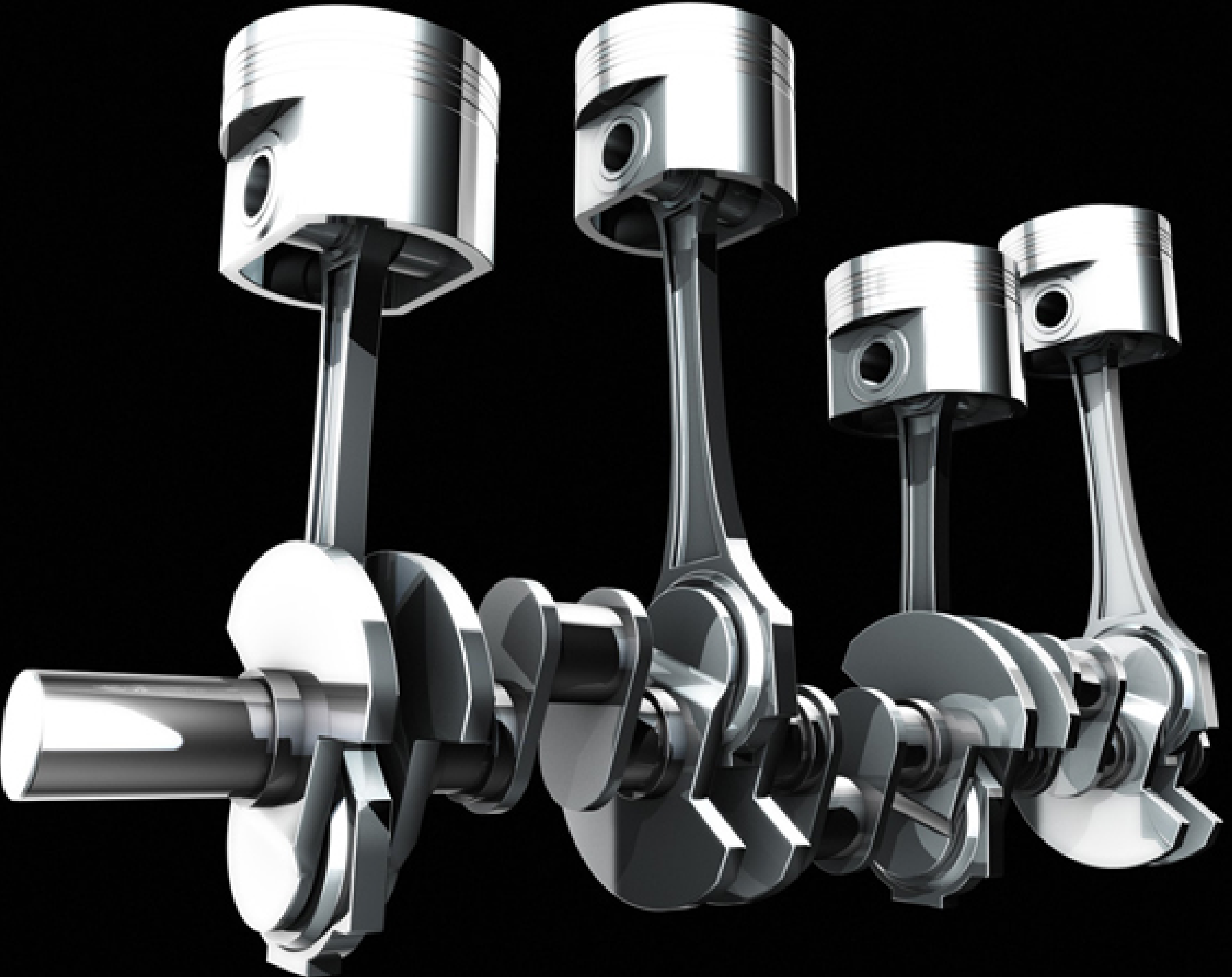

Piston Engines and Technologies

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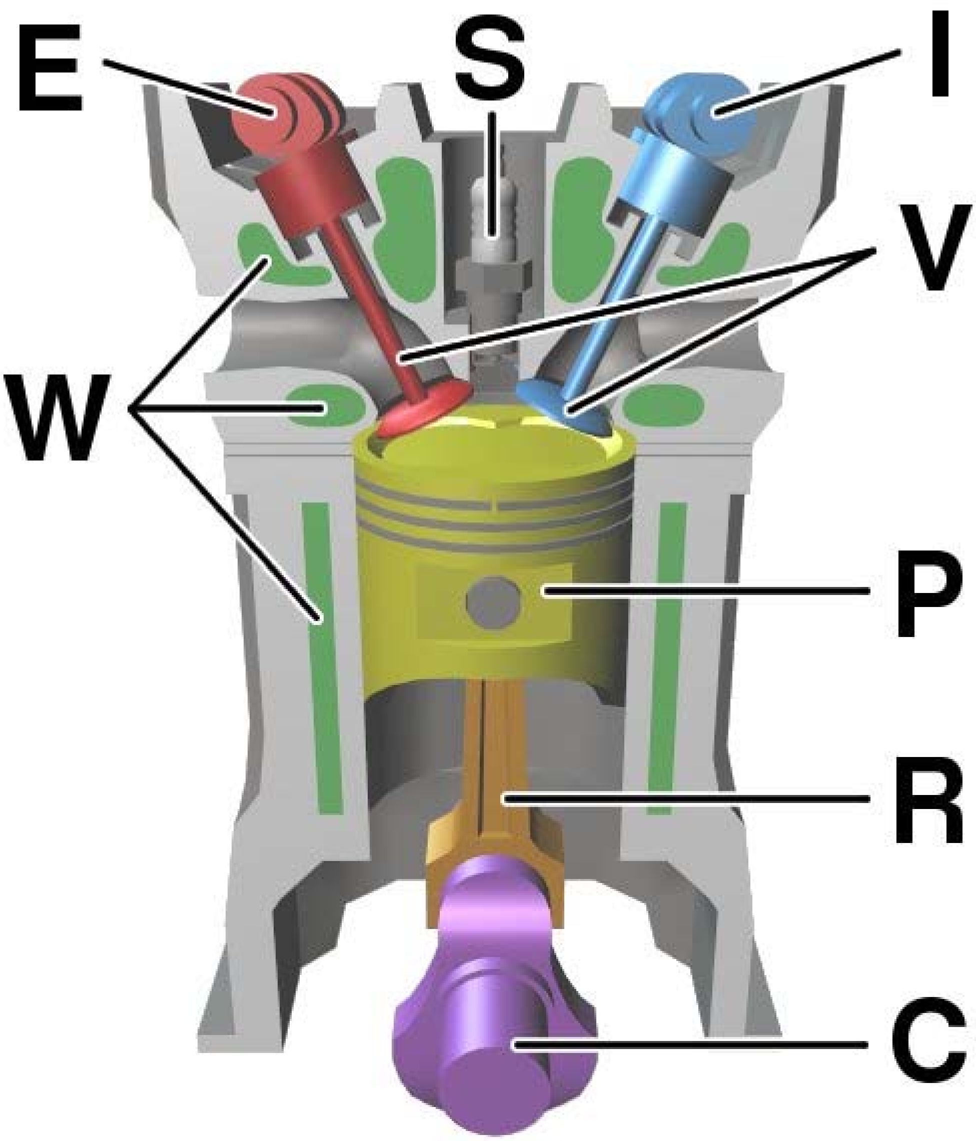
Chapter 1

Reciprocating Engine



Internal combustion piston engine
Components of a typical, four stroke cycle, internal combustion piston engine.

