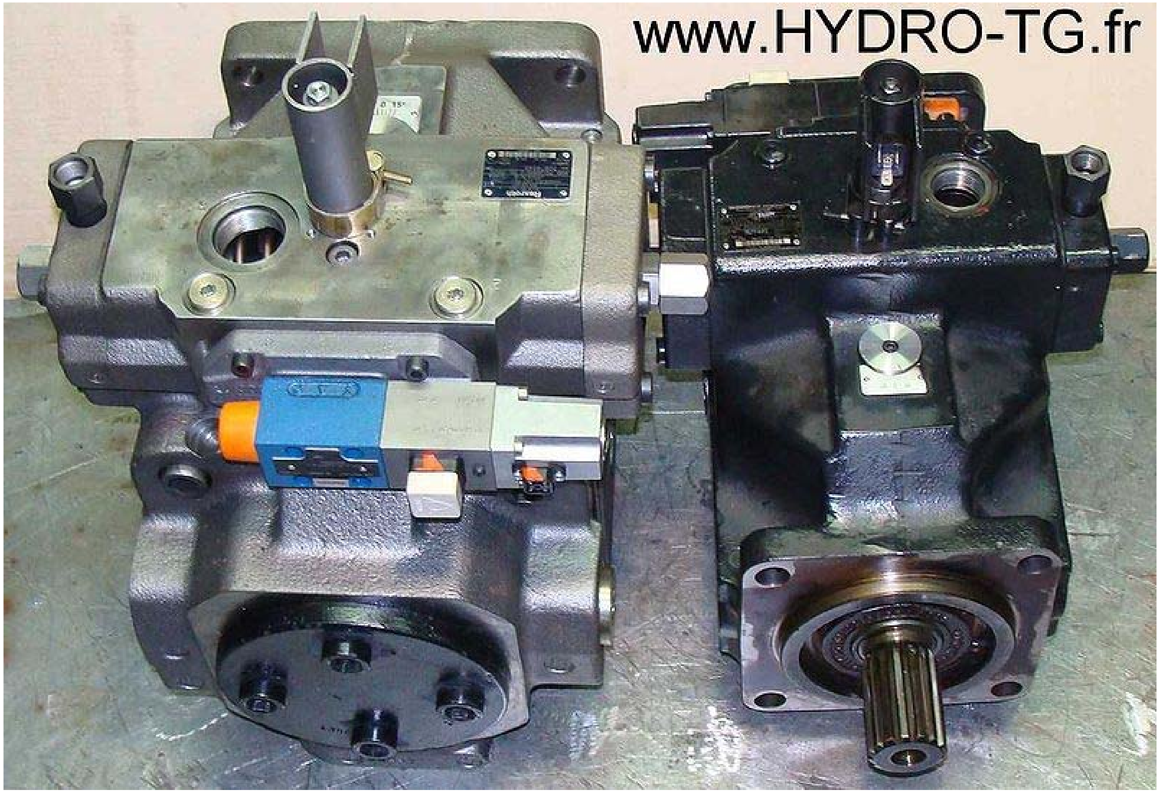
Position sensing hydraulic cylinders eliminate the need for a hollow cylinder rod. Instead, an external sensing “bar” utilizing Hall-Effect technology senses the position of the cylinder’s piston. This is accomplished by the placement of a permanent magnet within the piston. The magnet propagates a magnetic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

A note about popular terminology

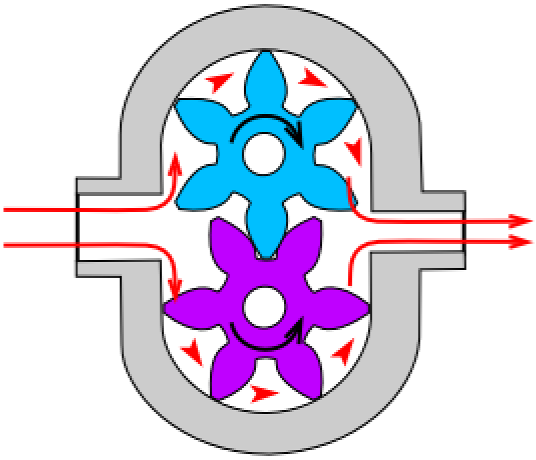
At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

Chapter 5

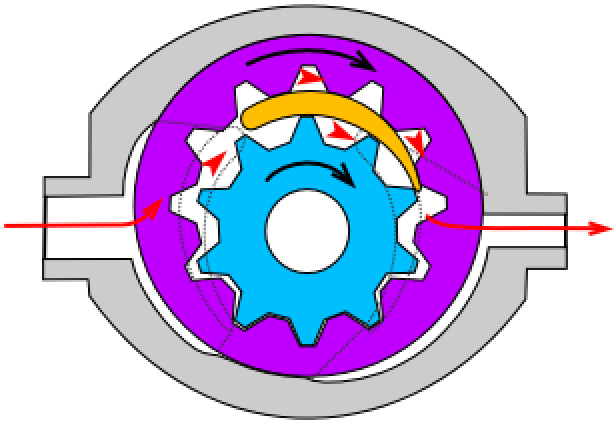
Hydraulic Pump



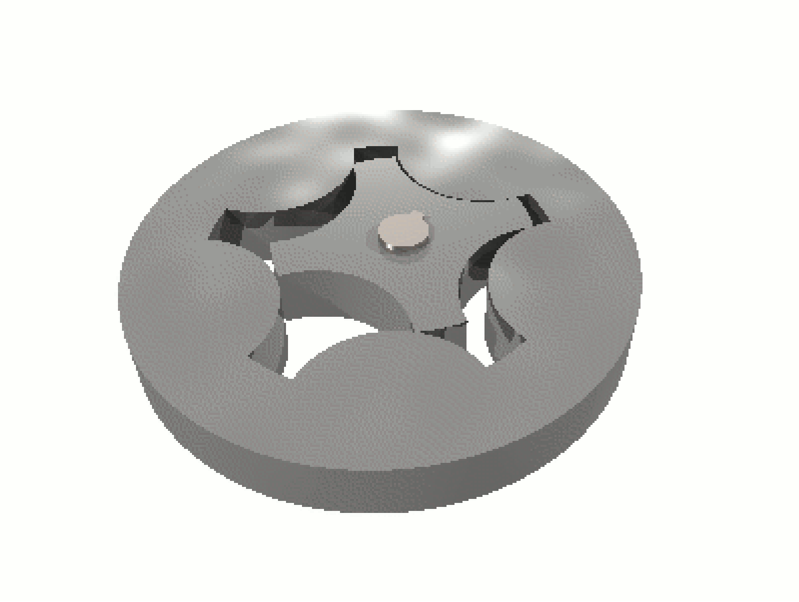
Hydraulic pump Rexroth A4VSO250



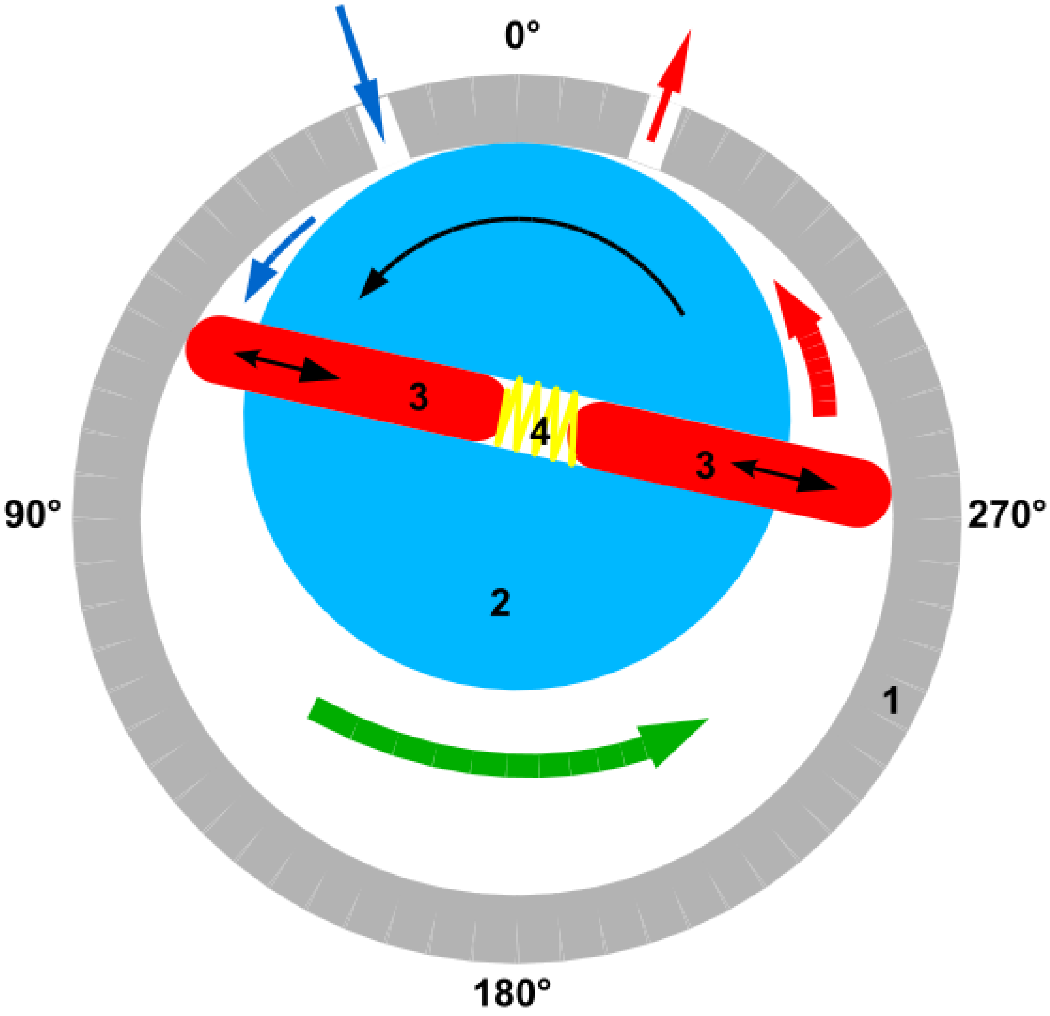
Gearpump with external teeth



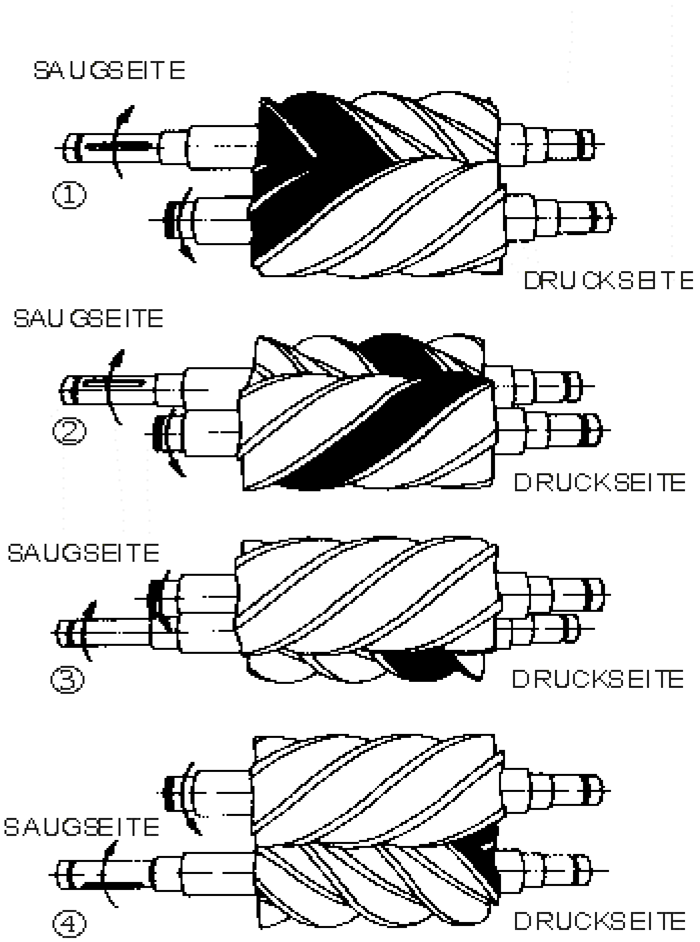
Gearpump with internal teeth



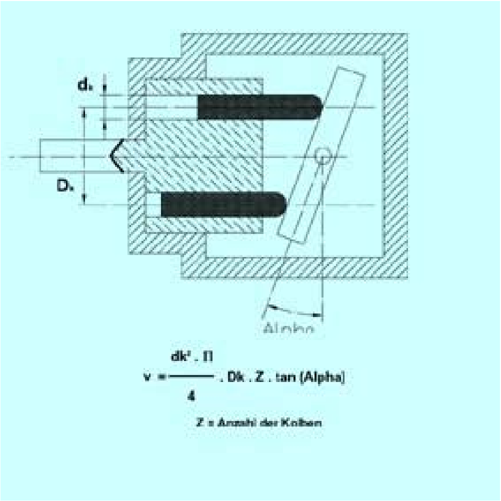
A gerotor (image does not show intake or exhaust)



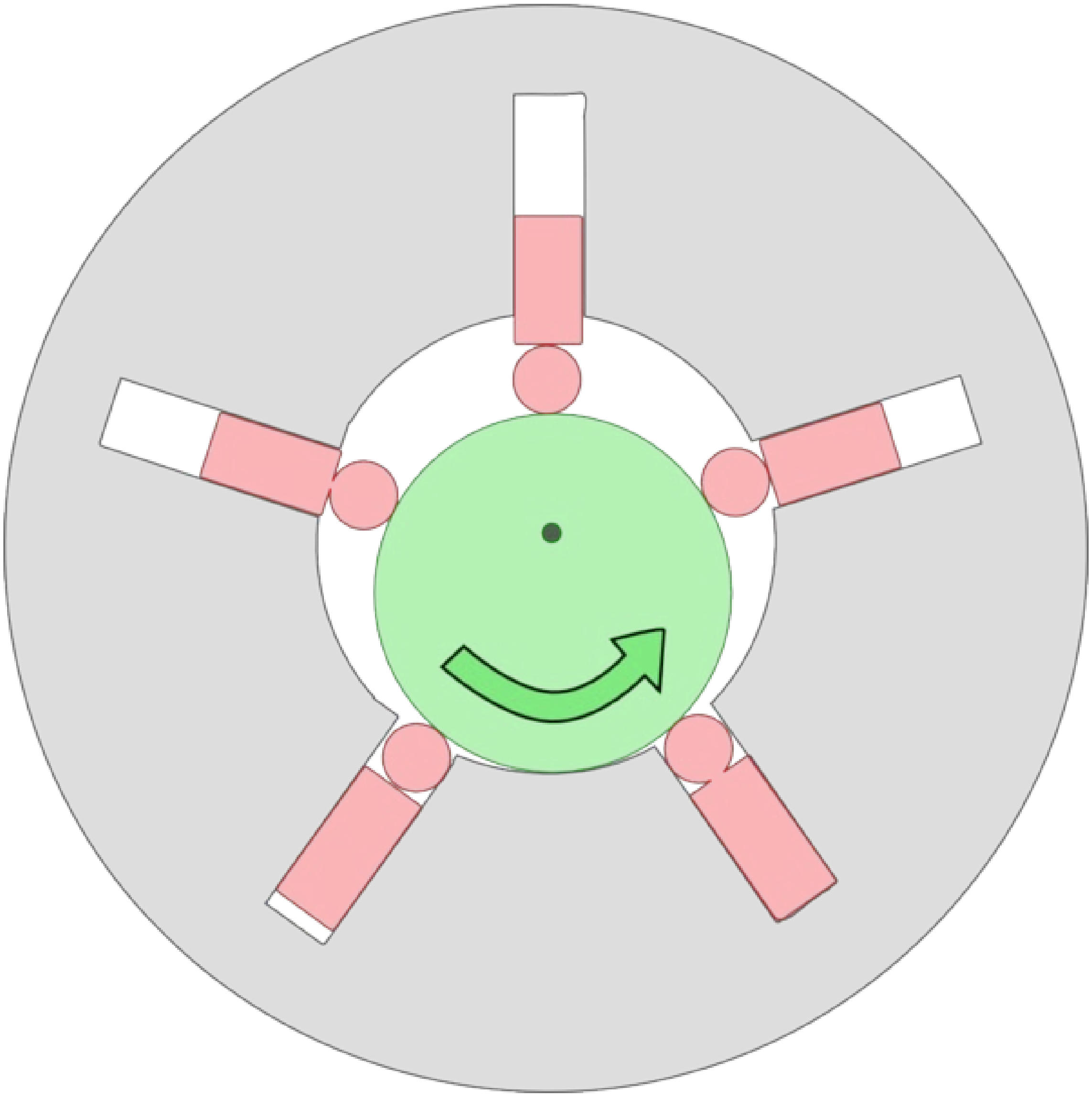
Fixed displacement vane pump



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

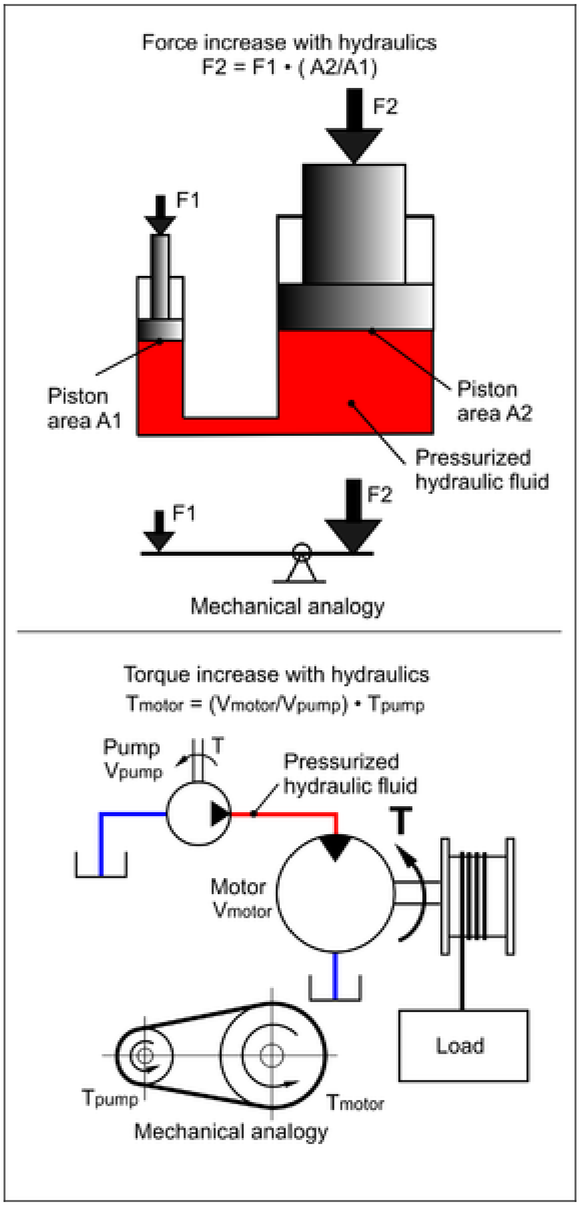
Chapter 6

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:

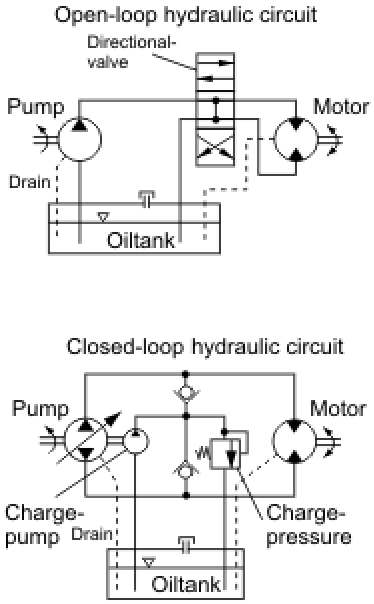
F = Ab * pb - Ah * ph
F = Pushing Force in N
Ab = (π/4) * (Bottom-diameter)^2 [in m2]
Ah = (π/4) * ((Bottom-diameter)^2-(Piston-rod-diameter)^2)) [in m2]
pb = pressure at bottom side in [N/m2]
ph = pressure at cylinder head side in [N/m2]

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.