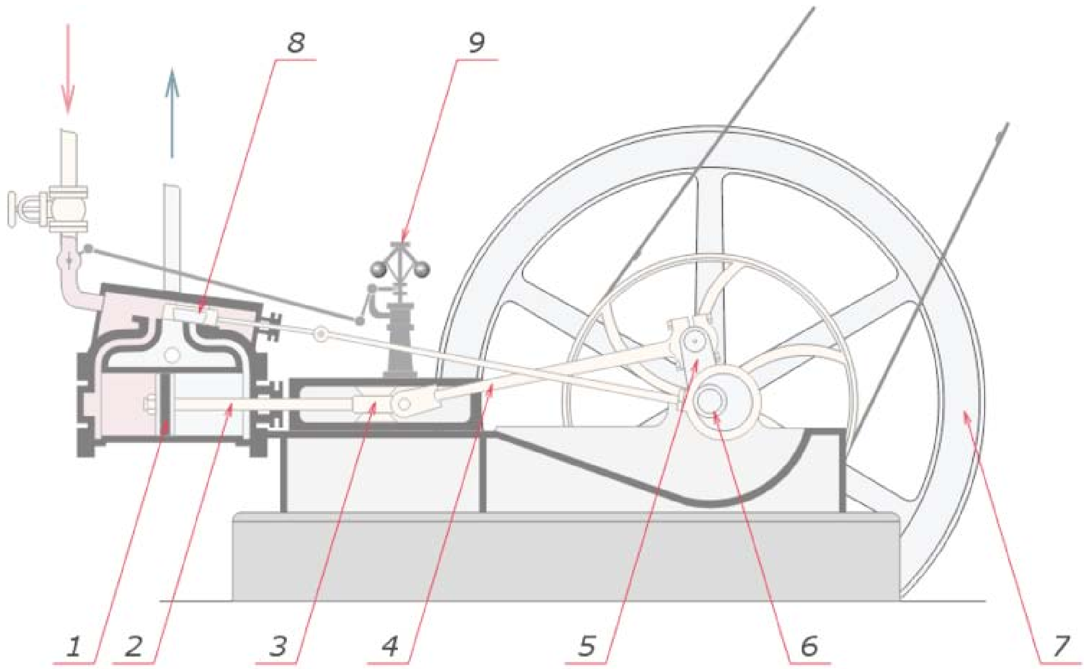
E - Exhaust camshaft
I - Intake camshaft
S - Spark plug
V - Valves
P - Piston
R - Connecting rod
C - Crankshaft
W - Water jacket for coolant flow

A **reciprocating engine**, also often known as a **piston engine**, is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion. This is describes the common features of all types. The main types are: the internal combustion engine, used extensively in motor vehicles; the steam engine, the mainstay of the Industrial Revolution; and the niche application Stirling engine.

Common features in all types

There may be one or more pistons. Each piston is inside a cylinder, into which a gas is introduced, either already hot and under pressure (steam engine), or heated inside the cylinder either by ignition of a fuel air mixture (internal combustion engine) or by contact with a hot heat exchanger in the cylinder (Stirling engine). The hot gases expand, pushing the piston to the bottom of the cylinder. The piston is returned to the cylinder top (Top Dead Centre) either by a flywheel or the power from other pistons connected to the same shaft. In most types the expanded or "exhausted" gases are removed from the cylinder by this stroke. The exception is the Stirling engine, which repeatedly heats and cools the same sealed quantity of gas.

In some designs the piston may be powered in both directions in the cylinder in which case it is said to be double acting.



Steam piston engine
A labeled schematic diagram of a typical single cylinder, simple expansion, double-acting high pressure steam engine. Power takeoff from the engine is by way of a belt.
1 - Piston
2 - Piston rod
3 - Crosshead bearing
4 - Connecting rod
5 - Crank
6 - Eccentric valve motion
7 - Flywheel
8 - Sliding valve
9 - Centrifugal governor.

In all types, the linear movement of the piston is converted to a rotating movement via a connecting rod and a crankshaft or by a swashplate. A flywheel is often used to ensure smooth rotation. The more cylinders a reciprocating engine has, generally, the more vibration-free (smoothly) it can operate. The power of a reciprocating engine is proportional to the volume of the combined pistons' displacement.

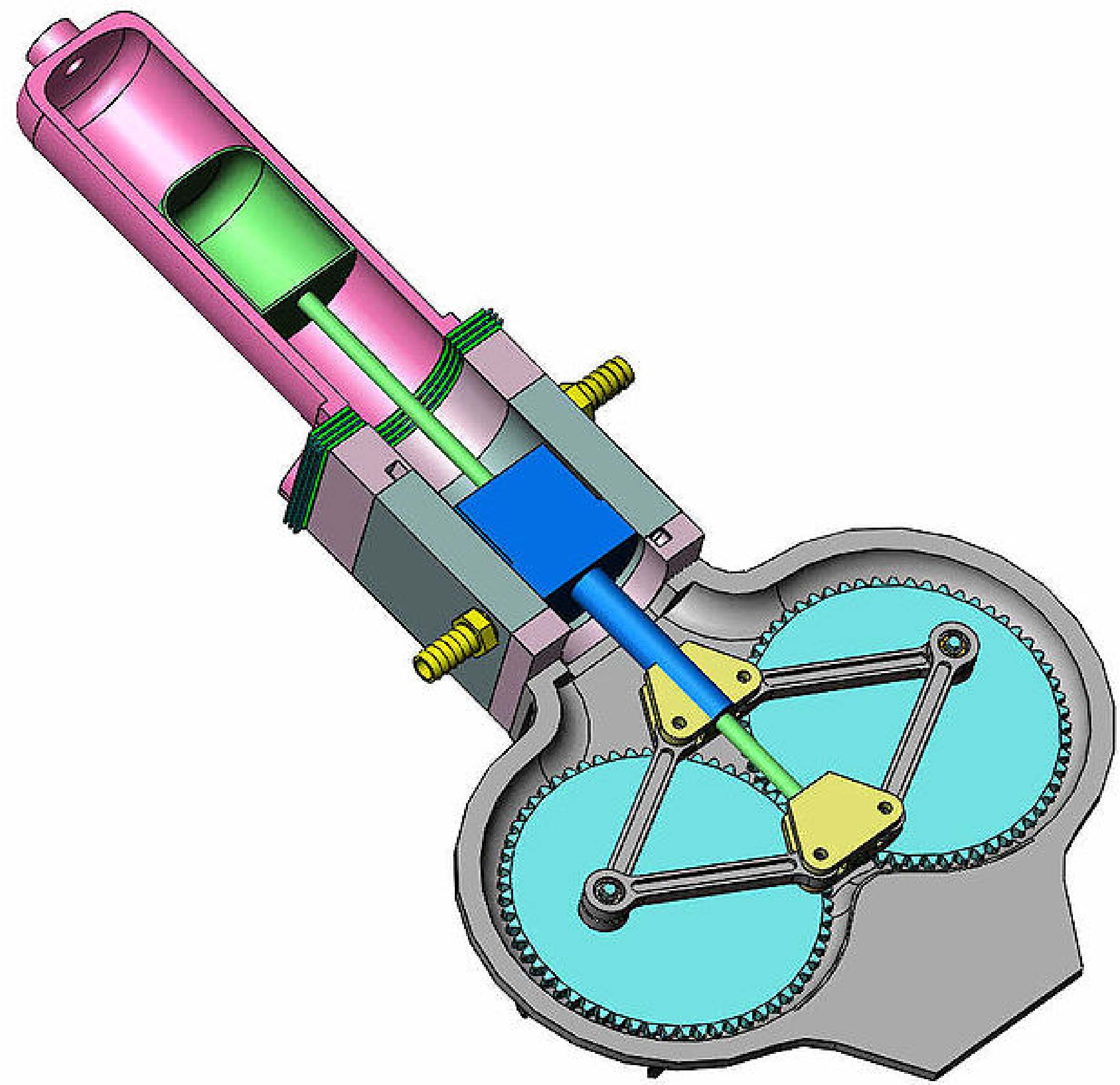
A seal needs to be made between the sliding piston and the walls of the cylinder so that the high pressure gas above the piston does not leak past it and reduce the efficiency of the engine. This seal is provided by one or more piston rings. These are rings made of a hard metal which are sprung into a circular groove in the piston head. The rings fit tightly in the groove and press against the cyinder wall to form a seal.

It is common for such engines to be classified by the number and alignment of cylinders and the total volume of displacement of gas by the pistons moving in the cylinders usually measured in cubic centimetres (cm^3 or cc) or litres (l) or (L) (US:liter). For example for internal combustion engines, single and two-cylinder designs are common in smaller vehicles such as motorcycles, while automobiles typically have between four and eight, and locomotives, and ships may have a dozen cylinders or more. Cylinder capacities may range from 10 cm^3 or less in model engines up to several thousand cubic centimetres in ships' engines.

The compression ratio is a measure of the performance in an internal-combustion engine or a Stirling Engine. It is the ratio between the volume of the cylinder, when the piston is at the bottom of its stroke, and the volume when the piston is at the top of its stroke.

The bore/stroke ratio is the ratio of the diameter of the piston, or "bore", to the length of travel within the cylinder, or "stroke". If this is around 1 the engine is said to be "square", if it is greater than 1, i.e. the bore is larger than the stroke, it is "oversquare". If it is less than 1 , i.e. the stroke is larger than the bore, it is "undersquare".

Cylinders may be aligned in line, in a V configuration, horizontally opposite each other , or radially around the crankshaft. Opposed-piston engines put two pistons working at opposite ends of the same cylinder and this has been extended into triangular arrangements such as the Napier Deltic.



Stirling piston engine
Rhombic Drive Beta Stirling Engine Design showing the second displacer piston (green) within the cylinder which shunts the working gas between the hot and cold ends , but produces no power itself.
Pink - Hot cylinder wall,
Dark grey - Cold cylinder wall,
Green - Displacer piston,
Dark blue - Power piston,
Light blue - Flywheels

In steam engines and internal combustion engines, valves are required to allow the entry and exit of gasses at the correct time in the piston's cycle. These are worked by cams or cranks driven by the shaft of the engine. Early designs used the D slide valve but this has been largely superseded by Piston valve or Poppet valve designs. In steam engines the point in the piston cycle at which the steam inlet valve closes is called the cutoff and this can often be controlled to adjust the torque supplied by the engine.

Internal combustion engines operate through a sequence of strokes which admit and remove gases to and from the cylinder. These operations are repeated cyclically and an engine is said to be 2-stroke, 4-stroke or 6-stroke depending on the number of strokes it takes to complete a cycle.

In some steam engines, the cylinders may be of varying size with the smallest bore cylinder working the highest pressure steam. This is then fed through one or more, increasingly larger bore cylinders successively, to extract power from the steam at increasingly lower pressures. These engines are called Compound engines.

History

An early known example of rotary to reciprocating motion can be found in a number of Roman saw mills (dating to the 3rd to 6th century AD) in which a crank and connecting rod mechanism converted the rotary motion of the waterwheel into the linear movement of the saw blades. Another early example was the reciprocating piston pump of Al-Jazari in 1206.

The reciprocating engine developed in Europe during the 18th century, first as the atmospheric engine then later as the steam engine. These were followed by the Stirling engine and internal combustion engine in the 19th century. Today the most common form of reciprocating engine is the internal combustion engine running on the combustion of petrol, diesel, Liquefied petroleum gas (LPG) or compressed natural gas (CNG) and used to power motor vehicles.

One of the most advanced reciprocating engines ever made was the 28-cylinder, 3,500 hp (2,600 kW) Pratt & Whitney R-4360 "Wasp Major" radial engine which powered the last generation of large piston-engined planes before the jet engine and turboprop took over from 1944 onward. It had a total engine capacity of 71.5 litres (2.52 cu ft).

The largest reciprocating engine in production at present, but not the largest ever built, is the Wärtsilä-Sulzer RTA96-C turbocharged two-stroke diesel engine of 2006 built by Japan’s Diesel United, Ltd. It is used to power the largest modern container ships such as the Emma Mærsk. It is five stories high (13.5 m/44 ft), 27 metres (89 ft) long, and weighs over 2,300 metric tons (2,500 short tons) in its largest 14 cylinders version producing more than 84.42 MW (114,800 bhp). Each cylinder has a capacity of 1,820 litres (64 cu ft), making a total capacity of 25,480 litres (900 cu ft) for the largest versions.

Engine capacity

For piston engines, an engine's capacity is the engine displacement, in other words the volume swept by all the pistons of an engine in a single movement. It is generally measured in litres (L) or cubic inches (c.i.d. *or* cu in *or* in^3) for larger engines, and cubic centimetres (abbreviated cc) for smaller engines. Engines with greater capacities are more powerful and provide greater torque at lower speed (rpm) and consumption of fuel increases accordingly.

Other modern non-internal combustion types

Reciprocating engines that are powered by compressed air, steam or other hot gases are still used in some applications such as to drive many modern torpedoes or as pollution-free motive power. Most steam-driven applications use steam turbines, which are more efficient than piston engines.

The French-designed FlowAIR vehicles use compressed air stored in a cylinder to drive a reciprocating engine in a pollution-free urban vehicle.

Torpedoes may use a working gas produced by high test peroxide or Otto fuel II, which pressurise without combustion. The 230 kg (510 lb) Mark 46 torpedo, for example, can travel 11 km (6.8 mi) underwater at 74 km/h (46 mph) fuelled by Otto fuel without oxidant.

Chapter 2

Cam-In-Block

The **cam-in-block** valvetrain layout of piston engines is one where the camshaft is placed within the cylinder block, usually beside and slightly above the crankshaft in a straight engine or directly above the crankshaft in the V of a V engine. This contrasts with an overhead camshaft (OHC) design which places the camshafts within the cylinder head and drives the valves directly or through short rocker arms.

Placing the camshaft inside the engine block has a long history in its use in valve-in-block engines, in straight and V configurations, the Ford flathead being exemplary of the type. Pushrod overhead valve engines with the cam in the block were long used in Chevrolet and Buick straight engines from the 1930s through the mid 1950s and in various similar six cylinder engines until the extensive employment of the V6 configuration in the 1980s.

There are three main cam-in-block designs:

- L-head, also known as *L-block*, *flathead* or *sidevalve*
- F-head
- I-head, also known as overhead valve (OHV)

L-head

flathead V twin engine, modified for power, depicted on cover of Hot Rod magazine. The "flat head" is evident. In this version the camshaft directly operates the distributor, the black object on the front face of the block (the red object)

L-head (*flathead*) refers to the pushrod valvetrain configuration in which the valves are placed in the engine block beside the pistons. The design was common on early engine designs, but has since fallen from use.

Generally L-head engines use a small chamber on one side of the cylinder to carry the valves. This has a number of advantages, primarily in that it makes the cylinder head much simpler. It also means that the valve can be operated by pushing directly up on it, as opposed to needing some sort of mechanical arrangement to push the valves down. It may also lead to slightly easier cooling, as the valves and operating rods are out of the way of the cylinder, making a cooling jacket simpler to construct. The line of intakes along the side of the engine lead to the name L-head, due to the cylinders having the shape of an upside-down L. This configuration is also known as sidevalve, as the valves are located be*side* the cylinders.

On the downside, the L-head engine also requires the airflow to make at least a 90° turn to enter the cylinder, which makes it less efficient; colloquially it's said that such an engine has poorer "breathing". Breathing was not greatly emphasized in past production cars because engines could not run long and reliably at high speed due to other factors. This was a minor concern given the benefits in simplicity.

Although L-head inline 4 and 6 cylinder engines were frequently used for automobiles, tractors, etc., the best known L-head automotive engine is the early 20th century Ford V-8, which has both sets of valves (intake and exhaust) located on the inside of the "Vee," and which are all operated by a single camshaft located above the crankshaft. The exhaust follows a lengthy path to leave the engine. This virtually guarantees that the engine will need an unusually large coolant radiator to avoid overheating under sustained heavy use. A flathead design in a V engine, with the air intake/fuel system and all of the exhaust and intake valves inside of the "V" requires that the exhaust gas be passed between the cylinders to outside of the V to the exhaust system. Exhaust heat is thus passed to the coolant (as it exits the engine between the cylinders). In the Ford V-8 flathead design, manufactured from 1932 through 1952, the center exhaust port on the outside of the block exhausts the gasses from two cylinders, exacerbating the high heat problem. This "very hot in the middle" problem makes this particular engine prone to heat-related stress and cracks in the cylinder block. In line engine exhaust gas exits the block more directly and does not cross between the cylinders and is a more temperature-stable design. Whenever exhaust ports and valves are in the cylinder head, exhausting heat has far less time to heat the coolant, and such engines are more durable under high load conditions and a similar sized engine will require less coolant radiator capacity than a flathead V-8.

Due to the heating and efficiency problems, L-head engines fell from high power uses such as aircraft engines fairly quickly, prior to World War I. They lived on for some time in the automotive world and were used in the World War II Jeep, for instance. L-heads are no longer used in automobile engines, although they remain in common use for small-engine applications in lawnmowers and generators. Because of their heat-retaining design, the size of valves and the compression ratio are limited (the valve/combustion chamber is away from the piston top typically creating a larger combustion space--a lower compression ratio), which in turn reduces available power and economy. Not all L-heads are cam-in-block engines; the location of the camshaft varies in this layout.

T-head

In some flathead engines, the exhaust valves were in a second set of similar chambers on the other side of the cylinder and driven by a second camshaft. This crossflow layout is referred to as a T-head.