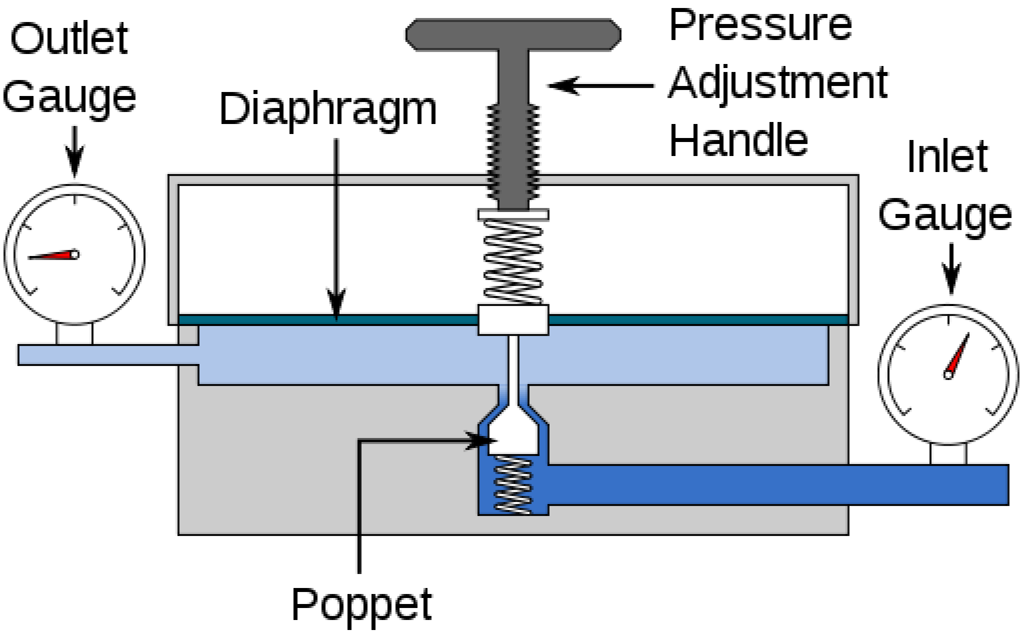
Chapter 7

Pressure Regulator

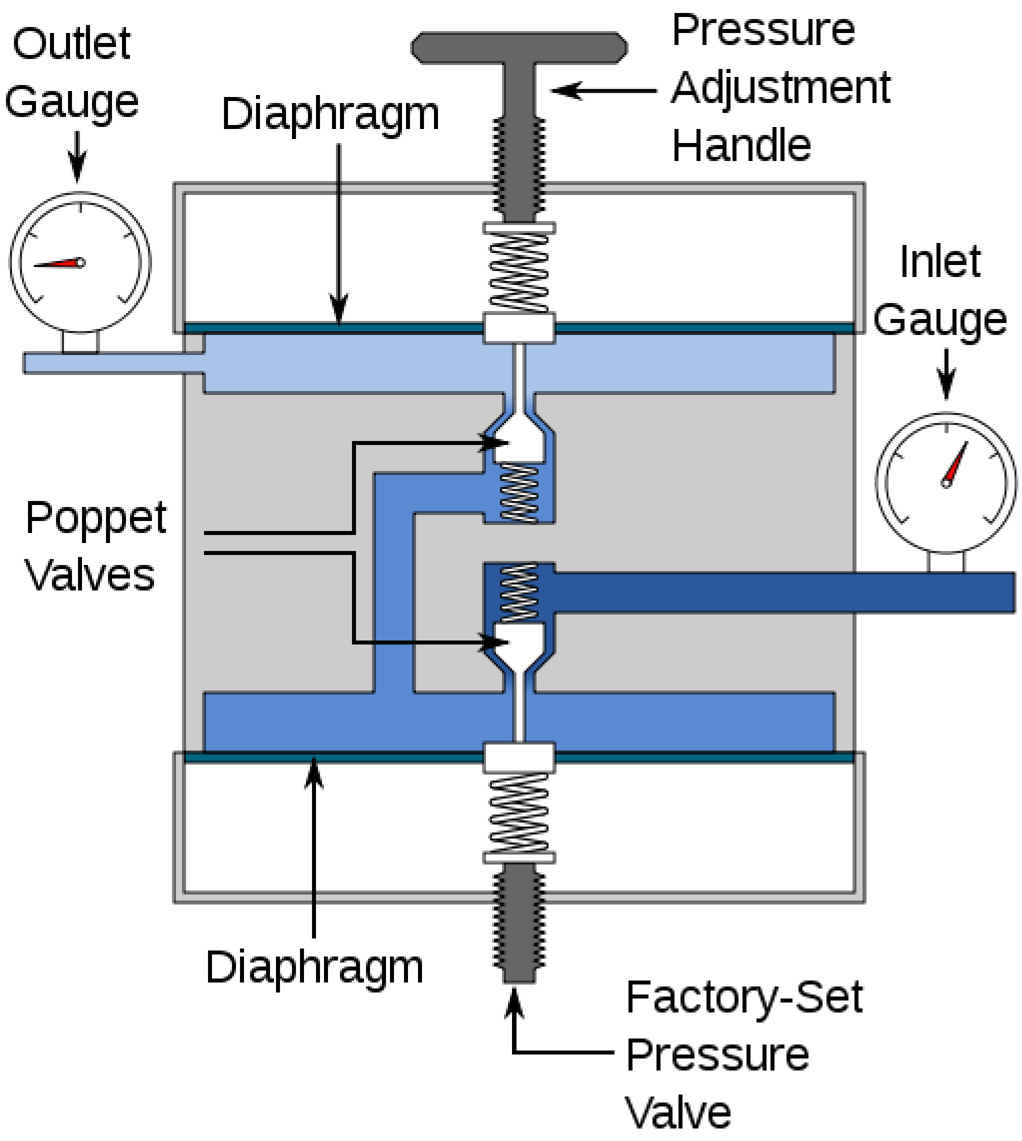
Oxygen and MAPP gas cylinders with two-stage pressure regulators

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).

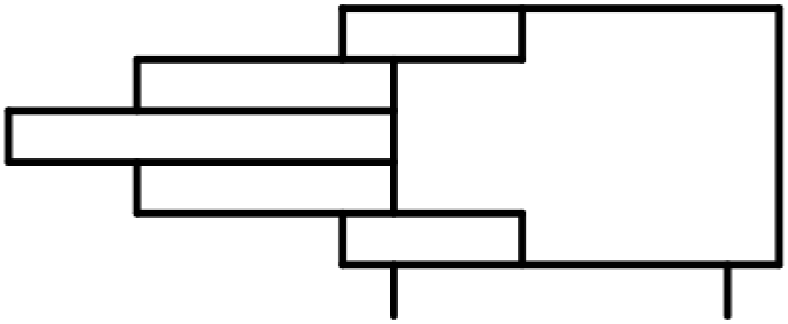
Mining Industry

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)

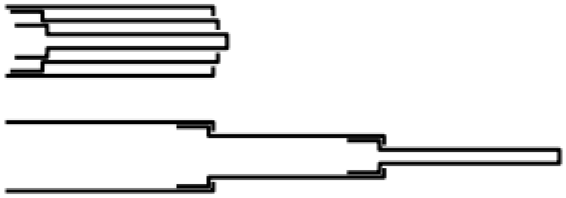
Telescopic cylinders are usually powered by hydraulics but some special light duty designs are powered by compressed air.

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.

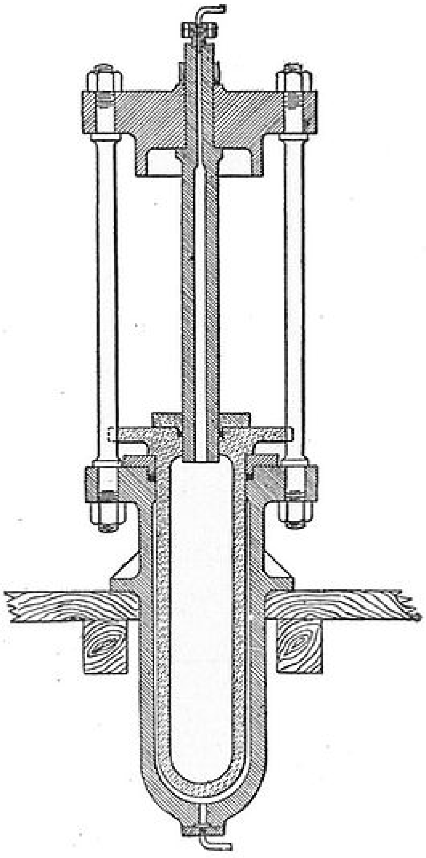
An example of this is erecting the mast of a large mobile drilling rig. The mast is erected to the vertical position using a telescopic cylinder. However, to lower the mast, gravity is not available for the initial tilt back from the vertical position. Thus, the plunger stage only of the telescopic actuator 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.

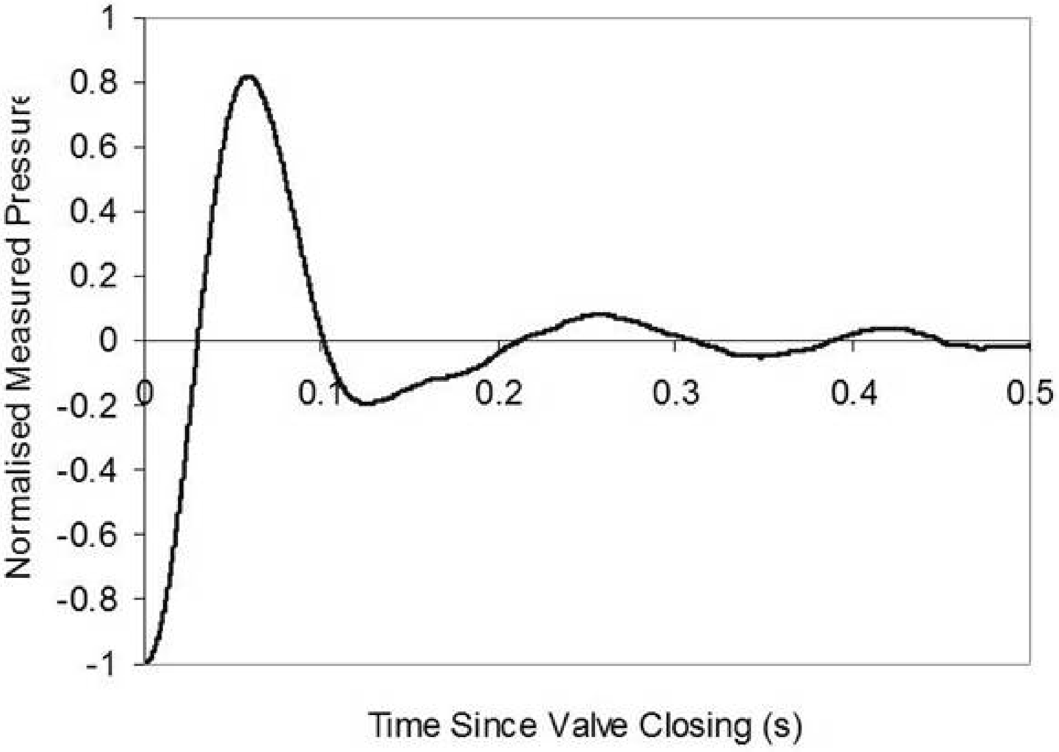
Where air filled traps are used, these eventually become depleted of their trapped air over a long period of time through absorption into the water. This can be cured by shutting off the supply, opening taps at the highest and lowest locations to drain the system (thereby restoring air to the traps),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

Hydraulic Engineering

Hydraulic Flood Retention Basin (HFRB)

View from Church Span Bridge, Bern, Switzerland

Riprap lining a lake shore

Hydraulic engineering as a sub-discipline of civil engineering is concerned with the flow and conveyance of fluids, principally water and sewage. One feature of these systems is the extensive use of gravity as the motive force to cause the movement of the fluids. This area of civil engineering is intimately related to the design of bridges, dams, channels, canals, and levees, and to both sanitary and environmental engineering.

Hydraulic engineering is the application of fluid mechanics principles to problems dealing with the collection, storage, control, transport, regulation, measurement, and use of water . Before beginning a hydraulic engineering project, one must figure out how much water is involved. The hydraulic engineer is concerned with the transport of sediment by the river, the interaction of the water with its alluvial boundary, and the occurrence of scour and disposition.

Fundamental Principles

A few examples of the fundamental principles of hydraulic engineering include fluid mechanics, fluid flow, behavior of real fluids, hydrology, pipelines, open channel hydraulics, mechanics of sediment transport, physical modeling, hydraulic machines, and drainage hydraulics.

Fluid Mechanics

Fundamentals of Hydraulic Engineering defines hydrostatics as the study of fluids at rest. Fluids at rest indicate that there exists a force, known as pressure, that acts upon its surroundings. This pressure, measured in N/m^2, is not constant throughout the body of fluid. Pressure, p, in a given body of fluid, increases with an increase in depth. Where the upward force on a body acts on the base and can be found by equation:

$$p=\rho gy$$

where,

ρ = density of water
g = specific gravity
y = depth of the body of liquid

Rearranging this equation gives you the “pressure head” $p/\rho g = y$. Four basic devices for finding pressure are a piezometer, manometer, differential manometer, Bourdon gauge, as well as an inclined manometer.

As Prasuhn states:

> On undisturbed submerged bodies, pressure acts along all surfaces of a body in a liquid, causing equal perpendicular forces in the body to act against the pressure of the liquid. This reaction is known as equilibrium. More advanced applications of pressure are that on plane surfaces, curved surfaces, dams, and quadrant gates, just to name a few.

Behavior of Real Fluids

1. Real and Ideal fluids

The main difference between an ideal fluid and a real fluid is that for ideal flow $p^1=p^2$ and for real flow $p^1>p^2$.

2. Viscous Flow

A viscous fluid will deform continuously under a shear force, whereas an ideal fluid doesn't deform.

3. Laminar Flow and Turbulence

The various effects of disturbance on a viscous flow are stable, transition and unstable.

Bernouilli's equation: $p/\rho g + u^2/2g = p_A/\rho g + u_A^2/2g = p_B/\rho g + u_B^2/2g$

where $p_B > p_A$

4. Boundary Layer

Assuming a flow is bounded on one side only, and that a rectilinear flow passing over a stationary flat plate which lies parallel to the flow, the flow just upstream of the plate has a uniform velocity. As the flow comes into contact with the plate, the layer of fluid actually 'adheres' to a solid surface. There is then a considerable shearing action between the layer of fluid on the plate surface and the second layer of fluid. The second layer is therefore forced to decelerate (though it is not quite brought to rest), creating a shearing action with the third layer of fluid, and so on. as the fluid passes further along the plate, the zone in which shearing action occurs tends to spread further outwards. this zone is known as the 'boundary layer'. The flow outside the boundary layer is free of shear and viscous-related forces so it is assumed to act like an ideal fluid. The flow inside the layer can be either viscous or turbulent, depending on Reynolds number.

Applications

Common topics of design for hydraulic engineers include hydraulic structures such as dams, levees, water distribution networks, water collection networks, sewage collection networks, storm water management, sediment transport, and various other topics related to transportation engineering and geotechnical engineering. Equations developed from the principles of fluid dynamics and fluid mechanics are widely utilized by other engineering disciplines such as mechanical, aeronautical and even traffic engineers.

Related branches include hydrology and rheology while related applications include hydraulic modeling, flood mapping, catchment flood management plans, shoreline management plans, estuarine strategies, coastal protection, and flood alleviation.

History

Earliest uses of hydraulic engineering were to irrigate crops and dates back to the Middle East and Africa. Controlling the movement and supply of water for growing food has been used for many thousands of years. One of the earliest hydraulic machines, the water clock was used in the early 2nd millennium BC. Other early examples of using gravity to move water include the Qanat system in ancient Persia and the very similar Turpan water system in ancient China as well as irrigation canals in Peru.