F-head

The F-head layout can be thought of as a combination of L-head and I-head: the intake manifold and its valves are located atop the cylinders (in the cylinder head, as in an I-head design) and are operated by pushrods, but the exhaust manifold and its valves are located beside the cylinders (in the block, as in an L-head design). The exhaust valves are either roughly or exactly parallel with the pistons; their faces point upwards and they are not operated by pushrods, but by direct contact with a lifter contacting the camshaft. Reverse variation of F-head with side intake and in head exhaust were also made- the Ford V8 overhead exhaust valve conversions to flathead engines were to decrease the overheating under load problems in commercial service. The Indian/Henderson 4 cylinder motorcycle engine family used both designs- the overhead exhaust was again an overheating consideration design.

This was a more expensive engine design. Its advantages over competing L-head engines included more power from its higher compression, better intake mixture flow, less susceptibility to pinging, and greater reliability from its cooling of the exhaust valve and its spring (and having half the number of pushrods of an OHV engine). With only one valve in the head, and one in the block, larger valves can be used than in an OHV engine, to offset the poorer airflow of a side exhaust valve.

For years the British motor car firms Rolls-Royce and Rover used this arrangement. From 1927-1929, the American firm Hudson used a 6-cylinder engine of this form as well, but this engine is not to be confused with that of the race-winning Hudsons of the 1950s. The last major use was the Willys Hurricane engine, used in civilian Jeeps in the 1950s and 1960s. It was replaced by the I-head design.

I-head

The I-head design is one in which the entry and exit valves and ports are contained in the cylinder head. It was developed by the Scottish-American David Dunbar Buick. It employed pushrod-actuated valves parallel to the pistons and is still in use today in some designs (notably several engines produced by General Motors).

It has several advantages over L- and F-head designs, but the most notable is the fact that the intake charge and exhaust gases have a more direct path into and out of the combustion chambers, increasing power, improving fuel efficiency and reducing noxious exhaust emissions.

Chapter 3

Compression Ratio

The **compression ratio** of an internal-combustion engine or external combustion engine is a value that represents the ratio of the volume of its combustion chamber from its largest capacity to its smallest capacity. It is a fundamental specification for many common combustion engines.

In a piston engine it is the ratio between the volume of the cylinder and combustion chamber when the piston is at the bottom of its stroke, and the volume of the combustion chamber when the piston is at the top of its stroke.

Picture a cylinder and its combustion chamber with the piston at the bottom of its stroke containing 1000 cc of air (900 cc in the cylinder plus 100 cc in the combustion chamber). When the piston has moved up to the top of its stroke inside the cylinder, and the remaining volume inside the head or combustion chamber has been reduced to 100 cc, then the compression ratio would be proportionally described as 1000:100, or with fractional reduction, a 10:1 compression ratio.

A high compression ratio is desirable because it allows an engine to extract more mechanical energy from a given mass of air-fuel mixture due to its higher thermal efficiency. High ratios place the available oxygen and fuel molecules into a reduced space along with the adiabatic heat of compression–causing better mixing and evaporation of the fuel droplets. Thus they allow increased power at the moment of ignition and the extraction of more useful work from that power by expanding the hot gas to a greater degree.

Higher compression ratios will however make gasoline engines subject to engine knocking if lower octane-rated fuel is used, also known as detonation. This can reduce efficiency or damage the engine if knock sensors are not present to retard the timing. However, knock sensors have been a requirement of the OBD-II specification used in 1996 model year vehicles and newer.

Diesel engines on the other hand operate on the principle of compression ignition, so that a fuel which resists autoignition will cause late ignition which will also lead to engine knock.

Formula

The ratio is calculated by the following formula:

$$\mathrm{CR} = \frac{\frac{\pi}{4} b^2 s + V_c}{V_c}$$, where

b= cylinder bore (diameter)

s= piston stroke length

V_c= clearance volume. It is the volume of the combustion chamber (including head gasket). This is the minimum volume of the space at the end of the compression stroke, i.e. when the piston reaches top dead center (TDC). Because of the complex shape of this space, it is usually measured directly rather than calculated.

Typical compression ratios

Petrol (gasoline) engine

Due to pinging (detonation), the compression ratio in a gasoline or petrol-powered engine will usually not be much higher than 10:1, although some production automotive engines built for high-performance from 1955–1972 had compression ratios as high as 13.0:1, which could run safely on the high-octane leaded gasoline then available.

A technique used to prevent the onset of knock is the high "swirl" engine that forces the intake charge to adopt a very fast circular rotation in the cylinder during compression that provides quicker and more complete combustion. Recently, with the addition of variable valve timing and knock sensors to delay ignition timing, it is possible to manufacture gasoline engines with compression ratios of over 11:1 that can use 87 MON (octane rating) fuel.

In engines with a 'ping' or 'knock' sensor and an electronic control unit, the CR can be as high as 13:1 (2005 BMW K1200S). In 1981, Jaguar released a cylinder head that allowed up to 14:1 compression; but settled for 12.5:1 in production cars. The cylinder head design was known as the "May Fireball" head; it was developed by a Swiss engineer Michael May.

Petrol/gasoline engine with pressure-charging

In a turbocharged or supercharged gasoline engine, the CR is customarily built at 9.32:1 or lower.

Petrol/gasoline engine for racing

Motorcycle racing engines can use compression ratios as high as 14:1, and it is not uncommon to find motorcycles with compression ratios above 12.0:1 designed for 86 or 87 octane fuel.

Ethanol and methanol engines

Ethanol and methanol can take significantly higher compression ratios than gasoline. Racing engines burning methanol and ethanol fuel often incorporate a CR of 14.5-16:1, with F1 engines coming closer to 17:1(which is very critical for maximizing volumetric/fuel efficiency at around 18000 rpm)

Gas-fueled engine

In engines running exclusively on LPG or CNG, the CR may be higher, due to the higher octane rating of these fuels.

Diesel engine

In an auto-ignition diesel engine, (no electrical sparking plug—the hot air of compression lights the injected fuel) the CR will customarily exceed 14:1. Ratios over 22:1 are common. The appropriate compression ratio depends on the design of the cylinder head. The figure is usually between 14:1 and 16:1 for direct injection engines and between 18:1 and 23:1 for indirect injection engines.

Fault finding and diagnosis

Measuring the compression pressure of an engine, with a pressure gauge connected to the spark plug opening, gives an indication of the engine's state and quality. There is, however, no formula to calculate compression ratio based on cylinder pressure.

If the nominal compression ratio of an engine is given, the pre-ignition cylinder pressure can be estimated using the following relationship:

$$p = p_0 \times \mathrm{CR}^\gamma$$

where $p_0$is the cylinder pressure at bottom dead center which is usually at 1 atm, CR is the compression ratio, and $\gamma$is the specific heat ratio for the working fluid, which is about 1.4 for air, and 1.3 for methane-air mixture.

For example, if an engine running on gasoline has a compression ratio of 10:1, the cylinder pressure at top dead center is

$$p_{\mathrm{TDC}} = 1\ \mathrm{bar} \times 10^{1.4} = 25.1\ \mathrm{bar}$$

This figure, however, will also depend on cam (i.e. valve) timing. Generally, cylinder pressure for common automotive designs should at least equal 10 bar, or, roughly estimated in pounds per square inch (psi) as between 15 and 20 times the compression ratio, or in this case between 150 psi and 200 psi, depending on cam timing. Purpose-built racing engines, stationary engines etc. will return figures outside this range.

Factors including late intake valve closure (relatively speaking for camshaft profiles outside of typical production car range, but not necessarily into the realm of competition engines) can produce a misleadingly low figure from this test. Excessive connecting rod clearance, combined with extremely high oil pump output (rare but not impossible) can sling enough oil to coat the cylinder walls with enough oil to facilitate reasonable piston ring seal artificially give a misleadingly high figure, on engines with compromised ring seal.

This can actually be used to some slight advantage. If a compression test does give a low figure, and it has been determined it is not due to intake valve closure/camshaft characteristics, then one can differentiate between the cause being valve/seat seal issues and ring seal by squirting engine oil into the spark plug orifice, in a quantity sufficient to disperse across the piston crown and the circumference of the top ring land, and thereby effect the mentioned seal. If a second compression test is performed shortly thereafter, and the new reading is much higher, it would be the ring seal that is problematic, whereas if the compression test pressure observed remains low, it is a valve sealing (or more rarely head gasket, or breakthrough piston or rarer still cylinder wall damage) issue.

If there is a significant (greater than 10%) difference between cylinders, that may be an indication that valves or cylinder head gaskets are leaking, piston rings are worn or that the block is cracked.

If a problem is suspected then a more comprehensive test using a leak-down tester can locate the leak.

Saab variable-compression engine

Because cylinder bore diameter, piston stroke length and combustion chamber volume are almost always constant, the compression ratio for a given engine is almost always constant, until engine wear takes its toll.

One exception is the experimental Saab Variable Compression engine (SVC). This engine, designed by Saab Automobile, uses a technique that dynamically alters the volume of the combustion chamber (V_c), which, via the above equation, changes the compression ratio (CR).

To alter V_c, the SVC 'lowers' the cylinder head closer to the crankshaft. It does this by replacing the typical one-part engine block with a two-part unit, with the crankshaft in the lower block and the cylinders in the upper portion. The two blocks are hinged together at one side (imagine a book, lying flat on a table, with the front cover held an inch or so above the title page). By pivoting the upper block around the hinge point, the V_c (imagine the air between the front cover of the book and the title page) can be modified. In practice, the SVC adjusts the upper block through a small range of motion, using a hydraulic actuator.

Variable Compression Ratio (VCR) engines

The SAAB SVC is an advanced and workable addition to the world of VCR engines, the first being built and tested by Harry Ricardo in the 1920s. This work led to him devising the octane rating system that is still in use today. SAAB has recently been involved in working with the 'Office of Advanced Automotive Technologies', to produce a modern petrol VCR engine that showed an efficiency comparable with that of a Diesel. Many companies have been carrying out their own research in to VCR Engines, including Nissan, Volvo, PSA/Peugeot-Citroën and Renault but so far with no publicly demonstrated results.

The Atkinson cycle engine was one of the first attempts at variable compression. Since the compression ratio is the ratio between dynamic and static volumes of the combustion chamber the Atkinson cycle's method of increasing the length of the powerstroke compared to the intake stroke ultimately altered the compression ratio at different stages of the cycle.

Cortina Variable Compression engine

American inventor Paul Cortina is the latest entry into variable compression engine development. The Cortina engine is the only variable compression concept that slides the entire reciprocating assembly toward and away from the cylinder head. The advantage of this approach is that there is no complication to the workings of the reciprocating assembly itself, nor is there any complication outside of the engine. The way this is accomplished is by sliding the reciprocating assembly on a splined output shaft that is positioned perpendicular to a typical engine’s output orientation. The novel use of a barrel cam in place of a tradition crankshaft uses fewer parts than competing designs and adds the option of a true Atkinson cycle. It also has a more favorable leverage curve than a traditional crankshaft. Since the connecting rods stay straight, with a barrel cam cycling the pistons, it also is possible to box in the lower cylinder for use as an internal supercharger.

Dynamic compression ratio

The calculated compression ratio, as given above, presumes that the cylinder is sealed at the bottom of the stroke, and that the volume compressed is the actual volume.

However: intake valve closure (sealing the cylinder) always takes place after BDC, which may cause some of the intake charge to be compressed backwards out of the cylinder by the rising piston at very low speeds; only the percentage of the stroke after intake valve closure is compressed. Intake port tuning and scavenging may allow a greater mass of charge (at a higher than atmospheric pressure) to be trapped in the cylinder than the static volume would suggest (This "corrected" compression ratio is commonly called the "*dynamic compression ratio*".

This ratio is higher with more conservative (i.e., earlier, soon after BDC) intake cam timing, and lower with more radical (i.e., later, long after BDC) intake cam timing, but always lower than the static or "nominal" compression ratio.

The actual position of the piston can be determined by trigonometry, using the stroke length and the connecting rod length (measured between centers). The absolute cylinder pressure is the result of an exponent of the dynamic compression ratio. This exponent is a polytropic value for the ratio of variable heats for air and similar gases at the temperatures present. This compensates for the temperature rise caused by compression, as well as heat lost to the cylinder. Under ideal (adiabatic) conditions, the exponent would be 1.4, but a lower value, generally between 1.2 and 1.3 is used, since the amount of heat lost will vary among engines based on design, size and materials used, but provides useful results for purposes of comparison. For example, if the static compression ratio is 10:1, and the dynamic compression ratio is 7.5:1, a useful value for cylinder pressure would be $(7.5)^{1.3}$ × atmospheric pressure, or 13.7 bar. (× 14.7 psi at sea level = 201.8 psi. The pressure shown on a gauge would be the absolute pressure less atmospheric pressure, or 187.1 psi.)

The two corrections for dynamic compression ratio affect cylinder pressure in opposite directions, but not in equal strength. An engine with high static compression ratio and late intake valve closure will have a DCR similar to an engine with lower compression but earlier intake valve closure.

Additionally, the cylinder pressure developed when an engine is running will be higher than that shown in a compression test for several reasons.

- The much higher velocity of a piston when an engine is running versus cranking allows less time for pressure to bleed past the piston rings into the crankcase.
- a running engine is coating the cylinder walls with much more oil than an engine that is being cranked at low RPM, which helps the seal.
- the higher temperature of the cylinder will create higher pressures when running vs. a static test, even a test performed with the engine near operating temperature.
- A running engine does not stop taking air & fuel into the cylinder when the piston reaches BDC; The mixture that is rushing into the cylinder during the downstroke develops momentum and continues briefly after the vacuum ceases (in the same respect that rapidly opening a door will create a draft that continues after movement of the door ceases). This is called scavenging. Intake tuning, cylinder head design, valve timing and exhaust tuning determine how effectively an engine scavenges.

Compression ratio versus overall pressure ratio

Compression ratio and overall pressure ratio are interrelated as follows:

Compression ratio	2:1	3:1	5:1	10:1	15:1	20:1	25:1	35:1
Pressure ratio	2.64:1	4.66:1	9.52:1	25.12:1	44.31:1	66.29:1	90.60:1	145.11:1

The reason for this difference is that compression ratio is defined via the volume reduction:

$$\mathrm{CR} = \frac{V_1}{V_2},$$

while pressure ratio is defined as the pressure increase:

$$\mathrm{PR} = \frac{P_2}{P_1}.$$

In calculating the pressure ratio, we assume that an adiabatic compression is carried out (i.e. that no heat energy is supplied to the gas being compressed, and that any temperature rise is solely due to the compression). We also assume that air is a perfect gas. With those two assumptions we can define the relationship between change of volume and change of pressure as follows:

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} \Rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

where γ is the ratio of specific heats for air (approximately 1.4). The values in the table above are derived using this formula. Note that in reality the ratio of specific heats changes with temperature and that significant deviations from adiabatic behavior will occur.

Chapter 4

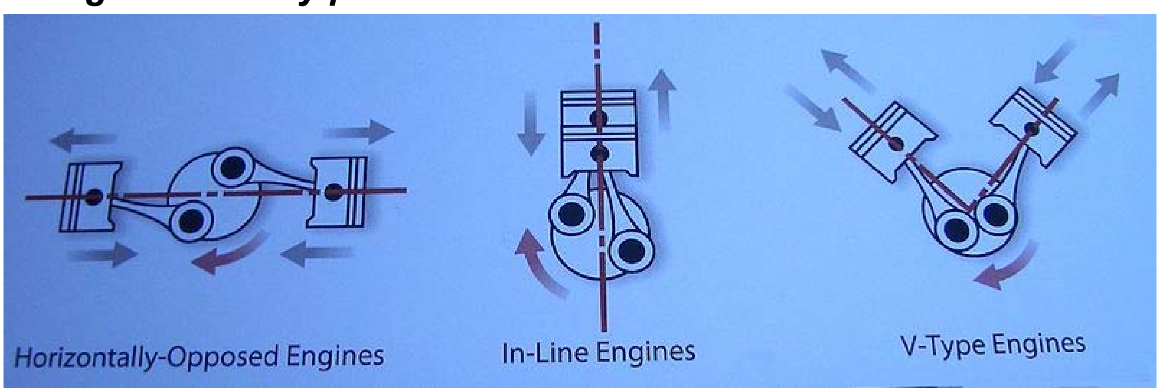
Engine Configuration

Engine configuration is an engineering term for the layout of the major components of a reciprocating piston internal combustion engine. These components are the cylinders and crankshafts in particular but also, sometimes, the camshaft(s).

Many apparently 'standard' names for configurations are historic, arbitrary, or overlapping. For example, the 180° V engine is so named because the crankshaft is related to a V engine more closely than it is related to other opposed-piston engines such as the boxer. Others would consider it a flat engine because of its shape.