In ancient China, hydraulic engineering was highly developed, and engineers constructed massive canals with levees and dams to channel the flow of water for irrigation, as well as locks to allow ships to pass through. Sunshu Ao is considered the first Chinese hydraulic engineer. Another important Hydraulic Engineer in China, Ximen Bao was credited of starting the practice of large scale canal irrigation during the Warring States Period (481 BC-221 BC), even today hydraulic engineers remain a respectable position in China. Before becoming President, Hu Jintao was a hydraulic engineer and holds an engineering degree from Tsinghua University

Eupalinos of Megara, was an ancient Greek engineer who built the Tunnel of Eupalinos on Samos Island in the 6th century BC, an important feat of both civil and hydraulic engineering. The civil engineering aspect of this tunnel was the fact that it was dug from both ends which required the diggers to maintain an accurate path so that the two tunnels met and that the entire effort maintained a sufficient slope to allow the water to flow.

Hydraulic engineering was highly developed in Europe under the aegis of the Roman Empire where it was especially applied to the construction and maintenance of aqueducts to supply water to and remove sewage from their cities. In addition to supplying the needs of their citizens they used hydraulic mining methods to prospect and extract alluvial gold deposits in a technique known as hushing, and applied the methods to other ores such as those of tin and lead.

Further advances in hydraulic engineering occurred in the Muslim world between the 8th to 16th centuries, during what is known as the Islamic Golden Age. Of particular importance was the 'water management technological complex' which was central to the Islamic Green Revolution and, by extension, a precondition for the emergence of modern technology. The various components of this 'toolkit' were developed in different parts of the Afro-Eurasian landmass, both within and beyond the Islamic world. However, it was in the medieval Islamic lands where the technological complex was assembled and standardized, and subsequently diffused to the rest of the Old World. Under the rule of a single Islamic Caliphate, different regional hydraulic technologies were assembled into "an identifiable water management technological complex that was to have a global impact." The various components of this complex included canals, dams, the *qanat* system from Persia, regional water-lifting devices such as the *noria, shaduf* and screwpump from Egypt, and the windmill from Islamic Afghanistan. Other original Islamic developments included the *saqiya* with a flywheel effect from Islamic Spain, the reciprocating suction pump and crankshaft-connecting rod mechanism from Iraq, the geared and hydropowered water supply system from Syria, and the water purification methods of Islamic chemists.

Modern times

In many respects the fundamentals of hydraulic engineering haven't changed since ancient times. Liquids are still moved for the most part by gravity through systems of canals and aqueducts, though the supply reservoirs may now be filled using pumps. The need for water has steadily increased from ancient times and the role of the hydraulic engineer is a critical one in supplying it. For example, without the efforts of people like William Mulholland the Los Angeles area would not have been able to grow as it has because it simply doesn't have enough local water to support its population. The same is true for many of our worlds largest cities. In much the same way, the central valley of California could not have become such an important agricultural region without effective water management and distribution for irrigation.

In a somewhat parallel way to what happened in California the creation of the Tennessee Valley Authority(TVA) brought work and prosperity to the South by building dams to generate cheap electricity and control flooding in the region, making rivers navigable and generally modernizing life the region.

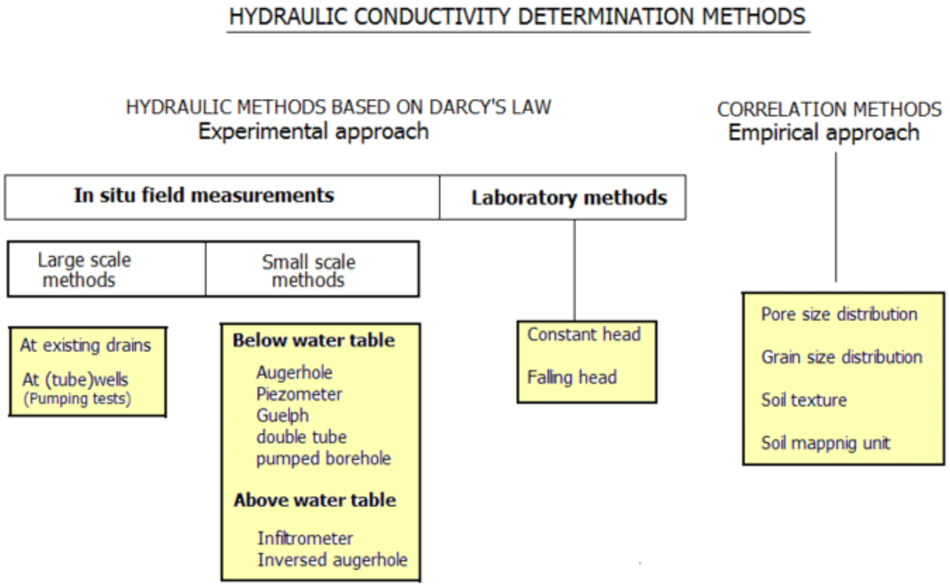
The modern hydraulic engineer uses the same kinds of computer-aided design (CAD) tools as many of the other engineering disciplines while also making use of technologies like computational fluid dynamics to perform the calculations to accurately predict flow characteristics, GPS mapping to assist in locating the best paths for installing a system and laser-based surveying tools to aid in the actual construction of a system.

Chapter 12

Hydraulic Conductivity

Hydraulic conductivity, symbolically represented as K, is a property of vascular plants, soil or rock, that describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity, K_{sat}, describes water movement through saturated media.

Methods of determination



Overview of determination methods

There are two broad categories of determining hydraulic conductivity:

- *Empirical* approach by which the hydraulic conductivity is correlated to soil properties like pore size and particle size (grain size) distributions, and soil texture
- *Experimental* approach by which the hydraulic conductivity is determined from hydraulic experiments using Darcy's law

The experimental approach is broadly classified into:

- Laboratory tests using soil samples subjected to hydraulic experiments
- *Field tests* (on site, in situ) that are differentiated into:
    - small scale field tests, using observations of the water level in cavities in the soil
    - large scale field tests, like pump tests in wells or by observing the functioning of existing horizontal drainage systems.

The small scale field tests are further subdivided into:

- infiltration tests in cavities *above* the water table
- slug tests in cavities *below* the water table

Estimation by empirical approach

Estimation from grain size

Shepherd derived an empirical formula for approximating hydraulic conductivity from grain size analyses:

$$K = a(D_{10})^b$$

where

a and b are empirically derived terms based on the soil type, and
D_{10} is the diameter of the 10 percentile grain size of the material

Note: Shepherd's Figure 3 clearly shows the use of D_{50}, not D_{10}, measured in mm. Therefore the equation should be $K = a(D_{50})^b$. His figure shows different lines for materials of different types, based on analysis of data from others with D_{50} up to 10 mm.

Pedotransfer function

A pedotransfer function (PTF) is a specialized empirical estimation method, used primarily in the soil sciences, however has increasing use in hydrogeology. There are many different PTF methods, however, they all attempt to determine soil properties, such as hydraulic conductivity, given several measured soil properties, such as soil particle size, and bulk density.

Determination by experimental approach

There are relatively simple and inexpensive laboratory tests that may be run to determine the hydraulic conductivity of a soil: constant-head method and falling-head method.

Laboratory methods

Constant-head method

The constant-head method is typically used on granular soil. This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. By knowing the quantity *Q* of water measured, length *L* of specimen, cross-sectional area *A* of the specimen, time *t* required for the quantity of water *Q* to be discharged, and head *h*, the hydraulic conductivity can be calculated:

$$Q = Avt$$

where *v* is the flow velocity. Using Darcy's Law:

$$v = Ki$$

and expressing the hydraulic gradient *i* as:

$$i = \frac{h}{L}$$

where *h* is the difference of hydraulic head over distance *L*, yields:

$$Q = \frac{AKht}{L}$$

Solving for *K* gives:

$$K = \frac{QL}{Ath}$$

Falling-head method

The falling-head method is totally different than the constant head methods in its initial setup; however, the advantage to the falling-head method is that can be used for both fine-grained and coarse-grained soils. The soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil without maintaining a constant pressure head.

$$K = \frac{2.3aL}{At} \log\left(\frac{h_1}{h_2}\right)$$

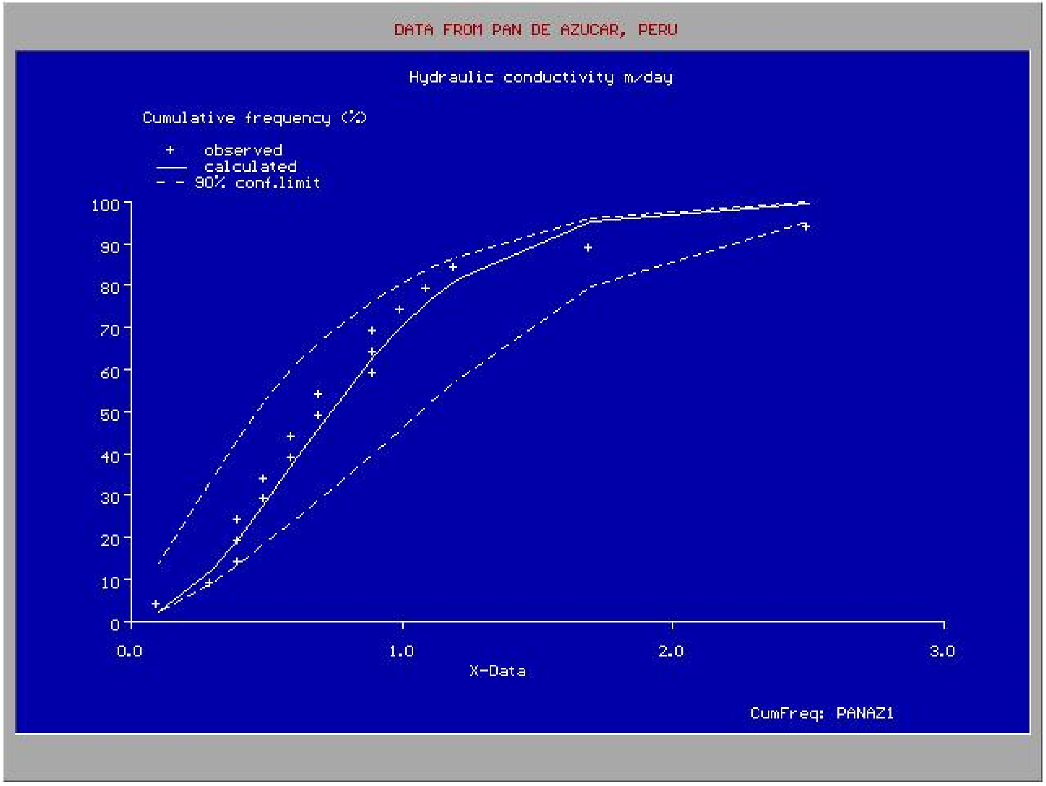
In-situ (field) methods

Augerhole method

There are also in-situ methods for measuring the hydraulic conductivity in the field. When the water table is shallow, the augerhole method, a slug test, can be used for determining the hydraulic conductivity below the water table.
The method was developed by Hooghoudt (1934) in The Netherlands and introduced in the US by Van Bavel en Kirkham (1948).
The method uses the following steps:

1. an augerhole is perforated into the soil to below the water table
2. water is bailed out from the augerhole
3. the rate of rise of the water level in the hole is recorded
4. the K-value is calculated from the data as :

K_h = C (Ho-Ht) / t



Cumulative frequency distribution (lognormal) of hydraulic conductivity (X-data) where: K_h = horizontal saturated hydraulic conductivity (m/day), H = depth of the waterlevel in the hole relative to the water table in the soil (cm), Ht = H at time t, Ho = H at time t = 0, t = time (in seconds) since the first measurement of H as Ho, and F is a factor depending on the geometry of the hole:

$$F = 4000r / h'(20+D/r)(2-h'/D)$$

where: r = radius of the cylindrical hole (cm), h' is the average depth of the water level in the hole relative to the water table in the soil (cm) , found as h'=(Ho+Ht)/2 , and D is the depth of the bottom of the hole relative to the water table in the soil (cm).

The picture shows a large variation of K-values measured with the augerhole method in an area of 100 ha. The ratio between the highest and lowest values is 25. The cumulative frequency distribution is lognormal and was made with the CumFreq program.

Related magnitudes

Transmissivity

An aquifer may consist of *n* soil layers. The *transmissivity* for horizontal flow (T_i) of the $i-th$ soil layer with a *saturated* thickness d_i and horizontal hydraulic conductivity Kh_i is:

$$T_i = Kh_i \, d_i$$

Transmissivity is directly proportional to horizontal hydraulic conductivity (Kh_i) and thickness (d_i). Expressing Kh_i in m/day and d_i in m, the transmissivity (T_i) is found in units m^2/day.
The transmissivity is a measure of how much water can be transmitted horizontally, such as to a pumping well.

> *Transmissivity* should not be confused with the similar word transmittance used in optics, meaning the fraction of incident light that passes through a sample.

The total transmissivity (Tt) of the aquifer is :

$$Tt = \Sigma T_i = \Sigma Kh_i \, d_i$$

where Σ signifies the summation over all layers: i= 1, 2, 3, . . .n
The *apparent* horizontal hydraulic conductivity (Kh_A) of the aquifer is:

$$Kh_A = Tt / Dt$$

where Dt is the total thickness of the aquifer: Dt= Σd_i , with i= 1, 2, 3, . . .n

The transmissivity of an aquifer can be determined from pumping tests.

Influence of the water table

When a soil layer is above the water table, it is not saturated and does not contribute to the transmissivity. When the soil layer is entirely below the water table, its saturated thickness corresponds to the thickness of the soil layer itself. When the water table is inside a soil layer, the saturated thickness corresponds to the distance of the water table to the bottom of the layer. As the water table may behave dynamically, this thickness may change from place to place or from time to time, so that the transmissivity may vary accordingly.

In a semi-confined aquifer, the water table is found within a soil layer with a negligibly small transmissivity, so that changes of the total transmissivity (Dt) resulting from changes in the level of the water table are negligibly small.

When pumping water from an unconfined aquifer, where the water table is inside a soil layer with a significant transmissivity, the water table may be drawn down whereby the transmissivity reduces and the flow of water to the well diminishes.

Resistance

The *resistance* to vertical flow (R_i) of the $i-th$ soil layer with a *saturated* thickness d_i and vertical hydraulic conductivity Kv_i is:

$$R_i = d_i / Kv_i$$

Expressing Kv_i in m/day and d_i in m, the resistance (R_i) is expressed in days.

The total resistance (Rt) of the aquifer is :

$$Rt = \Sigma R_i = \Sigma d_i / Kv_i$$

where Σ signifies the summation over all layers: $i= 1, 2, 3, \ldots n$

The *apparent* vertical hydraulic conductivity (Kv_A) of the aquifer is:

$$Kv_A = Dt / Rt$$

where Dt is the total thickness of the aquifer: $Dt = \Sigma d_i$, with $i= 1, 2, 3, \ldots n$

The resistance plays a role in aquifers where a sequence of layers occurs with varying horizontal permeability so that horizontal flow is found mainly in the layers with high horizontal permeability while the layers with low horizontal permeability transmit the water mainly in a vertical sense.

Anisotropy

When the horizontal and vertical hydraulic conductivity (Kh_i and Kv_i) of the $i-th$ soil layer differ considerably, the layer is said to be anisotropic with respect to hydraulic conductivity.

When the *apparent* horizontal and vertical hydraulic conductivity (Kh_A and Kv_A) differ considerably, the aquifer is said to be anisotropic with respect to hydraulic conductivity.

An aquifer is called *semi-confined* when a saturated layer with a relatively small horizontal hydraulic conductivity (the semi-confining layer or aquitard) overlies a layer with a relatively high horizontal hydraulic conductivity so that the flow of groundwater in the first layer is mainly vertical and in the second layer mainly horizontal.
The resistance of a semi-confining toplayer of an aquifer can be determined from pumping tests.
When calculating flow to drains or to a well field in an aquifer with the aim to control the water table, the anisotropy is to be taken into account, otherwise the result may be erroneous.

Relative properties

Because of their high porosity and permeability, sand and gravel aquifers have higher hydraulic conductivity than clay or unfractured granite aquifers. Sand or gravel aquifers would thus be easier to extract water from (e.g., using a pumping well) because of their high transmissivity, compared to clay or unfractured bedrock aquifers.

Hydraulic conductivity has units with dimensions of length per time (e.g., m/s, ft/day and (gal/day)/ft^2); transmissivity then has units with dimensions of length squared per time. The following table gives some typical ranges (illustrating the many orders of magnitude which are likely) for *K* values.

Hydraulic conductivity (*K*) is one of the most complex and important of the properties of aquifers in hydrogeology as the values found in nature:

- range over many orders of magnitude (the distribution is often considered to be lognormal),
- vary a large amount through space (sometimes considered to be randomly spatially distributed, or stochastic in nature),
- are directional (in general *K* is a symmetric second-rank tensor; e.g., vertical *K* values can be several orders of magnitude smaller than horizontal *K* values),
- are scale dependent (testing a m^3 of aquifer will generally produce different results than a similar test on only a cm^3 sample of the same aquifer),
- must be determined indirectly through field pumping tests, laboratory column flow tests or inverse computer simulation, (sometimes also from grain size analyses), and
- are very dependent (in a non-linear way) on the water content, which makes solving the unsaturated flow equation difficult. In fact, the variably saturated *K* for a single material varies over a wider range than the saturated *K* values for all types of materials.

Ranges of values for natural materials

Table of saturated hydraulic conductivity (*K*) values found in nature

Values are for typical fresh groundwater conditions — using standard values of viscosity and specific gravity for water at 20°C and 1 atm.

<table>
<tr><td><i>K</i> (cm/s)</td><td>10^2</td><td>10^1</td><td>10^0=1</td><td>10^{-1}</td><td>10^{-2}</td><td>10^{-3}</td><td>10^{-4}</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td></tr>
<tr><td><i>K</i> (ft/day)</td><td>10^5</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td></tr>
<tr><td>Relative Permeability</td><td colspan="4">Pervious</td><td colspan="4">Semi-Pervious</td><td colspan="5">Impervious</td></tr>
<tr><td>Aquifer</td><td colspan="5">Good</td><td colspan="4">Poor</td><td colspan="4">None</td></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Fat / Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
</table>

Chapter 13

Hydropower

Saint Anthony Falls, United States.

Hydropower, **hydraulic power** or **water power** is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the widespread availability of commercial electric power, hydropower was used for irrigation, and operation of various machines, such as watermills, textile machines, sawmills, dock cranes, and domestic lifts.

Another method used a trompe to produce compressed air from falling water, which could then be used to power other machinery at a distance from the water.