The names *W engine* and *rotary engine* have each been used for several unconnected designs. The *H-4* and *H-6* engines produced by Subaru are not H engines at all, but boxer engines.

Categorisation by piston motion



Engine types include:

- Single cylinder engines
- Inline engine designs:
    - Straight engine, with all of the cylinders placed in a single row

        - U engine, two separate straight engines with crankshafts linked by a central gear.
            - The **square four** is a U engine where the two straight engines have two cylinders each.
    - V engine, with two banks of cylinders at an angle, most commonly 60 or 90 degrees.
    - Flat engine, two banks of cylinders directly opposite each other on either side of the crankshaft.
        - H engine, two crankshafts.
    - W engine. Combination of V and straight, giving 3 banks, or two V's intertwined giving 4 banks.
    - Opposed piston engine, with multiple crankshafts, an example being:
        - Delta engines, with three banks of cylinders and three crankshafts
    - X engine.
- Radial designs, including most:
    - Rotary engine designs. Mostly seen on pre-WWII aircraft.
- Pistonless rotary engines, notably:
    - Wankel engine.

The standard names for some configurations are historic, arbitrary, or both, with some overlap. For example, the cylinder banks of a 180° V engine do not in any way form a V, but it is regarded as a V engine because of its crankshaft and big end configuration, which result in performance characteristics similar to a V engine. But it is also considered a flat engine because of its shape. On the other hand, some engines which have none of the typical V engine crankshaft design features and consequent performance characteristics are also regarded as V engines, purely because of their shape. Similarly, the Volkswagen Group VR6 engine is a hybrid of the V engine and the straight engine, and can not be definitively labeled as either.

Other categorisations

By valve placement

The majority of four stroke engines have poppet valves, although some aircraft engines have sleeve valves. Valves may be located in the cylinder block (side valves), or in the cylinder head (overhead valves). Modern engines are invariably of the latter design. There may be two, three, four or five valves per cylinder, with the intake valves outnumbering the exhaust valves in case of an odd number.

By camshaft placement

Poppet valves are opened by means of a camshaft which revolves at half the crankshaft speed. This can be either chain, gear or toothed belt driven from the crankshaft, and can be located in the crankcase (where it may serve one or more banks of cylinders) or in the cylinder head.

If the camshaft is located in the crankcase, a valve train of pushrods and rocker arms will be required to operate overhead valves. Mechanically simpler are side valves, where the valve stems rested directly on the camshaft. However, this gives poor gas flows within the cylinder head as well as heat problems and fell out of favor for automobile use.

The majority of modern automobile engines place the camshaft on the cylinder head in an overhead camshaft (OHC) design. There may be one or two camshafts in the cylinder head; a single camshaft design is called single overhead camshaft (SOHC). A design with two camshafts per cylinder head is called double overhead camshaft (DOHC). Note that the camshafts are counted per cylinder head, so a V engine with one camshaft in each of its two cylinder heads is still an SOHC design, and a V engine with two camshafts per cylinder head would be described as 2xDOHC, or informally as a 'quad cam' engine.

With overhead camshafts, the valvetrain will be shorter and lighter, as no pushrods are required. Some single camshaft designs still have rocker arms; this facilates adustment of mechanical clearances.

If there are two camshafts in the cylinder head, the cams can sometimes bear directly on cam followers on the valve stems. This is the usual arrangement for a four-valves-per-cylinder design. This latter arrangement is the most inertia free, allows the most unimpeded gas flows in the engine and is the usual arrengement for high performance automobile engines. It also permits the spark plug to be located in the centre of the cylinder head, which promotes better combustion characteristics.

Very large engines (e.g. marine engines) can have either extra camshafts or extra lobes on the camshaft to enable the engine to run in either direction.

A disadvantage of overhead cams is that a much longer chain (or belt) is needed to drive the cams than with a camshaft located in the cylinder block, usually a tensioner is also needed. A break in the belt may destroy the engine if pistons touch open valves at top dead centre.

Chapter 5

Stroke Ratio

In a reciprocating piston engine, the **stroke ratio**, defined by either **bore/stroke ratio** or **stroke/bore ratio**, is a term which is used to describe the ratio between the diameter of the cylinder bore and the length of the piston stroke within its cylinders. This can be used for either an internal combustion engine, such as a petrol- or diesel engine, where the fuel is burned within the cylinders of the engine, or external combustion engine, such as a steam engine, where the combustion of the fuel takes place *outside* the working cylinders of the engine.

While the stroke ratio can provide insight into the goals of an engine's designer, it has no direct effect on the speed at which an engine reaches maximum torque: holding displacement constant, lengthening the crank throw reduces the piston area by an exactly corresponding amount.

Conventions

In a piston engine, there are two different ways of describing the *stroke ratio* of its cylinders, and these are often mixed together causing confusion. These are: *bore/stroke* ratio, and *stroke/bore* ratio.

Bore/stroke ratio

Bore/stroke is the most commonly used term, which is mainly used in the North America, Europe, United Kingdom, Asia, Australia, and some other countries.

The diameter of the cylinder bore is divided by the length of the piston stroke to give the ratio.

Stroke/bore ratio

Stroke/bore ratio is generally more rare than **bore/stroke** ratio, but is used in some countries, like in Finland for example.

The length of the piston stroke is divided by the diameter of the cylinder bore to give the ratio.

Stroke/bore ratio is similar to the bore/stroke ratio with the following exception:

When stroke/bore value is over 1:1 the engine is long-stroke or undersquare and when the stroke/bore value is under 1:1 the engine is short-stroke or oversquare. The square engine has a value of 1:1 in both cases.

For example an engine with 110 millimetres (4.33 in) stroke and 80 millimetres (3.15 in) bore, stroke/bore value 1.375, is an undersquare or long-stroke engine. An engine that has 70 millimetres (2.76 in) stroke and 100 millimetres (3.94 in) bore, stroke/bore value 0.7, is oversquare or short-stroke.

Square, undersquare and oversquare engines

The following terms describe the naming conventions for the various configurations of the relationship ratio between the diameter of the cylinder bore and the length of the piston stroke within the cylinders of a piston engine.

Square engine

An engine is described as a **square engine** when it has equal bore *and* stroke dimensions, giving a bore/stroke value of exactly 1:1.

For example an engine which has 95 millimetres (3.74 in) bore, and an identical 95 millimetres (3.74 in) stroke, has a bore/stroke value of:

95 mm / 95 mm = 1.00

Usually engines that have a bore/stroke ratio of 0.95 to 1.04 are referred as square engines.

Square engine examples

The Volkswagen Group W16 engine as used in the Bugatti Veyron is an example of a square engine - with an identical bore and stroke of 86.0 millimetres (3.39 in). Another example of a square engine is the 1970s Ford 400M with a 4.00" bore and stroke.

The Mercedes-Benz M117 engine with a displacement of 5547 cubic centimeters is an example of a nearly square engine with a bore of 96.5 millimeters and a stroke of 94.8 millimeters.

The Cadillac 500-V8 manufactured from 1970-1976 is a nearly square engine with a 4.300 inch bore and a 4.304 inch stroke.

Nissan's SR20DE is a square engine, with a bore and stroke of 86mm.

The 1973-1976 Kawasaki Z-1 and KZ(Z)900 had a 66 mm bore and a 66 mm stroke, also making it a square engine.

Oversquare, or short-stroke engine

An engine is described as **oversquare** or **short-stroke** if its cylinders have a greater bore diameter than its stroke length - giving a ratio value of greater than 1:1.

For example an engine which has 100 millimetres (3.94 in) bore and 80 millimetres (3.15 in) stroke has a bore/stroke value of:

100 mm / 80 mm = 1.25:1

An oversquare engine allows for more and larger valves in the head of the cylinder, lower friction losses (due to the reduced distance travelled during each engine rotation) and lower crank stress (due to the lower peak piston speed relative to engine speed). Because these characteristics favor higher engine speeds, oversquare engines are often tuned to develop peak torque at a relatively high speed.

The reduced stroke length allows for a shorter cylinder and sometimes a shorter connecting rod, generally making oversquare engines less tall than undersquare engines of similar engine displacement but wider and longer (for engines with vertical cylinder axes).

By changing the crankshaft and modifying the connecting rod(s), piston(s) and/or engine block an engine can be "de-stroked". This reduces the displacement and consequently the torque of the engine, but can allow it to run at higher speeds and in fact develop greater peak power.

Oversquare engine examples

Oversquare engines are extremely common, including both Chevrolet and Ford small block V8s. Most Boxer (horizontally-opposed) engines (such as those built by Volkswagen, Porsche, and Subaru) feature oversquare designs since any increase in stroke length would result in twice the increase in overall engine size.

This is particularly crucial in Subaru's front-engine layout, where the steering angle of the front wheels is limited largely by the size of the engine. Although oversquare engines have a reputation for being high-strung, low-torque machines, the Subaru EJ engine develops peak torque at speeds as low as 3200 RPM.

Extreme examples of oversquare engine designs are found in Formula One race cars, whose rules tightly limit displacement and thereby require that power be achieved through high engine speeds. Stroke ratios of 2.5:1 are typical, with engines capable of 19,000 RPM.

Undersquare, or long-stroke engine

An engine is described as **undersquare** or **long-stroke** if its cylinders have a smaller bore (width, diameter) than its stroke (length of piston travel) - giving a ratio value of less than 1:1.

For example an engine which has 90 millimetres (3.54 in) bore and 120 millimetres (4.72 in) stroke has a bore/stroke value of:

90 mm / 120 mm = 0.75:1

At a given engine speed, a longer stroke increases engine friction (since the piston travels a greater distance per stroke) and increases stress on the crankshaft (due to the higher peak piston speed). The smaller bore also reduces the area available for valves in the cylinder head, requiring them to be smaller or fewer in number. Because these factors favor lower engine speeds, undersquare engines are most often tuned to develop peak torque at relatively low speeds.

An undersquare engine will typically be more compact in the directions perpendicular to piston travel but larger in the direction parallel to piston travel.

An engine can be "stroked" by replacing the crankshaft with a so-called "stroker" crankshaft and modifying the connecting rod(s), piston(s) or engine block to accommodate the increased piston travel. This increases the displacement and therefore the torque of the engine, but may reduce the peak speed at which it is safe to run.

Undersquare engine examples

Many inline engines, particularly those mounted transversely in front-wheel-drive cars, utilize an undersquare design. The smaller bore allows for a shorter engine that increases room available for the front wheels to steer. Examples of this include many Volkswagen, Honda, and Mazda engines. Some rear-wheel-drive cars that borrow engines from front-wheel-drive cars (such as the Mazda Miata) use an undersquare design.

Despite their reputation as low-speed torque machines, some undersquare engines are designed for quite high speeds. The Honda Integra Type R's B18C5 engine has one of the highest redlines of any production engine, yet features an undersquare design. The 2011 Ford Coyote engine is a modern undersquare engine with a 7,000 rpm redline.

Many British automobile companies used undersquare designs through the 1950s, largely because of a motor tax system that taxed cars by their cylinder bore. This includes the Austin A-Series engine, and many Nissan derivatives.

The Chrysler Slant-6 engine, in its most common 225 cubic inch (3.7 litre) version, is a massively undersquare engine, with a 86 millimetres (3.39 in) bore and a 105 millimetres (4.13 in) stroke, producing most of its power right on the peak of its torque curve. The Achilles heel of this engine, otherwise known for its exceptional durability, is being over-revved by inexperienced drivers. Red line for a factory engine is under 4,500 revolutions per minute (rpm); red line with aftermarket connecting rods is about 5,500 rpm. On the other hand, a well-maintained Slant-6 can be made to idle as low as 75 rpm (though this is *not* a recommended speed - neither the alternator nor the oil pump will function adequately). In some circles, the Slant-6 is nicknamed "The Stump-Puller" for its diesel engine-like low-speed torque. Appropriate gearing and driving skill is required for performance use.

Willys also used mostly undersquare engines; in fact the L134 and F134 engines, with their fairly small 79.4 millimetres (3.13 in) bore and 111.1 millimetres (4.37 in) stroke, are probably the most undersquare engines ever built (for Jeeps).

The Dodge Power Wagon, among other vehicles, used a straight-six Chrysler Flathead engine of 230 cubic inches (3.8 litre) with a bore of 83 millimetres (3.27 in) and a stroke of 117 millimetres (4.61 in), yielding a substantially under-square stroke ratio of 0.70.

Virtually all piston aircraft engines used in military aircraft were long stroke engines. The PW R-2800, Wright R-3350, PW R-4360, Rolls-Royce Merlin (1650), Allison V-1710, and Hispano-Suiza 12Y-Z are only a few of more than a hundred examples.

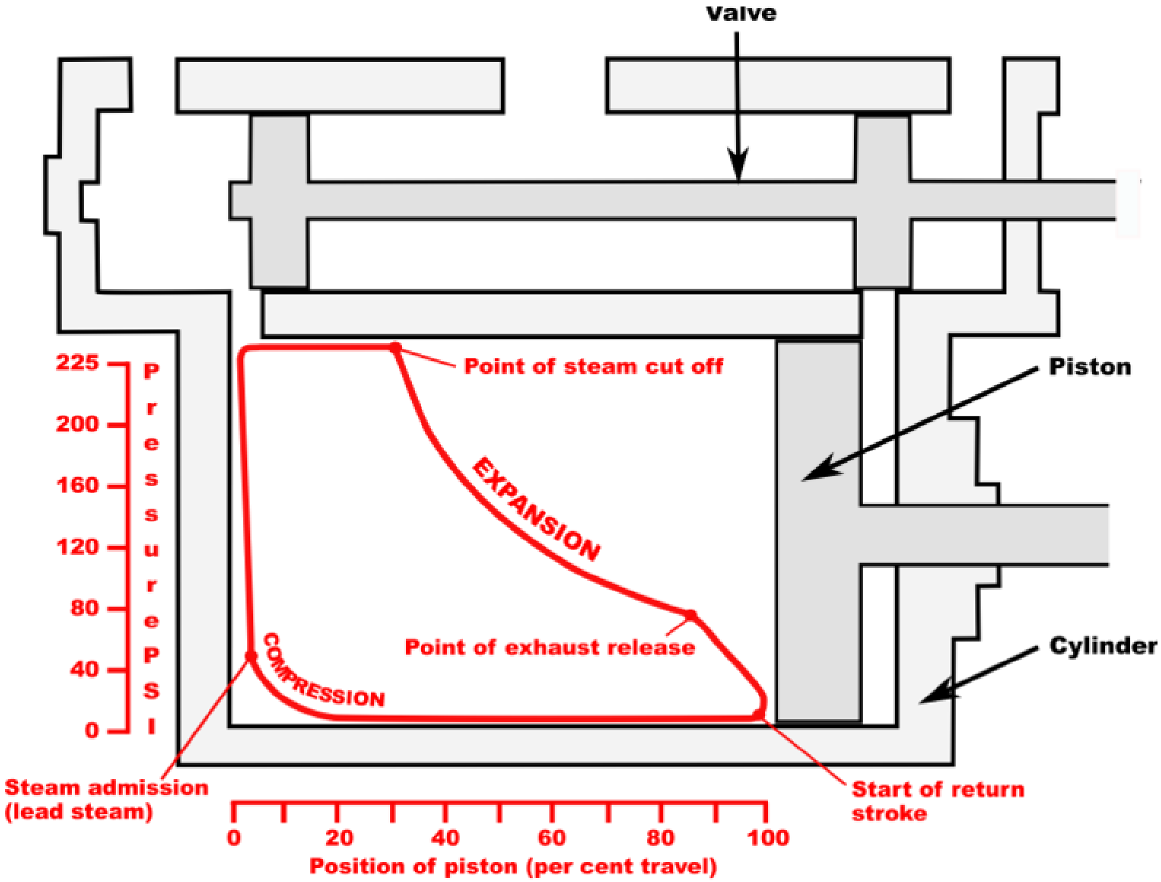
Chapter 6

Cutoff (Steam Engine)

In a steam engine, **cutoff** is the point in the piston stroke at which the inlet valve is closed. On a steam locomotive, the cutoff is controlled by the reverser.

The point at which the inlet valve closes and stops the entry of steam into the cylinder from the boiler plays a crucial role in the control of a steam engine. Once the valve has closed, steam trapped in the cylinder expands adiabatically. The steam pressure drops as it expands. A late cutoff delivers full steam pressure to move the piston through its entire stroke, for maximum start-up forces. But, since there will still be unexploited pressure in the cylinder at the end of the stroke, this is achieved at the expense of engine efficiency. In this situation the steam will still have considerable pressure remaining when it is exhausted resulting in the characteristic “chuff chuff” sound of a steam engine. An early cutoff has greater thermodynamic efficiency but provides less average force on the piston and is used for running the engine at higher speeds. The steam engine is the only thermodynamic engine design that can provide its maximum torque at zero revolutions.