In hydrology, hydropower is manifested in the force of the water on the riverbed and banks of a river. It is particularly powerful when the river is in flood. The force of the water results in the removal of sediment and other materials from the riverbed and banks of the river, causing erosion and other alterations.

History

Early uses of waterpower 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.

Waterwheels and mills

Hydropower has been used for hundreds of years. In India, water wheels and watermills were built; in Imperial Rome, water powered mills produced flour from grain, and were also used for sawing timber and stone; in China, watermills were widely used since the Han Dynasty. The power of a wave of water released from a tank was used for extraction of metal ores in a method known as hushing. The method was first used at the Dolaucothi gold mine in Wales from 75 AD onwards, but had been developed in Spain at such mines as Las Medulas. Hushing was also widely used in Britain in the Medieval and later periods to extract lead and tin ores. It later evolved into hydraulic mining when used during the California gold rush.

In China and the rest of the Far East, hydraulically operated "pot wheel" pumps raised water into irrigation canals. At the beginning of the Industrial revolution in Britain, water was the main source of power for new inventions such as Richard Arkwright's water frame. Although the use of water power gave way to steam power in many of the larger mills and factories, it was still used during the 18th and 19th centuries for many smaller operations, such as driving the bellows in small blast furnaces (e.g. the Dyfi Furnace) and gristmills, such as those built at Saint Anthony Falls, which uses the 50-foot (15 m) drop in the Mississippi River.

In the 1830s, at the peak of the canal-building era, hydropower was used to transport barge traffic up and down steep hills using inclined plane railroads.

Hydraulic power pipes

Hydraulic power networks also existed, using pipes carrying pressurized liquid to transmit mechanical power from a power source, such as a pump, to end users. These were extensive in Victorian cities in the United Kingdom. A hydraulic power network was also in use in Geneva, Switzerland. The world famous Jet d'Eau was originally the only over pressure valve of this network.

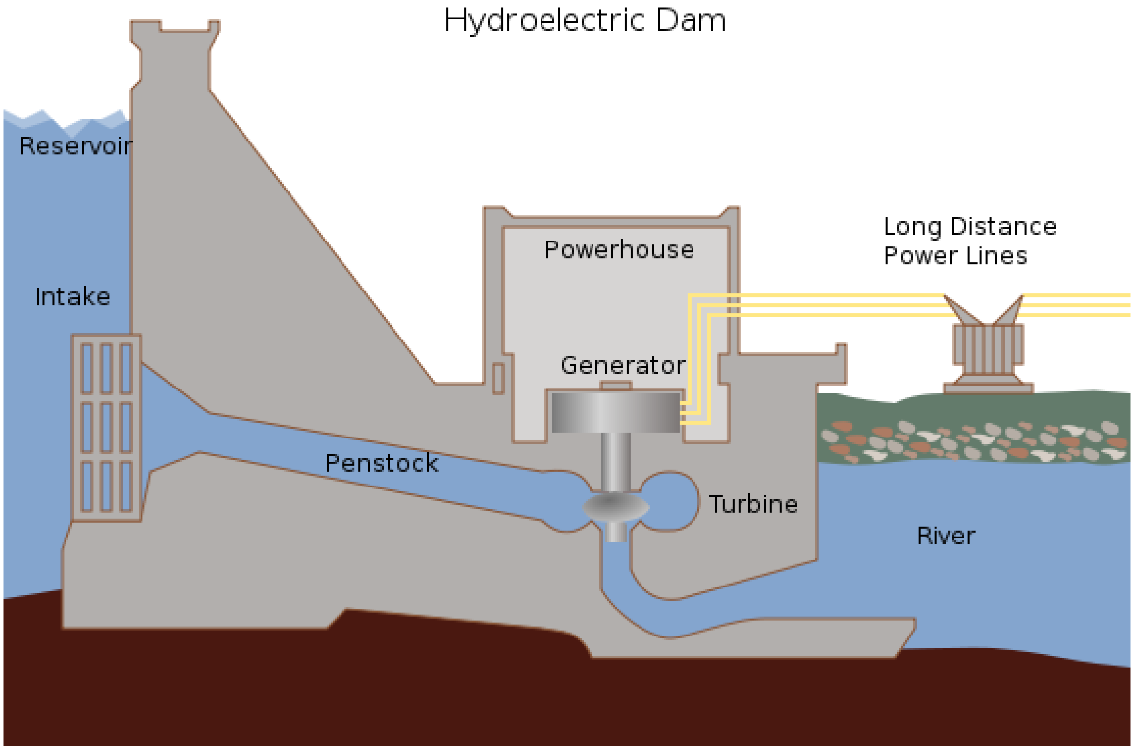
Compressed air hydro

Where there is a plentiful head of water it can be made to generate compressed air directly without moving parts. A falling column of water is mixed with air bubbles generated through turbulence at the inlet. This is allowed to fall down a shaft into a subterranean chamber where the air separates from the water. The weight of falling water compresses the air in the top of the chamber. A submerged outlet from the chamber allows water to flow to the surface at a lower height than the intake. An outlet in the roof of the chamber supplies the compressed air to the surface. A facility on this principal was built on the Montreal River at Ragged Shutes near Cobalt, Ontario in 1910 and supplied 5,000 horsepower to nearby mines.

Modern usage

There are several forms of water power currently in use or development. Some are purely mechanical but many primarily generate electricity. Broad categories include:

Hydroelectricity



A conventional dammed-hydro facility (hydroelectric dam) is the most common type of hydroelectric power generation.

- Conventional hydroelectric, referring to hydroelectric dams.
- Run-of-the-river hydroelectricity, which captures the kinetic energy in rivers or streams, without the use of dams.

- Pumped-storage hydroelectricity, to pump up water, and use its head to generate in times of demand.
- Tidal power, which captures energy from the tides in horizontal direction.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.

Marine energy

A Pelamis wave device under test at the European Marine Energy Centre (EMEC), Orkney, Scotland.

- Marine current power, which captures the kinetic energy from marine currents.
- Osmotic power, which channels river water into a container separated from sea water by a semi-permeable membrane.
- Ocean thermal energy, which exploits the temperature difference between deep and shallow waters.
- Tidal power, which captures energy from the tides in horizontal direction. Also a popular form of hydroelectric power generation.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.
- Wave power, the use ocean surface waves to generate power.

Calculating the amount of available power

A hydropower resource can be measured according to the amount of available power, or energy per unit time. In large reservoirs, the available power is generally only a function of the hydraulic head and rate of fluid flow. In a reservoir, the head is the height of water in the reservoir relative to its height after discharge. Each unit of water can do an amount of work equal to its weight times the head.

The amount of energy, *E*, released when an object of mass *m* drops a height *h* in a gravitational field of strength *g* is given by

$$E = mgh$$

The energy available to hydroelectric dams is the energy that can be liberated by lowering water in a controlled way. In these situations, the power is related to the mass flow rate.

$$\frac{E}{t} = \frac{m}{t}gh$$

Substituting *P* for $^{E}\!/_{t}$ and expressing $^{m}\!/_{t}$ in terms of the volume of liquid moved per unit time (the rate of fluid flow, φ) and the density of water, we arrive at the usual form of this expression:

$$P = \rho \phi g h$$

or

A simple formula for approximating electric power production at a hydroelectric plant is:

P = hrgk

where P is Power in kilowatts, h is height in meters, r is flow rate in cubic meters per second, g is acceleration due to gravity of 9.8 m/s2, and k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher with larger and more modern turbines.

Some hydropower systems such as water wheels can draw power from the flow of a body of water without necessarily changing its height. In this case, the available power is the kinetic energy of the flowing water.

$$P = \frac{1}{2}\rho \phi v^2$$

where *v* is the speed of the water, or with

$$\phi = A v$$

where *A* is the area through which the water passes, also

$$P = \frac{1}{2} \rho A v^3$$

Over-shot water wheels can efficiently capture both types of energy.

Chapter 14

Hydraulic Mining

Hydraulic mining, or **hydraulicking**, is a form of mining that uses high-pressure jets of water to dislodge rock material or move sediment. In the placer mining of gold or tin, the resulting water-sediment slurry is directed through sluice boxes to remove the gold.

Precursor - ground sluicing

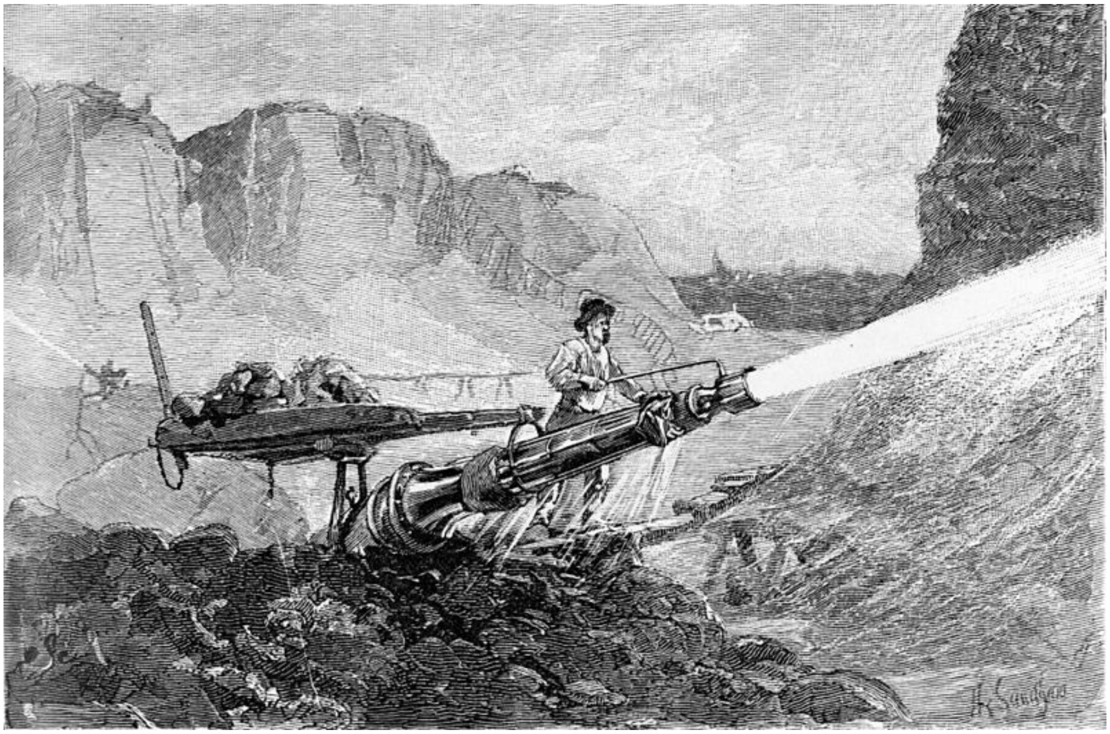
Hydraulicking had its precursor in the millennia-old practice of ground sluicing, also known as "hushing", in which surface streams of water were diverted so as to erode gold-bearing gravels. The Romans used ground sluicing to remove overburden and then gold-bearing debris in Las Médulas of Spain, and Dolaucothi in Britain. The method was also used in Elizabethan Britain for developing lead, tin and copper mines.

Panoramic view of Las Médulas

Roman era

Water was used on a large scale by Roman engineers in the first centuries BC and AD when the Roman empire was expanding rapidly in Europe. Using a process later known as hushing, the Romans stored a large volume of water in a reservoir immediately above the area to be mined; the water was then quickly released. The resulting wave of water removed overburden and exposed bedrock. Gold veins in the bedrock were then worked using a number of techniques, and water power was used again to remove debris. The remains at Las Medulas and in surrounding areas show badland scenery on a gigantic scale owing to hydraulicking of the rich alluvial gold deposits. Las Medulas is now a UNESCO World Heritage site. The site shows the remains of at least seven large aqueducts of up to 30 miles in length feeding large supplies of water into the site. The gold-mining operations were described in vivid terms by Pliny the Elder in his Naturalis Historia published in the first century AD. Pliny was a procurator in Hispania Terraconensis in the 70's and must have witnessed for himself the operations. The use of hushing has been confirmed by field survey and archaeology at Dolaucothi in South Wales, the only known Roman gold mine in Britain.

California hydraulicking



Hydraulic mining for gold in California, from *The Century Magazine* January 1883

The modern form of hydraulicking, using jets of water directed under very high pressure through hoses and nozzles at gold-bearing upland paleogravels, was first used by Edward Matteson near Nevada City, California in 1853 during the California Gold Rush. Matteson used canvas hose which was later replaced with crinoline hose by the 1860s. In

California, hydraulic mining often brought water from higher locations for long distances to holding ponds several hundred feet above the area to be mined. Insofar as California hydraulic mining exploited primarily river gravels, it was one form of placer mining, that is, working of alluvium (river sediments).

Gold miners excavate an eroded bluff with jets of water at a placer mine in Dutch Flat, California sometime between 1857 and 1870.

Early placer miners in California discovered that the more gravel they could process, the more gold they were likely to find. Instead of working with pans, sluice boxes, long toms, and rockers, miners collaborated to find ways to process larger quantities of gravel more rapidly. Hydraulic mining became the largest-scale, and most devastating, form of placer mining. Water was redirected into an ever-narrowing channel, through a large canvas hose, and out through a giant iron nozzle, called a "monitor." The extremely high pressure stream was used to wash entire hillsides through enormous sluices.

By the early 1860s, while hydraulic mining was at its height, small-scale placer mining had largely exhausted the rich surface placers, and the mining industry turned to hard rock (called quartz mining in California) or hydraulic mining, which required larger organizations and much more capital. By the mid-1880s, it is estimated that 11 million ounces of gold (worth approximately US$7.5 billion at mid-2006 prices) had been recovered by hydraulic mining in the California Gold Rush.

Environmental consequences

A man leans over a wooden sluice. Rocks line the outside of the wood boards that create the sluice.

While generating millions of dollars in tax revenues for the state and supporting a large population of miners in the mountains, hydraulic mining had a devastating effect on riparian natural environment and agricultural systems in California. Millions of tons of earth and water were delivered to mountain streams that fed rivers flowing into the Sacramento Valley. Once the rivers reached the relatively flat valley, the water slowed, the rivers widened, and the sediment was deposited in the floodplains and river beds causing them to rise, shift to new channels, and overflow their banks, causing major flooding, especially during the spring melt.

Cities and towns in the Sacramento Valley experienced an increasing number of devastating floods, while the rising riverbeds made navigation on the rivers increasingly difficult. Perhaps no other city experienced the boon and the bane of gold mining as much as Marysville. Situated at the confluence of the Yuba and Feather rivers, Marysville was the final "jumping off" point for miners heading to the northern foothills to seek their fortune. Steamboats from San Francisco, carrying miners and supplies, navigated up the Sacramento River, then the Feather River to Marysville where they would unload their passengers and cargo. Marysville eventually constructed a complex levee system to protect the city from floods and sediment. Hydraulic mining greatly exacerbated the problem of flooding in Marysville and shoaled the waters of the Feather River so severely that few steamboats could navigate from Sacramento to the Marysville docks.

The spectacular eroded landscape left at the site of hydraulic mining can be viewed at Malakoff Diggins State Historic Park in Nevada County, California. A similar landscape can be seen at Las Médulas in northern Spain, where Roman engineers ground sluiced the rich gold alluvial deposits of the river Sil. Pliny the Elder mentions in his Naturalis Historia that Spain had encroached on the sea and local lakes as a result of ground sluicing operations.

Legal ramifications

Vast areas of farmland in the Sacramento Valley were deeply buried by the mining sediment. Frequently devastated by flood waters, farmers demanded an end to hydraulic mining. In the most renowned legal fight of farmers against miners, the farmers sued the hydraulic mining operations and the landmark case of *Edwards Woodruff v. North Bloomfield Mining and Gravel Company* made its way to the United States District Court in San Francisco where Judge Lorenzo Sawyer decided in favor of the farmers in 1884, declaring that hydraulic mining was “a public and private nuisance” and enjoining its operation in areas tributary to navigable streams and rivers. Hydraulic mining was recommenced after 1893 when the United States Congress passed the Camminetti Act which allowed such mining if sediment detention structures were constructed. This led to a number of operations above brush dams and log crib dams. Most of the water-delivery infrastructure had been destroyed by an 1891 flood, so this later stage of mining was carried on at a much smaller scale in California.

Beyond California

The Oriental Claims near Omeo, Australia were mined between the 1850s and 1900s; hydraulic sluicing left man-made cliffs up to 30 metres (98 ft) high such as seen here throughout the area

Lee Moor china clay pit in Devon showing hydraulic mining

Although often associated with California due to its adoption and widespread use there, the technology was exported widely, to Oregon (Jacksonville in 1856), Colorado (Clear Creek, Central City and Breckenridge in 1860), Montana (Bannack in 1865), Arizona (Lynx Creek in 1868), Idaho (Idaho City in 1863), South Dakota (Deadwood in 1876), Alaska, British Columbia (Canada), and overseas. It was used extensively in Dahlonega, Georgia and continues to be used in developing nations, often with devastating environmental consequences. The devastation caused by this method of mining caused Edwin Carter, the "Log Cabin Naturalist," to switch from mining to collecting wildlife specimens from 1875-1900 in Breckenridge, Colorado, USA.

Hydraulic mining was also used during the Australian gold rushes where it was called hydraulic sluicing. One notable location was at the Oriental Claims near Omeo in

Victoria where it was used between the 1850s and early 1900s, with abundant evidence of the damage still being visible today.

Hydraulic mining was used extensively in the Central Otago Gold Rush that took place in the 1860s in the South Island of New Zealand, where it was also known as *sluicing*.

Starting in the 1870s, hydraulic mining became a mainstay of alluvial tin mining on the Malay Peninsula.

Hydraulicking was formerly used in Polk County, Florida to mine phosphate rock.

Hydraulic mining is the principal way that kaolinite clay is mined in Cornwall and Devon, in South-West England.

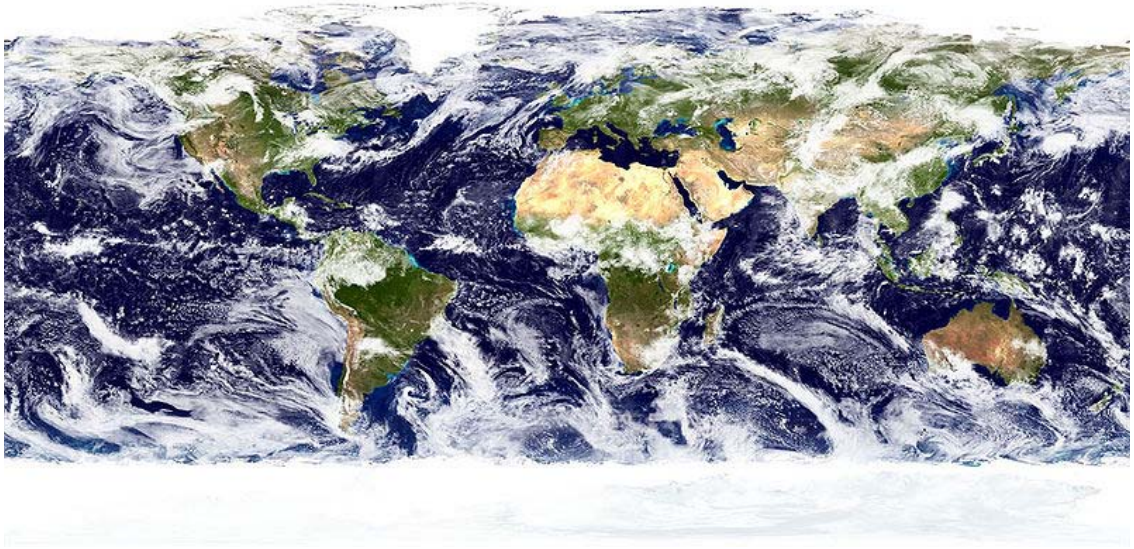
In addition to its use in true mining, hydraulic mining can be used as an excavation technique, principally to demolish hills. For example, the Denny Regrade in Seattle was largely accomplished by hydraulic mining.

Underground hydraulic mining

High-pressure water jets have also been used in the underground mining of coal, to break up the coal seam and wash the resulting coal slurry toward a collection point.

Chapter 15

Hydrology



Water covers 70% of the Earth's surface.

Hydrology is the study of the movement, distribution, and quality of water throughout the Earth, including the hydrologic cycle, water resources and environmental watershed sustainability. A practitioner of hydrology is a hydrologist, working within the fields of either earth or environmental science, physical geography, geology or civil and environmental engineering.

Domains of hydrology include hydrometeorology, surface hydrology, hydrogeology, drainage basin management and water quality, where water plays the central role. Oceanography and meteorology are not included because water is only one of many important aspects.

Hydrological research can inform environmental engineering, policy and planning.

The term *hydrology* is from Greek: ὕδωρ, *hydōr*, "water"; and λόγος, *logos*, "study".

History of hydrology

Hydrology has been a subject of investigation and engineering for millennia. For example, about 4000 B.C. the Nile was dammed to improve agricultural productivity of previously barren lands. Mesopotamian towns were protected from flooding with high earthen walls. Aqueducts were built by the Greeks and Ancient Romans, while the History of China shows they built irrigation and flood control works. The ancient Sinhalese used hydrology to build complex irrigation Works in Sri Lanka, also known for invention of the Valve Pit which allowed construction of large reservoirs, anicuts and canals which still function.

Marcus Vitruvius, in the first century B.C., described a philosophical theory of the hydrologic cycle, in which precipitation falling in the mountains infiltrated the Earth's surface and led to streams and springs in the lowlands. With adoption of a more scientific approach, Leonardo da Vinci and Bernard Palissy independently reached an accurate representation of the hydrologic cycle. It was not until the 17th century that hydrologic variables began to be quantified.

Pioneers of the modern science of hydrology include Pierre Perrault, Edme Mariotte and Edmund Halley. By measuring rainfall, runoff, and drainage area, Perrault showed that rainfall was sufficient to account for flow of the Seine. Marriotte combined velocity and river cross-section measurements to obtain discharge, again in the Seine. Halley showed that the evaporation from the Mediterranean Sea was sufficient to account for the outflow of rivers flowing into the sea.

Advances in the 18th century included the Bernoulli piezometer and Bernoulli's equation, by Daniel Bernoulli, the Pitot tube. The 19th century saw development in groundwater hydrology, including Darcy's law, the Dupuit-Thiem well formula, and Hagen-Poiseuille's capillary flow equation.

Rational analyses began to replace empiricism in the 20th century, while governmental agencies began their own hydrological research programs. Of particular importance were Leroy Sherman's unit hydrograph, the infiltration theory of Robert E. Horton, and C.V. Theis's Aquifer test/equation describing well hydraulics.

Since the 1950s, hydrology has been approached with a more theoretical basis than in the past, facilitated by advances in the physical understanding of hydrological processes and by the advent of computers and especially Geographic Information Systems (GIS).

Hydrologic cycle

The central theme of hydrology is that water circulates throughout the Earth through different pathways and at different rates. The most vivid image of this is in the evaporation of water from the ocean, which forms clouds. These clouds drift over the land and produce rain. The rainwater flows into lakes, rivers, or aquifers. The water in lakes, rivers, and aquifers then either evaporates back to the atmosphere or eventually flows back to the ocean, completing a cycle. Water changes its state of being several times throughout this cycle.

Overview

Branches of hydrology

Chemical hydrology is the study of the chemical characteristics of water.
Ecohydrology is the study of interactions between organisms and the hydrologic cycle.
Hydrogeology is the study of the presence and movement of ground water.
Hydroinformatics is the adaptation of information technology to hydrology and water resources applications.
Hydrometeorology is the study of the transfer of water and energy between land and water body surfaces and the lower atmosphere.
Isotope hydrology is the study of the isotopic signatures of water.
Surface hydrology is the study of hydrologic processes that operate at or near Earth's surface.
Drainage basin management covers water-storage, in the form of reservoirs, and flood-protection.
Water quality includes the chemistry of water in rivers and lakes, both of pollutants and natural solutes.

Related topics

Oceanography is the more general study of water in the oceans and estuaries.
Meteorology is the more general study of the atmosphere and of weather, including precipitation as snow and rainfall.
Limnology is the study of lakes. It covers the biological, chemical, physical, geological, and other attributes of all inland waters (running and standing waters, both fresh and saline, natural or man-made).

Applications of hydrology

- Determining the water balance of a region.
- Determining the agricultural water balance.
- Designing riparian restoration projects.
- Mitigating and predicting flood, landslide and drought risk.
- Real-time flood forecasting and flood warning.
- Designing irrigation schemes and managing agricultural productivity.
- Part of the hazard module in catastrophe modeling.
- Providing drinking water.
- Designing dams for water supply or hydroelectric power generation.
- Designing bridges.
- Designing sewers and urban drainage system.
- Analyzing the impacts of antecedent moisture on sanitary sewer systems.
- Predicting geomorphological changes, such as erosion or sedimentation.

- Assessing the impacts of natural and anthropogenic environmental change on water resources.
- Assessing contaminant transport risk and establishing environmental policy guidelines.

Hydrologic measurements

Measurement is fundamental for assessing water resources and understanding the processes involved in the hydrologic cycle. Because the hydrologic cycle is so diverse, hydrologic measurement methods span many disciplines: including soils, oceanography, atmospheric science, geology, geophysics and limnology, to name a few. Here, hydrologic measurement methods are organized by hydrologic sub-disciplines. Each of these subdisciplines is addressed briefly with a practical discussion of the methods used to date and a bibliography of background information.

Quantifying groundwater flow and transport

- Aquifer characterization
    - Flow direction
        - Piezometer - groundwater pressure and, by inference, groundwater depth (see: aquifer test)
        - Conductivity, storativity, transmisivity
        - Geophysical methods

- Vadose zone characterization
    - Infiltration
        - Infiltrometer - infiltration
    - Soil moisture
        - Capacitance probe-soil moisture
        - Time domain reflectometer - soil moisture
        - Tensiometer - soil moisture
        - Solute sampling
        - Geophysical methods

Quantifying surface water flow and transport

- Direct and indirect discharge measurements
    - Stream gauge - stream flow (see: discharge (hydrology))
    - Tracer techniques
    - Chemical transport
    - Sediment transport and erosion
    - Stream-aquifer exchange

Quantifying exchanges at the land-atmosphere boundary

- Precipitation

    - Bulk rain events
        - Disdrometer - precipitation characteristics
        - Radar - cloud properties, rain rate estimation, hail and snow detection
        - Rain gauge - rain and snowfall
        - Satellite - rainy area identification, rain rate estimation, land-cover/land-use, soil moisture
        - Sling psychrometer - humidity
    - Snow, hail and ice
    - Dew, mist and fog
- Evaporation
    - from water surfaces
    - Evaporation -Symon's evaporation pan
    - from plant surfaces
    - through the boundary layer
- Transpiration
    - Natural ecosystems
    - Agronomic ecosystems
- Momentum
- Heat flux
    - Energy budgets

Uncertainty analyses
Remote sensing of hydrologic processes

- Land based sensors
- Airborne Sensors
- Satellite sensors

Water quality

- Sample collection
- In-situ methods
- Physical measurements (includes sediment concentration)
- Collection of samples to quantify Organic Compounds
- Collection of samples to quantify Inorganic Compounds
- Analysis of aqueous Organic Compounds
- Analysis of aqueous Inorganic Compounds
- Microbiological sampling and analysis

Integrating measurement and modeling

- Budget analyses
- Parameter estimation
- Scaling in time and space
- Data assimilation

Hydrologic prediction

Observations of hydrologic processes are used to make predictions of the future behaviour of hydrologic systems (water flow, water quality). One of the major current concerns in hydrologic research is "Prediction in Ungauged Basins" (PUB), i.e. in basins where no or only very few data exist.

Statistical hydrology

By analysing the statistical properties of hydrologic records, such as rainfall or river flow, hydrologists can estimate future hydrologic phenomena, assuming the characteristics of the processes remain unchanged.

These estimates are important for engineers and economists so that proper risk analysis can be performed to influence investment decisions in future infrastructure and to determine the yield reliability characteristics of water supply systems. Statistical information is utilised to formulate operating rules for large dams forming part of systems which include agricultural, industrial and residential demands.

Hydrologic modeling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Two major types of hydrologic models can be distinguished:

- Models based on data. These models are black box systems, using mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). Commonly used techniques are regression, transfer functions, and system identification. The simplest of these models may be linear models, but it is common to deploy non-linear components to represent some general aspects of a catchment's response without going deeply into the real physical processes involved. An example of such an aspect is the well-known behaviour that a catchment will respond much more quickly and strongly when it is already wet than when it is dry.

- Models based on process descriptions. These models try to represent the physical processes observed in the real world. Typically, such models contain representations of surface runoff, subsurface flow, evapotranspiration, and channel flow, but they can be far more complicated. These models are known as deterministic hydrology models. Deterministic hydrology models can be subdivided into single-event models and continuous simulation models.

Recent research in hydrologic modeling tries to have a more global approach to the understanding of the behaviour of hydrologic systems to make better predictions and to face the major challenges in water resources management.

Hydrologic transport

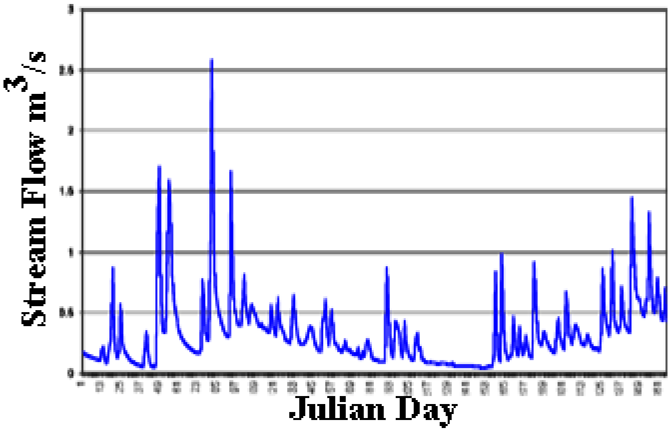
Water movement is a significant means by which other material, such as soil or pollutants, are transported from place to place. Initial input to receiving waters may arise from a point source discharge or a line source or area source, such as surface runoff. Since the 1960s rather complex mathematical models have been developed, facilitated by the availability of high speed computers. The most common pollutant classes analyzed are nutrients, pesticides, total dissolved solids and sediment.

Chapter 16

Hydrograph

A **hydrograph** is a graph showing changes in the discharge of a river over a period of time.

It can also refer to a graph showing the volume of water reaching a particular outfall, or location in a sewerage network, related to time. Hydrographs are commonly used in the design of sewerage, more specifically, the design of surface water sewerage systems and combined systems.



Stream hydrograph. Increases in stream flow follow rainfall or snowmelt. The gradual decay in flow after the peaks reflects diminishing supply from groundwater.

Terminology

The discharge is measured at a certain point in a river and is typically time variant.

- **Rising limb:** The rising limb of hydrograph, also known as concentration curve represents the increase in discharge due to the gradual building up of storage in channels and over the catchment surface.

- **Recession limb:** The recession limb extends from the point of inflection at the end of the crest segment to the commencement of the natural groundwater flow (baseflow). It represents the withdrawal of water from the storage built up in the basin during the earlier phases of the hydrograph.
- **Peak discharge:** the highest point on the hydrograph when there is the greatest amount of water in the river
- **Lag time:** Lag time is the amount of time it takes from when precipitation falls within the river basin to when it reaches the river.
- **Discharge:** volume of water in a river at a given time

Types of hydrograph can include:

- Storm hydrographs
- Flood hydrographs
- Annual hydrographs aka regimes
- Direct Runoff Hydrograph
- Effective Runoff Hydrograph

Surface water hydrography

In surface water hydrology, a hydrograph is a time record of the discharge of a stream, river or watershed outlet. Rainfall is typically the main input to a watershed and the streamflow is often considered the output of the watershed; a hydrograph is a representation of how a watershed responds to rainfall. They are used in hydrology and water resources planning.

A watershed's response to rainfall depends on a variety of factors which affect the shape of a hydrograph:

- Watershed topography and geology (i.e. bedrock permeability)
- The area of a basin receiving rainfall
- Land-use (e.g. agriculture, urban development, forestry operations)
- Drainage density
- Duration of rainfall and precipitation intensity and type
- Evapotranspiration rates
- River geometrics
- The season
- Vegetation type and cover
- River conditions (e.g. dams)
- Initial conditions (e.g. the degree of saturation of the soil and aquifers)
- Soil permeability and thickness

A hydrograph is often compared to a hyetograph of the watershed.

Unit Hydrograph

A **unit hydrograph** is used to more easily represent the effect of rainfall in a particular basin. It is a hypothetical unit response of the watershed to a unit input of rainfall. This allows easy calculation of the response to any arbitrary input (rainfall), by simply performing a convolution between the rain input and the unit hydrograph output.

An **instantaneous unit hydrograph** is a further refinement of the concept; for an IUH, the input rainfall is assumed to all take place at a discrete point in time (obviously, this isn't the case for actual rainstorms). Making this assumption can greatly simplify the analysis involved in constructing a unit hydrograph, and it is necessary for the creation of a **geomorphologic instantaneous unit hydrograph**.

The creation of a GIUH is possible given nothing more than topologic data for a particular drainage basin. In fact, only the number of streams of a given order, the mean length of streams of a given order, and the mean land area draining directly to streams of a given order are absolutely required (and can be estimated rather than explicitly calculated if necessary). It is therefore possible to calculate a GIUH for a basin without any data about stream height or flow, which may not always be available.

Factors affecting the hydrograph

- Soil Saturation is dependant on previous rainfall, or otherwise known as Antecedent rainfall.
- The surroundings; Rural or Urban (Could be less impermeable surface, or the surface type could vary)
- Vegetation type (Deforestation and amount of interception)
- Steepness of surrounding land, or 'relief' land
- Drainage density (Number of tributaries)
- Geology (Rock Type; Impermeable=flashier hydrographs. Or Permeable)
- Season dependant; Very dry weather creates a crust on the river bed. Wet winters create increase in discharge.
- Soil Type (Clay, sand etc.) Clay would create a flashy hydrograph, but there could be a continium between the two.
- Shape of drainage basin (circular or elongated).
- Precipitation (distribution of rainfall rates and locations)

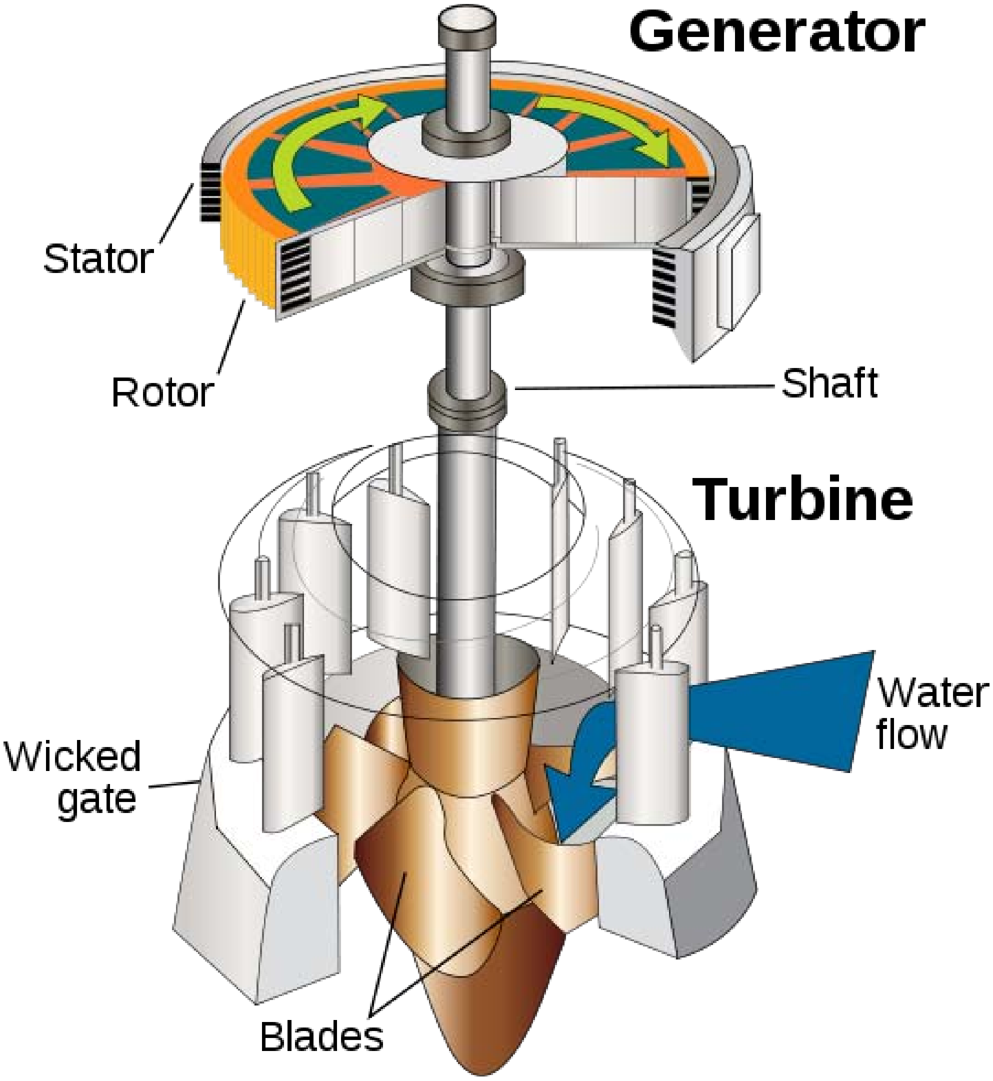
Subsurface hydrology hydrograph

In subsurface hydrology (hydrogeology), a hydrograph is a record of the water level (the observed hydraulic head in wells screened across an aquifer).

Typically, a hydrograph is recorded for monitoring of heads in aquifers during non-test conditions (e.g., to observe the seasonal fluctuations in an aquifer). When an aquifer test is being performed, the resulting observations are typically called drawdown, since they are subtracted from pre-test levels and often only the change in water level is dealt with.

Chapter 17

Water Turbine



Kaplan turbine and electrical generator cut-away view.

The runner of the small water turbine

A **water turbine** is a rotary engine that takes energy from moving water.

Water turbines were developed in the 19th century and were widely used for industrial power prior to electrical grids. Now they are mostly used for electric power generation. They harness a clean and renewable energy source.

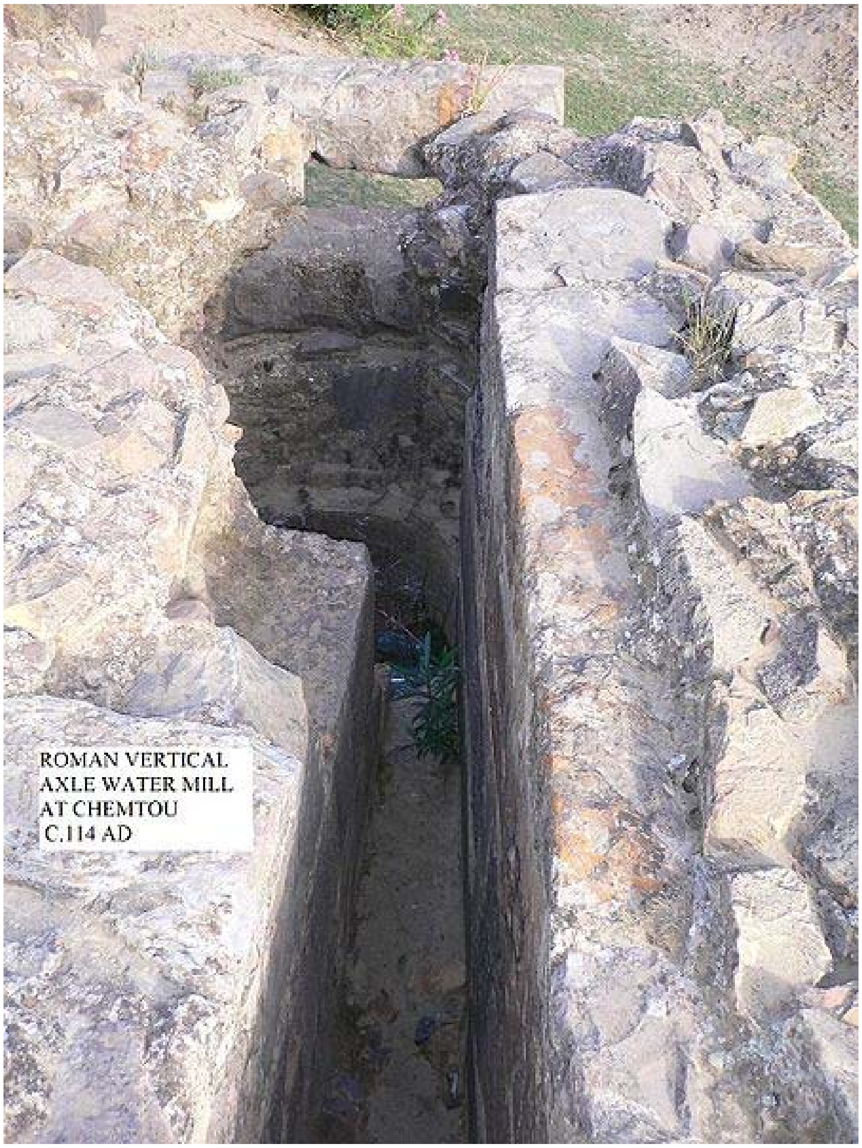
History

Water wheels have been used for thousands of years for industrial power. Their main shortcoming is size, which limits the flow rate and head that can be harnessed. The migration from water wheels to modern turbines took about one hundred years. Development occurred during the Industrial revolution, using scientific principles and methods. They also made extensive use of new materials and manufacturing methods developed at the time.

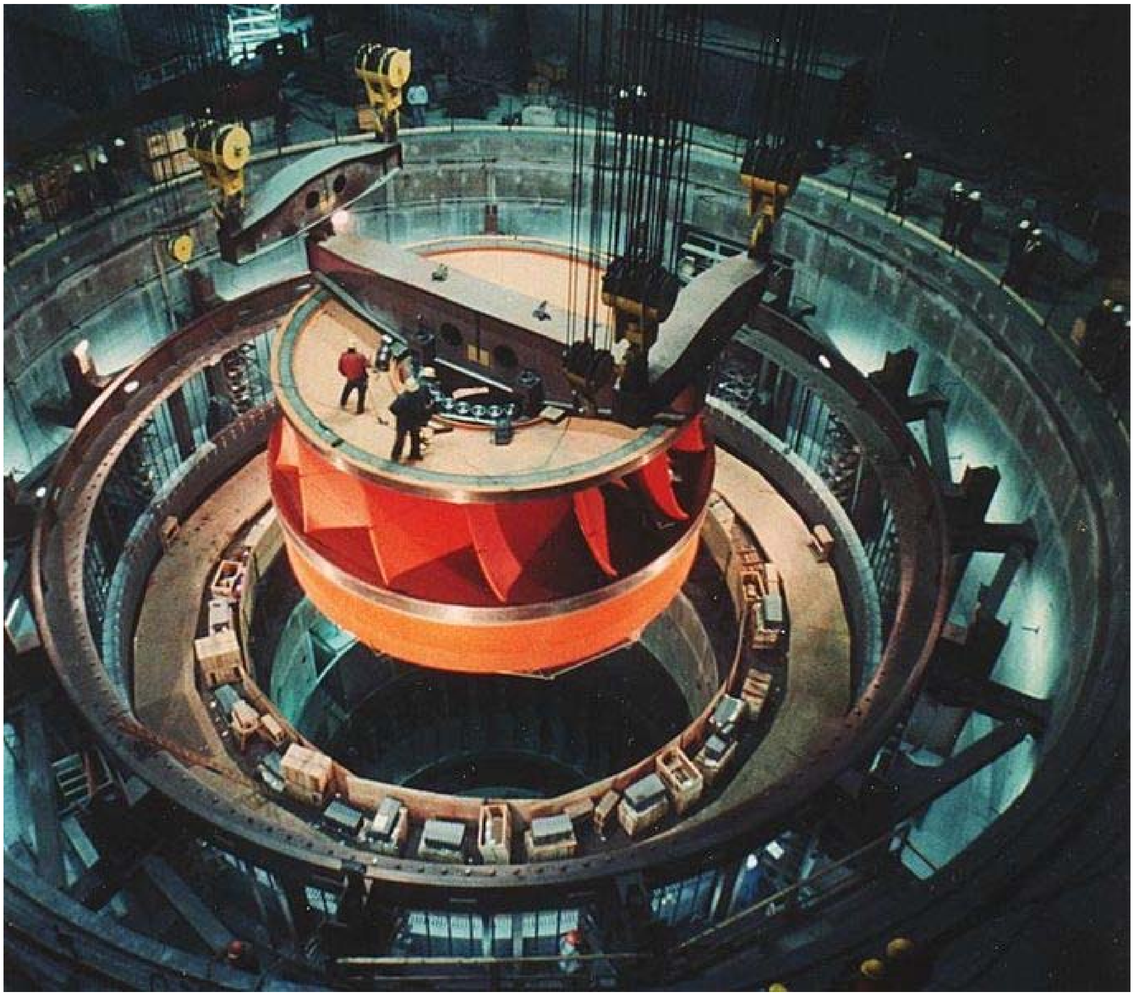
Swirl

The word turbine was introduced by the French engineer Claude Bourdin in the early 19th century and is derived from the Latin word for "whirling" or a "vortex". The main difference between early water turbines and water wheels is a swirl component of the water which passes energy to a spinning rotor. This additional component of motion allowed the turbine to be smaller than a water wheel of the same power. They could process more water by spinning faster and could harness much greater heads. (Later, impulse turbines were developed which didn't use swirl).

Time line



Roman turbine mill at Chemtou, Tunisia. The tangential water inflow of the millrace made the submerged horizontal wheel in the shaft turn like a true turbine.



A Francis turbine runner, rated at nearly one million hp (750 MW), being installed at the Grand Coulee Dam, United States.

A propeller-type runner rated 28,000 hp (21 MW)

The earliest known water turbines date to the Roman Empire. Two helix-turbine mill sites of almost identical design were found at Chemtou and Testour, modern-day Tunisia, dating to the late 3rd or early 4th century AD. The horizontal water wheel with angled blades was installed at the bottom of a water-filled, circular shaft. The water from the mill-race entered tangentially the pit, creating a swirling water column which made the fully submerged wheel act like a true turbine.

Ján Andrej Segner developed a reactive water turbine in the mid-18th century. It had a horizontal axis and was a precursor to modern water turbines. It is a very simple machine that is still produced today for use in small hydro sites. Segner worked with Euler on some of the early mathematical theories of turbine design.

In 1820, Jean-Victor Poncelet developed an inward-flow turbine.

In 1826, Benoit Fourneyron developed an outward-flow turbine. This was an efficient machine (~80%) that sent water through a runner with blades curved in one dimension. The stationary outlet also had curved guides.

In 1844, Uriah A. Boyden developed an outward flow turbine that improved on the performance of the Fourneyron turbine. Its runner shape was similar to that of a Francis turbine.

In 1849, James B. Francis improved the inward flow reaction turbine to over 90% efficiency. He also conducted sophisticated tests and developed engineering methods for water turbine design. The Francis turbine, named for him, is the first modern water turbine. It is still the most widely used water turbine in the world today. The Francis turbine is also called a radial flow turbine, since water flows from the outer circumference towards the centre of runner.

Inward flow water turbines have a better mechanical arrangement and all modern reaction water turbines are of this design. As the water swirls inward, it accelerates, and transfers energy to the runner. Water pressure decreases to atmospheric, or in some cases subatmospheric, as the water passes through the turbine blades and loses energy.

Around 1890, the modern fluid bearing was invented, now universally used to support heavy water turbine spindles. As of 2002, fluid bearings appear to have a mean time between failures of more than 1300 years.

Around 1913, Viktor Kaplan created the Kaplan turbine, a propeller-type machine. It was an evolution of the Francis turbine but revolutionized the ability to develop low-head hydro sites.

A new concept

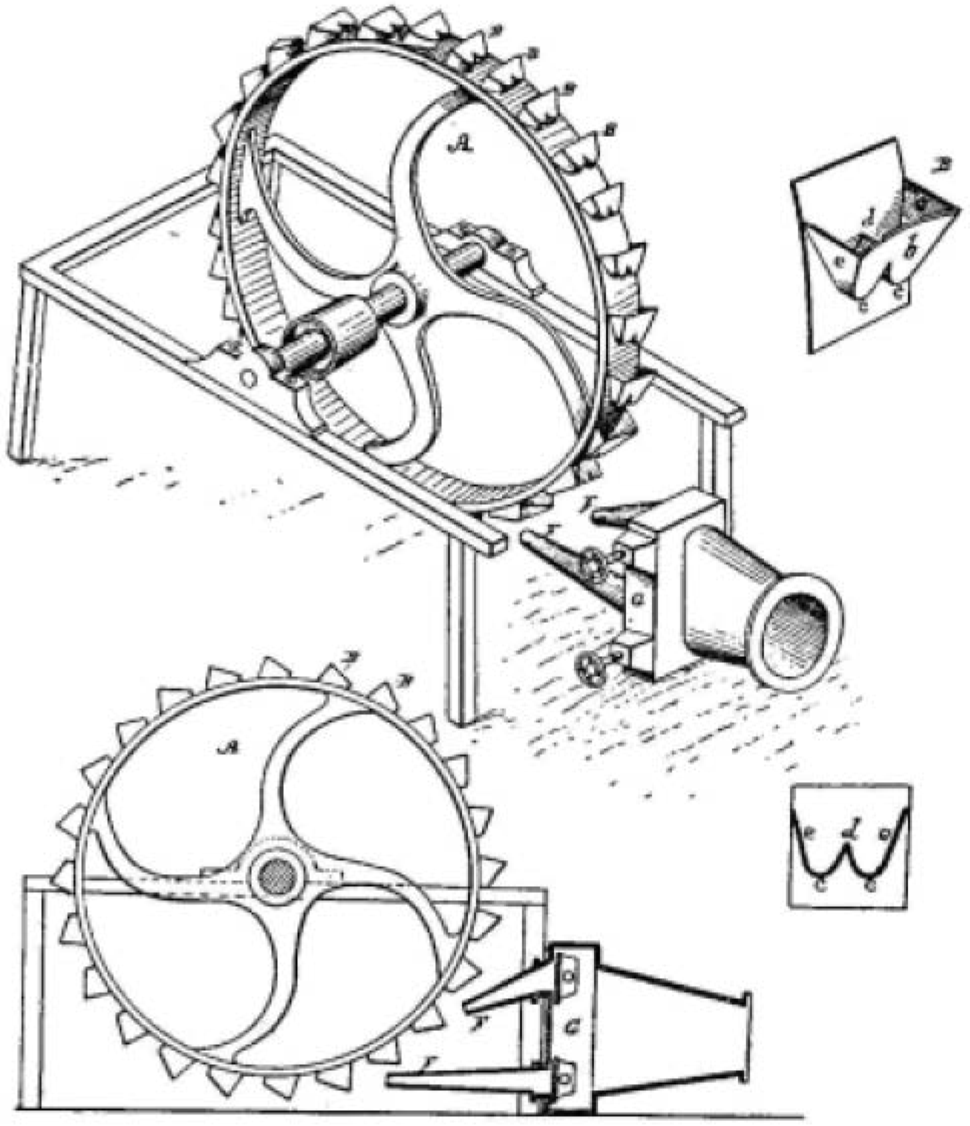


Figure from Pelton's original patent (October 1880)

All common water machines until the late 19th century (including water wheels) were basically reaction machines; water *pressure* head acted on the machine and produced work. A reaction turbine needs to fully contain the water during energy transfer.

In 1866, California millwright Samuel Knight invented a machine that took the impulse system to a new level. Inspired by the high pressure jet systems used in hydraulic mining in the gold fields, Knight developed a bucketed wheel which captured the energy of a free jet, which had converted a high head (hundreds of vertical feet in a pipe or penstock) of water to kinetic energy. This is called an impulse or tangential turbine. The water's velocity, roughly twice the velocity of the bucket periphery, does a u-turn in the bucket and drops out of the runner at low velocity.

In 1879, Lester Pelton(1829-1908), experimenting with a Knight Wheel, developed a double bucket design, which exhausted the water to the side, eliminating some energy loss of the Knight wheel which exhausted some water back against the center of the wheel. In about 1895, William Doble improved on Pelton's half-cylindrical bucket form with an elliptical bucket that included a cut in it to allow the jet a cleaner bucket entry. This is the modern form of the Pelton turbine which today achieves up to 92% efficiency. Pelton had been quite an effective promoter of his design and although Doble took over the Pelton company he did not change the name to Doble because it had brand name recognition.

Turgo and Crossflow turbines were later impulse designs.

Theory of operation

Flowing water is directed on to the blades of a turbine runner, creating a force on the blades. Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the water flow to the turbine

Water turbines are divided into two groups; reaction turbines and impulse turbines.

The precise shape of water turbine blades is a function of the supply pressure of water, and the type of impeller selected.

Reaction turbines

Reaction turbines are acted on by water, which changes pressure as it moves through the turbine and gives up its energy. They must be encased to contain the water pressure (or suction), or they must be fully submerged in the water flow.

Newton's third law describes the transfer of energy for reaction turbines.

Most water turbines in use are reaction turbines and are used in low (<30m/98 ft) and medium (30-300m/98–984 ft)head applications. In reaction turbine pressure drop occurs in both fixed and moving blades.

Impulse turbines

Impulse turbines change the velocity of a water jet. The jet pushes on the turbine's curved blades which changes the direction of the flow. The resulting change in momentum (impulse) causes a force on the turbine blades. Since the turbine is spinning, the force acts through a distance (work) and the diverted water flow is left with diminished energy.

Prior to hitting the turbine blades, the water's pressure (potential energy) is converted to kinetic energy by a nozzle and focused on the turbine. No pressure change occurs at the turbine blades, and the turbine doesn't require a housing for operation.

Newton's second law describes the transfer of energy for impulse turbines.

Impulse turbines are most often used in very high (>300m/984 ft) head applications .

Power

The power available in a stream of water is;

$$P = \eta \cdot \rho \cdot g \cdot h \cdot \dot{q}$$

where:

- P = power (J/s or watts)
- η = turbine efficiency
- ρ = density of water (kg/m^3)
- g = acceleration of gravity ($9.81\ m/s^2$)
- h = head (m). For still water, this is the difference in height between the inlet and outlet surfaces. Moving water has an additional component added to account for the kinetic energy of the flow. The total head equals the *pressure head* plus *velocity head*.

- $\dot{q}$= flow rate (m^3/s)

Pumped storage

Some water turbines are designed for pumped storage hydroelectricity. They can reverse flow and operate as a pump to fill a high reservoir during off-peak electrical hours, and then revert to a turbine for power generation during peak electrical demand. This type of turbine is usually a Deriaz or Francis in design.

Efficiency

Large modern water turbines operate at mechanical efficiencies greater than 90%.

Types of water turbines

Various types of water turbine runners. From left to right: Pelton Wheel, two types of Francis Turbine and Kaplan Turbine

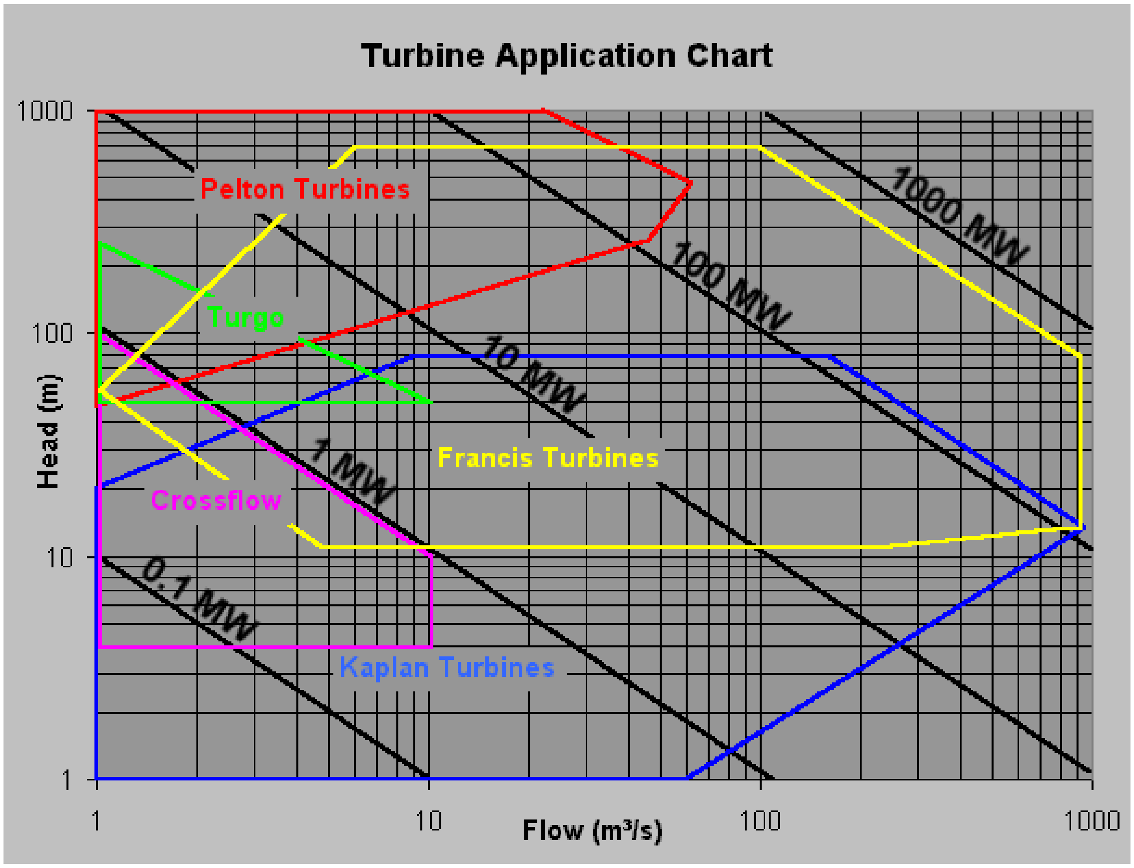
Reaction turbines:

- Francis
- Kaplan, Propeller, Bulb, Tube, Straflo
- Tyson, Gorlov (Freeflow types)

Impulse turbine

- Pelton
- Turgo
- Michell-Banki (also known as the Crossflow or Ossberger turbine)

Design and application



Turbine selection is based mostly on the available water head, and less so on the available flow rate. In general, impulse turbines are used for high head sites, and reaction turbines are used for low head sites. Kaplan turbines with adjustable blade pitch are well-adapted to wide ranges of flow or head conditions, since their peak efficiency can be achieved over a wide range of flow conditions.

Small turbines (mostly under 10 MW) may have horizontal shafts, and even fairly large bulb-type turbines up to 100 MW or so may be horizontal. Very large Francis and Kaplan machines usually have vertical shafts because this makes best use of the available head, and makes installation of a generator more economical. Pelton wheels may be either vertical or horizontal shaft machines because the size of the machine is so much less than the available head. Some impulse turbines use multiple water jets per runner to increase specific speed and balance shaft thrust.

Typical range of heads

• Hydraulic wheel turbine	$0.2 < H < 4$ (H = head in m)
• Archimedes' screw turbine	$1 < H < 10$
• Kaplan	$2 < H < 40$
• Francis	$10 < H < 350$

• Pelton	$50 < H < 1300$
• Turgo	$50 < H < 250$

Specific speed

The specific speed n_s of a turbine characterizes the turbine's shape in a way that is not related to its size. This allows a new turbine design to be scaled from an existing design of known performance. The specific speed is also the main criteria for matching a specific hydro site with the correct turbine type. The specific speed is the speed with which the turbine turns for a particular discharge Q, with unit head and thereby is able to produce unit power.

Affinity laws

Affinity Laws allow the output of a turbine to be predicted based on model tests. A miniature replica of a proposed design, about one foot (0.3 m) in diameter, can be tested and the laboratory measurements applied to the final application with high confidence. Affinity laws are derived by requiring similitude between the test model and the application.

Flow through the turbine is controlled either by a large valve or by wicket gates arranged around the outside of the turbine runner. Differential head and flow can be plotted for a number of different values of gate opening, producing a hill diagram used to show the efficiency of the turbine at varying conditions.

Runaway speed

The **runaway speed** of a water turbine is its speed at full flow, and no shaft load. The turbine will be designed to survive the mechanical forces of this speed. The manufacturer will supply the runaway speed rating.

Maintenance

A Francis turbine at the end of its life showing cavitation pitting, fatigue cracking and a catastrophic failure. Earlier repair jobs that used stainless steel weld rods are visible.

Turbines are designed to run for decades with very little maintenance of the main elements; overhaul intervals are on the order of several years. Maintenance of the runners and parts exposed to water include removal, inspection, and repair of worn parts.

Normal wear and tear includes pitting from cavitation, fatigue cracking, and abrasion from suspended solids in the water. Steel elements are repaired by welding, usually with stainless steel rods. Damaged areas are cut or ground out, then welded back up to their original or an improved profile. Old turbine runners may have a significant amount of stainless steel added this way by the end of their lifetime. Elaborate welding procedures may be used to achieve the highest quality repairs.

Other elements requiring inspection and repair during overhauls include bearings, packing box and shaft sleeves, servomotors, cooling systems for the bearings and generator coils, seal rings, wicket gate linkage elements and all surfaces.

Environmental impact

Water turbines are generally considered a clean power producer, as the turbine causes essentially no change to the water. They use a renewable energy source and are designed to operate for decades. They produce significant amounts of the world's electrical supply.

Historically there have also been negative consequences, mostly associated with the dams normally required for power production. Dams alter the natural ecology of rivers, potentially killing fish, stopping migrations, and disrupting peoples' livelihoods. For example, American Indian tribes in the Pacific Northwest had livelihoods built around salmon fishing, but aggressive dam-building destroyed their way of life. Dams also cause less obvious, but potentially serious consequences, including increased evaporation of water (especially in arid regions), build up of silt behind the dam, and changes to water temperature and flow patterns. Some people believe that it is possible to construct hydropower systems that divert fish and other organisms away from turbine intakes without significant damage or loss of power; historical performance of diversion structures have been poor. In the United States, it is now illegal to block the migration of fish, for example the endangered great white sturgeon in North America, so fish ladders must be provided by dam builders. The actual performance of fish ladders is often poor.

Chapter 18

Drainage

Deep inside a Sydney drain in New South Wales

Drainage is the natural or artificial removal of surface and sub-surface water from an area. Many agricultural soils need drainage to improve production or to manage water supplies.

History

Early history

The ancient Indus systems of sewerage and drainage that were developed and used in cities throughout the civilization were far more advanced than any found in contemporary urban sites in the Middle East and even more efficient than those in some areas of modern Pakistan and India today. All houses in the major cities of Harappa and Mohenjodaro had access to water and drainage facilities. Waste water was directed to covered drains, which lined the major streets.

Drainage in the 19th century

Tank Stream, a historical drain in the City of Sydney

From the 1881 *Household Cyclopedia*:

This operation is always best performed in spring or summer, when the ground is dry. Main drains ought to be made in every part of the field where a cross-cut or open drain was formerly wanted; they ought to be cut four feet (1.2 m) deep, upon an average. This completely secures them from the possibility of being damaged by the treading of horses or cattle, and being so far below the small drains, clears the water finely out of them. In every situation, pipe-turfs for the main drains, if they can be had, are preferable. If good stiff clay, a single row of pipe-turf; if sandy, a double row. When pipe-turf cannot be got conveniently, a good wedge drain may answer well, when the subsoil is a strong, stiff clay; but if the subsoil be only moderately so, a thorn drain, with couples below, will do still better; and if the subsoil is very sandy, except pipes can be had, it is in vain to attempt under-draining the fiel d by any other method. It may be necessary to mention here that the size of the main drains ought to be regulated according to the length and declivity of the run, and t eihther it can be he quantity of water to be carried off by them.

It is always safe, however, to have the main drains large, and plenty of them; for economy here seldom turns out well.

Having finished the main drains, proceed next to make a small drain in every furrow of the field if the ridges formerly have not been less than fifteen feet (4.6 m) wide. But if that should be the case, first level the ridges, and make the drains in the best direction, and at such a distance from each other as may be thought necessary. If the water rises well in the bottom of the drains, they ought to be cut three feet (1 m) deep, and in this ease would dry the field sufficiently well, although they were from twenty-five to thirty feet (8 to 10 m) asunder; but if the water does not draw well to the bottom of the drains, two feet (0.6 m) will be a sufficient deepness for the pipe-drain, and two and a half feet (1 m) for the wedge drain. In no case ought they to be shallower where the field has been previously leveled. In this instance, however, as the surface water is carried off chiefly by the water sinking immediately into the top of the drains, it will be necessary to have the drains much nearer each other—say from fifteen to twenty feet (4.6 to 6 m). If the ridges are more than fifteen feet (4.6 m) wide, however broad and irregular they may be, follow invariably the line of the old furrows, as the best direction for the drains; and, where they are high-gathered ridges, from twenty to twenty-four inches will be a sufficient depth for the pipe-drain, and from twenty-four to thirty inches for the wedge-drain. Particular care should be taken in connecting the small and main drains together, so that the water may have a gentle declivity, with free access into the main drains.

When the drains are finished, the ridges are cleaved down upon the drains by the plough; and where they had been very high formerly, a second clearing may be given; but it is better not to level the ridges too much, for by allowing them to retain a little of their former shape, the ground being lowest immediately where the drains are, the surface water collects upon the top of the drains; and, by shrinking into them, gets freely away. After the field is thus finished, run the new ridges across the small drains, making them about ten feet (3 m) broad, and continue afterwards to plough the field in the same manner as dry land.

It is evident from the above method of draining that the expense will vary very much, according to the quantity of main drains necessary for the field, the distance of the small drains from each other, and the distance the turf is to be carried.

The advantage resulting from under-draining, is very great, for besides a considerable saving annually of water furrowing, cross cutting, etc., the land can often be ploughed and sown to advantage, both in the spring and in the fall of the year, when otherwise it would be found quite impracticable; every species of drilled crops, such as beans, potatoes, turnips, etc., can be cultivated successfully; and every species, both of green and white crops, is less apt to fail in wet and untoward seasons.

Wherever a burst of water appears in any particular spot, the sure and certain way of getting quit of such an evil is to dig hollow drains to such a depth below the surface as is required by the fall or level that can be gained, and by the quantity of water expected to proceed from the burst or spring. Having ascertained the extent of water to be carried off, taken the necessary levels, and cleared a mouth or loading passage for the water, begin the drain at the extremity next to that leader, and go on with the work till the top of the spring is touched, which probably will accomplish the intended object. But if it should not be completely accomplished, run off from the main drain with such a number of branches as may be required to intercept the water, and in this way disappointment will hardly be experienced. Drains, to be substantially useful, should seldom be less than three feet (1 m) in depth, twenty or twenty four inches thereof to be close packed with stones or wood, according to circumstances. The former are the best materials, but in many places are not to be got in sufficient quantities; recourse therefore, must often be made to the latter, though not so effectual or durable.

It is of vast importance to fill up drains as fast as they are dug out; because, if left open for any length of time, the earth is not only apt to fall in but the sides get into a broken, irregular state, which cannot afterwards be completely rectified. A proper covering of straw or sod should be put upon the top of the materials, to keep the surface earth from mixing with them; and where wood is the material used for filling up, a double degree of attention is necessary, otherwise the proposed improvement may be effectually frustrated.

The pit method of draining is a very effectual one, if executed with judgment. When it is sufficiently ascertained where the bed of water is deposited, which can easily be done by boring with an auger, sink a pit into the place of a size which will allow a man freely to work within its bounds. Dig this pit of such a depth as to reach the bed of the water meant to be carried off; and when this depth is attained, which is easily discerned by the rising of the water, fill up the pit with great land-stones and carry off the water by a stout drain to some adjoining ditch or mouth, whence it may proceed to the nearest river.

Current practices

A plastic flexible drainpipe, used to drain water from the roof of a residential house or building

Modern drainage systems incorporate geotextile filters that retain and prevent fine grains of soil from passing into and clogging the drain. Geotextiles are synthetic textile fabrics specially manufactured for civil and environmental engineering applications. Geotextiles are designed to retain fine soil particles while allowing water to pass through. In a typical drainage system they would be laid along a trench which would then be filled with coarse granular material: gravel, sea shells, stone or rock. The geotextile is then folded over the top of the stone and the trench is then covered by soil. Groundwater seeps through the geotextile and flows within the stone to an outfall. In high groundwater conditions a perforated plastic (PVC or PE) pipe is laid along the base of the drain to increase the volume of water transported in the drain.

Green Drain

Enzymatic drain cleaners can be a safer alternative to chemical drain cleaners, and are easier on the environment. They use bacteria or enzymes, which naturally feed on organic waste, such as hair and food waste that often block drains. These tiny organisms, then digest the waste and to recreate beneficial bacteria and enzymes throughout the septic system. In fact, drain cleaners enzyme originally used to clean septic tanks and sewage. Enzymatic drain cleaners are better for the environment because they prevent hazardous chemicals that may leak into soil and water from spreading. .

Alternatively, prefabricated plastic drainage systems made of HDPE called SmartDitch, often incorporating geotextile, coco fiber or rag filters can be considered. The use of these materials has become increasingly more common due to their ease of use which eliminates the need for transporting and laying stone drainage aggregate which is invariably more expensive than a synthetic drain and concrete liners.

Over the past 30 years geotextile and PVC filters have become the most commonly used soil filter media. They are cheap to produce and easy to lay, with factory controlled properties that ensure long term filtration performance even in fine silty soil conditions.

21st century alternatives

Seattle's Public Utilities created a pilot program called Street Edge Alternatives (SEA Streets) Project. The project focuses on designing a system "to provide drainage that more closely mimics the natural landscape prior to development than traditional piped systems". The streets are characterized by ditches along the side of the roadway, with plantings designed throughout the area. An emphasis on non curbed sidewalks allows water to flow more freely into the areas of permeable surface on the side of the streets. Because of the plantings the run off water from the urban area does not all directly go into the ground but can also be absorbed into the surrounding environment. According to the monitoring by Seattle Public Utilities, they report at 99 percent reduction of storm water leaving the drainage project

Drainage in construction

Piping being placed for a sink

The civil engineer or site engineer is responsible for drainage in construction projects. They set out from the plans all the roads, Street gutters, drainage, culverts and sewers involved in construction operations. During the construction of the work on site he/she will set out all the necessary levels for each of the previously mentioned factors.

Site engineers work alongside architects and construction managers, supervisors, planners, quantity surveyors, the general workforce, as well as subcontractors. Typically, most jurisdictions have some body of drainage law to govern to what degree a landowner can alter the drainage from his parcel.

Reasons for artificial drainage

An agricultural drainage channel outside Magome, Japan after a heavy rain. Note that protuberances create turbulent water, preventing sediment from settling in the channel.

Wetland soils may need drainage to be used for agriculture. In the northern USA and Europe, glaciation created numerous small lakes which gradually filled with humus to make marshes. Some of these were drained using open ditches and trenches to make mucklands, which are primarily used for high value crops such as vegetables.

The largest project of this type in the world has been in process for centuries in the Netherlands. The area between Amsterdam, Haarlem and Leiden was, in prehistoric times swampland and small lakes. Turf cutting (Peat mining), subsidence and shoreline erosion gradually caused the formation of one large lake, the Haarlemmermeer, or lake of Haarlem. The invention of wind powered pumping engines in the 15th century permitted drainage of some of the marginal land, but the final drainage of the lake had to await the design of large, steam powered pumps and agreements between regional authorities. The elimination of the lake occurred between 1849 and 1852, creating thousands of km² of new land.

Coastal plains and river deltas may have seasonally or permanently high water tables and must have drainage improvements if they are to be used for agriculture. An example is the flatwoods citrus-growing region of Florida. After periods of high rainfall, drainage pumps are employed to prevent damage to the citrus groves from overly wet soils. Rice production requires complete control of water, as fields need to be flooded or drained at different stages of the crop cycle. The Netherlands has also led the way in this type of drainage, not only to drain lowland along the shore, but actually pushing back the sea until the original nation has been greatly enlarged.

In moist climates, soils may be adequate for cropping with the exception that they become waterlogged for brief periods each year, from snow melt or from heavy rains. Soils that are predominantly clay will pass water very slowly downward, meanwhile plant roots suffocate because the excessive water around the roots eliminates air movement through the soil.
Other soils may have an impervious layer of mineralized soil, called a hardpan or relatively impervious rock layers may underlie shallow soils. Drainage is especially important in tree fruit production. Soils that are otherwise excellent may be waterlogged for a week of the year, which is sufficient to kill fruit trees and cost the productivity of the land until replacements can be established. In each of these cases appropriate drainage carries off temporary flushes of water to prevent damage to annual or perennial crops.

Drier areas are often farmed by irrigation, and one would not consider drainage necessary. However, irrigation water always contains minerals and salts, which can be concentrated to toxic levels by evapotranspiration. Irrigated land may need periodic flushes with excessive irrigation water and drainage to control soil salinity.

A typical drain in Bankstown, New South Wales.

Chapter 19

Reservoir

The Jhonghua Dam on the Dahan River in Taoyuan County, Taiwan.

A **reservoir** (etymology from French *réservoir* a "storehouse) or an **artificial lake** is used to store water. Reservoirs may be created in river valleys by the construction of a dam or may be built by excavation in the ground or by conventional construction techniques such a brickwork or cast concrete.

The term reservoir may also be used to describe underground reservoirs such as an oil or water well.

Types

Valley dammed reservoir

Lake Vyrnwy Reservoir. The dam spans the Vyrnwy Valley and was the first large stone dam built in the United Kingdom.

Stocks Reservoir in Lancashire, England.

A dam constructed in a valley relies on the natural topography to provide most of the basin of the reservoir. Dams are typically located at a narrow part of a valley downstream of a natural basin. The valley sides act as natural walls with the dam located at the narrowest practical point to provide strength and the lowest practical cost of construction. In many reservoir construction projects people have to be moved and re-housed, historical artifacts moved or rare environments relocated. Examples include the temples of Abu Simbel (which were moved before the construction of the Aswan Dam to create Lake Nasser from the Nile in Egypt) and the re-location of the village of Capel Celyn during the construction of Llyn Celyn.

Construction of a reservoir in a valley will usually necessitate the diversion of the river during part of the build often through a temporary tunnel or by-pass channel.

In hilly regions reservoirs are often constructed by enlarging existing lakes. Sometimes in such reservoirs the new top water level exceeds the watershed height on one or more of the feeder streams such as at Llyn Clywedog in Mid Wales. In such cases additional side dams are required to contain the reservoir.

Where the topography is poorly suited to a single large reservoir, a number of smaller reservoirs may be constructed in a chain such as in the River Taff valley where the three reservoirs Llwyn-on Reservoir, Cantref Reservoir and Beacons Reservoir form a chain up the valley.

Bank-side reservoir

Where water is taken from a river of variable quality or quantity, bank-side reservoirs may be constructed to store the water pumped or siphoned from the river. Such reservoirs are usually built partly by excavation and partly by the construction of a complete encircling bund or embankment which may exceed 6 km in circumference. Both the floor of the reservoir and the bund must have an impermeable lining or core, often made of puddled clay. The water stored in such reservoirs may have a residence time of several months during which time normal biological processes are able to substantially reduce many contaminants and almost eliminate any turbidity. The use of bank-side reservoirs also allows a water abstraction to be closed down for extended period at times when the river is unacceptably polluted or when flow conditions are very low due to drought. The London water supply system is one example of the use of bank-side storage for all the water taken from the River Thames and River Lee with many large reservoirs such as Queen Mary Reservoir visible along the approach to London Heathrow Airport.

Service reservoir

Service reservoirs store fully treated potable water close to the point of distribution. Many service reservoirs are constructed as water towers, often as elevated structures on concrete pillars where the landscape is relatively flat. Other service reservoirs are entirely underground, especially in more hilly or mountainous country. In the United Kingdom, Thames Water has many underground reservoirs in London built in the 1800s by the Victorians, most of which are lined with brick. Honor Oak Reservoir, which was completed in 1909, is believed to one of the largest of this type in Europe. The roof is supported on large brick pillars and arches and the outside surface is grassed over.

Service reservoirs perform several functions including ensuring sufficient head of water in the water distribution system and providing hydraulic capacitance in the system to even out peak demand from consumers enabling the treatment plant to run at optimum efficiency. Large service reservoirs can also be managed to so that energy costs in pumping are reduced by concentrating refilling activity at times of day when power costs are low.

History

Five thousand years ago, the craters of extinct volcanoes in Arabia were used as reservoirs by farmers for their irrigation water.

Dry climate and water scarcity in India led to early development of water management techniques, including the building of a reservoir at Girnar in 3000 BC. Artificial lakes dating to the 5th century BC have been found in ancient Greece. An artificial lake in present-day Madhya Pradesh province of India, constructed in the 11th century, covered 650 square metres (7,000 sq ft).

In Sri Lanka large reservoirs have been created by ancient Sinhalese kings in order to save the water for irrigation. The famous Sri Lankan king Parākramabāhu I of Sri Lanka stated " do not let a drop of water seep into the ocean without benefiting mankind ". He created the reservoir named Parakrama Samudra(sea of King Parakrama), which has astonished archaeologists.

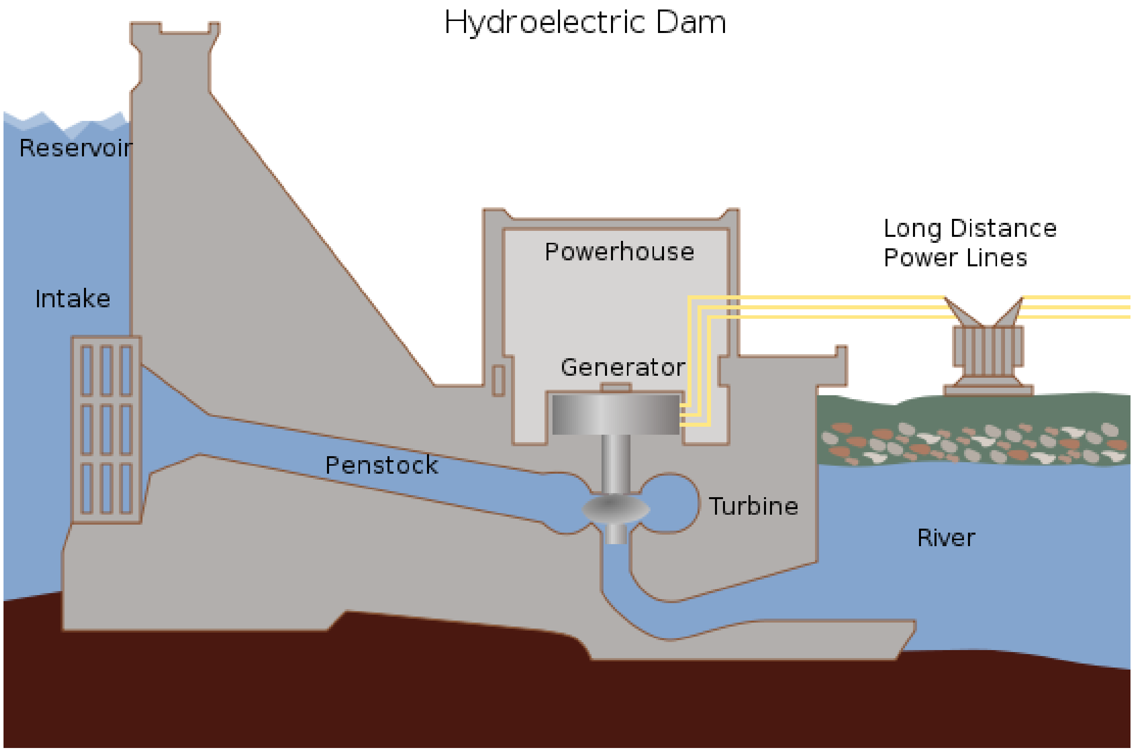
Uses

Direct water supply

Gibson Reservoir, Montana

Many dammed river reservoirs and most bank-side reservoirs are used to provide the raw water feed to a water treatment plant which delivers drinking water through water mains. The reservoir does not simply hold water until it is needed; it can also be the first part of the water treatment process. The time the water is held for before it is released is known as the *retention time*. This is a design feature that allows particles and silts to settle out, as well as time for natural biological treatment using algae, bacteria and zooplankton that naturally live within the water. However natural limnological processes in temperate climate lakes produces temperature stratification in the water body which tends to partition some elements such as manganese and phosphorus into deep, cold anoxic water during the summer months. In the autumn and winter the lake becomes fully mixed again. During drought conditions, it is sometimes necessary to draw down the cold bottom water and the elevated levels of manganese in particular can cause problems in water treatment plants.

Hydroelectricity



Hydroelectric dam in cross section.

A reservoir generating hydroelectric includes turbines connected to the retained water body by large diameter pipes. These generating sets may be at the base of the dam or some distance away. Some reservoirs generating hydro-electricity use pumped re-charge in which a high level reservoir is filled with water using high performance electric pumps at times when electricity demand is low and then uses this stored water to generate electricity by releasing the stored water into a low level reservoir when electricity demand is high. Such systems are called pump storage schemes.

Controlling watercourses

Reservoirs can be used in a number of ways to control how water flows through downstream waterways.

> **Downstream water supply** - water may be released from an upland reservoir so that it can be abstracted for drinking water lower down the system, sometimes hundred of miles further down downstream

Irrigation - water in an irrigation reservoir may be released into networks of canals for use in farmlands or secondary water systems. Irrigation may also be supported by reservoirs which maintain river flows allowing water to be abstracted for irrigation lower down the river.

Flood control - also known as an "*attenuation*" or "*balancing*" reservoir, flood control reservoirs collect water at times of very high rainfall, then release it slowly over the course of the following weeks or months. Some of these reservoirs are constructed across the river line with the onward flow controlled by an orifice plate. When river flow exceeds the capacity of the orifice plate water builds behind the dam but as soon as the flow rate reduces the water behind the dam slowly releases until the reservoir is empty again. In some cases such reservoirs only function a few times in a decade and the land behind the reservoir may be developed as community or recreational land. A new generation of balancing dams are being developed to combat the climatic consequences of climate change. They are called "Flood Detention Reservoirs". Because these reservoirs will remain dry for long periods, there may be a risk of the clay core drying out reducing its structural stability. Recent developments include the use of composite core fill made from recycled materials as an alternative to clay.

Canals - Where a natural watercourse's water is not available to be diverted into a canal, a reservoir may be built to guarantee the water level in the canal; for example, where a canal climbs to cross a range of hills through locks.

Recreational-only Kupferbach reservoir near Aachen/Germany.

Recreation - water may be released from a reservoir to artificially create or supplement white-water conditions for kayaking and other white-water sports. On salmonid rivers special releases (in Britain called *freshets*) are made to encourage natural migration behaviours in fish and to provide a variety of fishing conditions for anglers.

Flow balancing

Occasionally reservoirs are used to balance the flow in highly managed systems, taking in water during high flows and releasing it again during low flows. In order for this to work without pumping requires careful control of water levels using adjustable sluices. One example of this is Llyn Tegid in North Wales. This is a natural lake whose level was raised by a low dam and into which the River Dee flows or discharges depending upon flow conditions at the time as part of the River Dee regulation system. This mode of operation is a form of hydraulic capacitance in the river system.

Recreation

The water bodies provided by many reservoirs often allow some recreational uses such as fishing, boating, and other activities. Special rules may apply for the safety of the public and to protect the quality of the water and the ecology of the surrounding area. Many reservoirs now support and encourage less informal and less structured recreation such as natural history, bird watching, landscape painting, walking and hiking and often provide information boards and interpretation material to encourage responsible use.

Operation

Water falling as rain upstream of the reservoir together with any groundwater emerging as springs is stored in the reservoir. Any excess water can be spilled via a specifically designed spillway. Stored water may be piped by gravity for use as drinking water, to generate hydro-electricity or to maintain river flows to support downstream uses. Occasionally reservoirs can be managed to retain high rain-fall events to prevent or reduce downstream flooding. Some reservoirs support several uses and the operating rules may be complex.

Spillway of Llyn Brianne dam in Wales.

Most modern reservoirs have a specially designed draw-off tower that can discharge water from the reservoir at different levels both to access water as the reservoir draws down but also to allow water of a specific quality to be discharged into the downstream river as compensation water.

The operators of many upland or in-river reservoirs have obligations to release water into the downstream river to maintain river quality, support fisheries, maintain downstream industrial uses. maintain recreational use or for a range of other requirements. Such releases are known as *compensation water*.

Terminology

The terminology for reservoirs varies from country to country. In most of the world reservoir areas are expressed in km^2 whilst in the USA acres are commonly used. For volume either m^3 or km^3 are widely used with acre feet used in the USA.

The capacity, volume or storage of a reservoir is usually divided into distinguishable areas. *Dead* or *inactive* storage refers to water in a reservoir that cannot be drained by gravity through a dam's outlet works, spillway or power plant intake and can only be pumped out. Dead storage allows sediments to settle which improves water quality and also creates hydraulic head along with an area for fish during low levels. *Active* or *live* storage is the portion of the reservoir that can be utilized for flood control, power production, navigation and downstream releases. In addition, a reservoir's *flood control capacity* is the amount of water it can regulate during flooding. The *surcharge capacity* is the capacity of the reservoir above the spillway crest that cannot be regulated.

In the United States the water below the normal maximum level of a reservoir is called the *conservation pool*.

In the UK *top water level* describes the reservoir full state whist *fully drawn down* describes the minimum retained volume.

Modelling reservoir management

There is a wide variety of software for modelling reservoirs, from the specialist Dam Safety Program Management Tools (DSPMT) to the relatively simple WAFLEX, to integrated models like the Water Evaluation And Planning system (WEAP) that place reservoir operations in the context of system-wide demands and supplies.

Safety

In many countries large reservoirs are closely regulated to try and prevent or minimise failures of containment.

Whilst much of the effort is directed at the dam and its associated structures as the weakest part of the overall structure, the aim of such controls is to prevent an uncontrolled release of water from the reservoir. Reservoir failures can generate huge increases in flow down a river valley with the potential to wash away towns and villages and cause considerable loss of life such as the devastation following the failure of containment at Llyn Eigiau which killed 17 people.

A notable case of reservoirs being used as an instrument of War involved the British Royal Air Force Dambusters raid on Germany in World War II (codenamed "Operation Chastise"), in which three German reservoir dams were selected to be breached in order to impact on German infrastructure and manufacturing and power capabilities deriving from the Ruhr and Eder rivers. The economic and social impact was derived from the enormous volumes of previously stored water that swept down the valleys wreaking destruction. This raid later became the basis for several films.

Environmental impact

Whole life environmental impact

All reservoirs will have a monetary cost/benefit assessment made before construction to see if the project is worth proceeding with. However, such analysis can often omit the environmental impacts of dams and the reservoirs that they contain. Some impacts such as the greenhouse gas production associated with concrete manufacture are relatively easy to estimate. Other impact on the natural environment and social and cultural effects can be more difficult to assess and to weigh in the balance but identification and quantification of these issues are now commonly required in major construction projects in the developed world

Climate change

Depending upon the circumstances, a reservoir built for hydro-electricity generation can either reduce or increase the net production of greenhouse gases. An **increase** can occur if plant material in the flooded areas decays in an anaerobic environment releasing (methane and carbon dioxide). This apparently counter intuitive position arises because much carbon is released as methane which is approximately 8 time more potent as a greenhouse gas than carbon dioxide

A study for the National Institute for Research in the Amazon found that Hydroelectric reservoirs release a large pulse of carbon dioxide from above-water decay of trees left standing in the reservoirs, especially during the first decade after closing. This elevates the global warming impact of the dams to levels much higher than would occur by generating the same power from fossil fuels. According to the World Commission on Dams report (Dams And Development), when the reservoir is relatively large and no prior clearing of forest in the flooded area was undertaken, greenhouse gas emissions from the reservoir could be higher than those of a conventional oil-fired thermal generation plant. For instance, In 1990, the impoundment behind the Balbina Dam in Brazil(inaugurated in 1987) had over 20 times the impact on global warming than would generating the same power from fossil fuels, due to the large area flooded per unit of electricity generated.

A **decrease** can occur if the dam is used in place of traditional power generation, since electricity produced from hydroelectric generation does not give rise to any flue gas emissions from fossil fuel combustion (including sulfur dioxide, nitric oxide and carbon monoxide from coal). The Tucurui dam in Brazil (closed in 1984) had only 0.4 times the impact on global warming than would generating the same power from fossil fuels.

Biology

Dams can produce a block for migrating fish, trapping them in one area, producing food and a habitat for various water-birds. They can also flood various ecosystems on land and may cause extinctions.

Human Impact

Dams can severely reduce the amount of water from reaching countries downstream of them, causing water stress between the countries, e.g. the Sudan and Egypt, which damages farming businesses in the downstream countries, and reduces drinking water.

Farms and villages, e.g. Ashopton can be flooded by the creation of reservoirs, ruining many livelihoods. For this very reason, worldwide 80 million people have had to be forcibly relocated due to dam construction.

Limnology

The limnology of reservoirs has many similarities to that of lakes of equivalent size. There are however significant differences. Many reservoirs experience considerable variations in level producing significant areas that are intermittently underwater or dried out. This greatly limits the productivity or the water margins and limits the number of species able to survive in these conditions.

Upland reservoirs tend to have a much shorter residence time than natural lakes and this can lead to more rapid cycling of nutrients through the water body so that they are more quickly lost to the system. This may be seen as a mismatch between water chemistry and water biology with a tendency for the biological component to be more oligotrophic than the chemistry would suggest.

Conversely, lowland reservoirs drawing water from nutrient rich rivers, may show exaggerated eutrophic characteristics because the residence time in the reservoir is much greater than in the river and the biological systems have a much greater opportunity to utilise the available nutrients.

Deep reservoirs with multiple level draw off towers can discharge deep cold water into the downstream river greatly reducing the size of any hypolimnion. This in turn can reduce the concentrations of phosphorus released during any annual mixing event and may therefore reduce productivity.

The Dams in front of reservoirs act as knickpoints-the energy of the water falling from them reduces and deposition is a result below the Dams.

Earthquakes

Large reservoirs have been indicated as contributing to earthquakes, due to changes in loading and/or the height of the water table.

Micro climate

Reservoirs may change the local micro-climate increasing humidity and reducing extremes of temperature. Such effects are claimed by some South Australian winerys as increasing the quality of the wine production.