Explanation



Schematic Indicator diagram of pressure in a steam locomotive cylinder. The pressure in the cylinder declines after cutoff as the steam pushes the piston down its bore

Cutoff is one of the four valve events. Early cutoff is used to increase the efficiency of the engine by allowing the steam to expand for the rest of the power stroke, yielding more of its energy and conserving steam. This is known as expansive working. Late cutoff is used to provide maximum torque to the shaft at the expense of efficiency and is used to start the engine under load.

Cutoff is conventionally expressed as percentage of the power stroke of the piston; if the piston is at a quarter of its stroke at the cutoff point, the cutoff is stated as 25%.

Smaller stationary steam engines generally have a fixed cutoff point while, in large ones, the speed and power output is generally governed by altering the cutoff, frequently under governor control using an expansion valve or trip gear. In steam engines for transport, it is desirable to be able to alter the cutoff over a wide range. For starting and at low speed and heavy load, the cylinders need steam supply at maximum pressure for almost the full length of the stroke. In a two-cylinder locomotive, for example, the maximum or 'full gear' cutoff is typically about 85%. At high speeds, the cutoff may be 15% percent of the piston stroke or less. Steam engines used in boats and ships operate under a constant, unvarying load through the propeller and so have a fixed cutoff, with speed being controlled through the regulator.

Providing variable cutoff is an important function of the valve gear. Most valve gear designs provide it, the exception being early Stephenson valve gear.

Control mechanism on locomotives

Reversing lever

This is the most common form of reverser. It consists of a long lever mounted, parallel to the direction of travel, on the driver's side of the cab. It has a handle and sprung trigger at the top and is pivoted at the bottom so as to pass between two notched sector plates. The reversing rod, which connects to the valve gear, is attached to this lever, either above or below the pivot, in such a position as to give good leverage. A square pin is arranged so as to engage with the notches in the plates and hold the lever in the desired position when the trigger is released.

The advantages of this design are that change between forward and reverse gear can be made very quickly as is needed in, for example, a shunting engine. Disadvantages are that, because the lever must rest at one of the notches, fine adjustment of the cutoff to offer best running and economy is not possible. On large locomotives it can be difficult to prevent the mechanism from jumping into full forward gear ("nose-diving") when adjusting the cutoff once the locomotive has gathered speed: with such engines it was the practice of drivers to select an appropriate degree of cutoff before opening the regulator and to leave it in that position for the duration of the journey.

Screw reverser

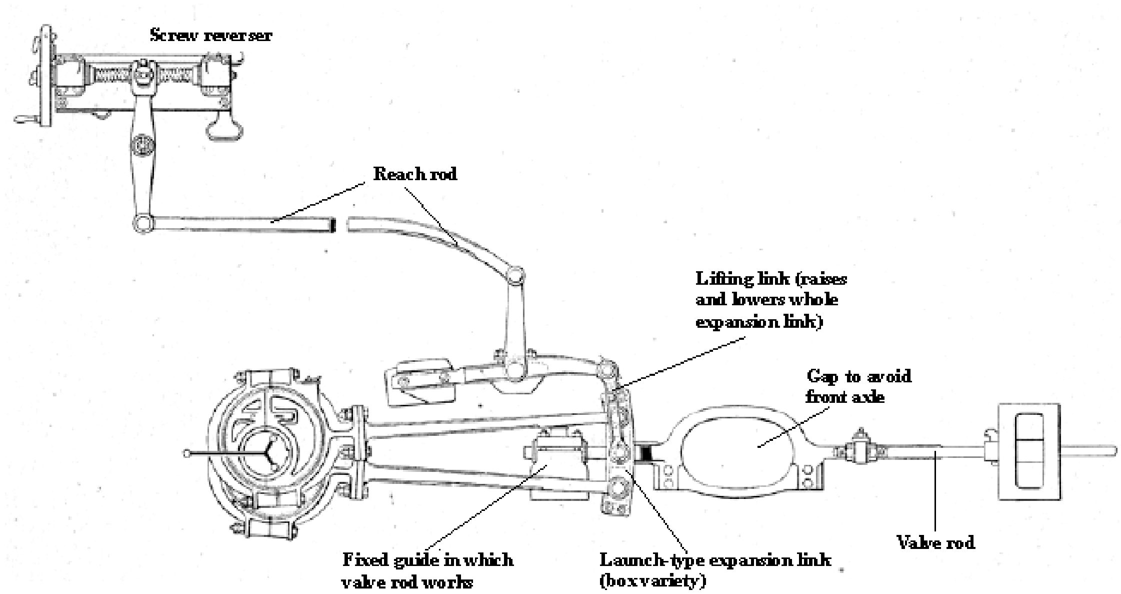
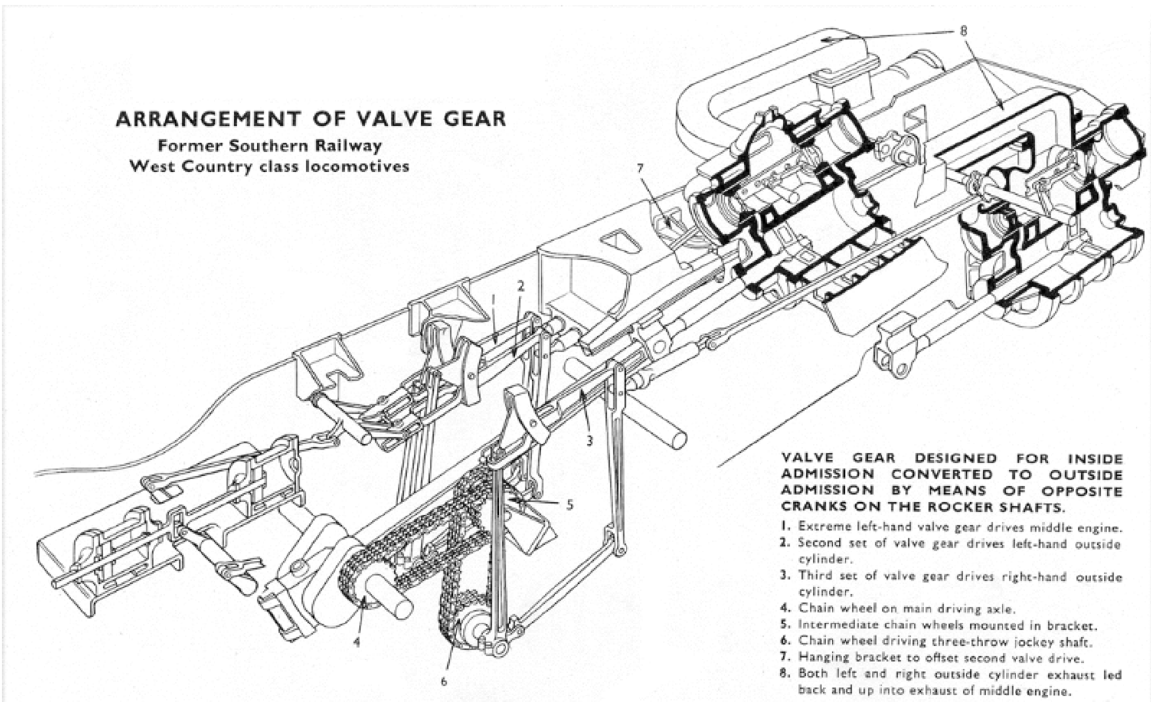


Diagram of Stephenson valve gear controlled by a screw reverser

In this mechanism the reversing rod is controlled by a screw and nut, worked by a wheel in the cab. The nut either operates on the reversing rod directly or through a lever, as above. The screw and nut may be cut with a double thread and a coarse pitch to move the mechanism as quickly as possible. The wheel is fitted with a locking lever to prevent creep and there is an indicator to show the percentage of cutoff in use. This method of altering the cutoff offers finer control than the sector lever, but it has the disadvantage of slow operation. It is most suitable for long-distance passenger engines where frequent changes of cutoff are not required and where fine adjustments offer the most benefit. On locomotives fitted with Westinghouse air brake equipment and Stephenson valve gear, it was common to use the screw housing as an air cylinder, with the nut extended to form a piston. Compressed air from the brake reservoirs was applied to one side of the piston to reduce the effort required to lift the heavy expansion link, with gravity assisting in the opposite direction.



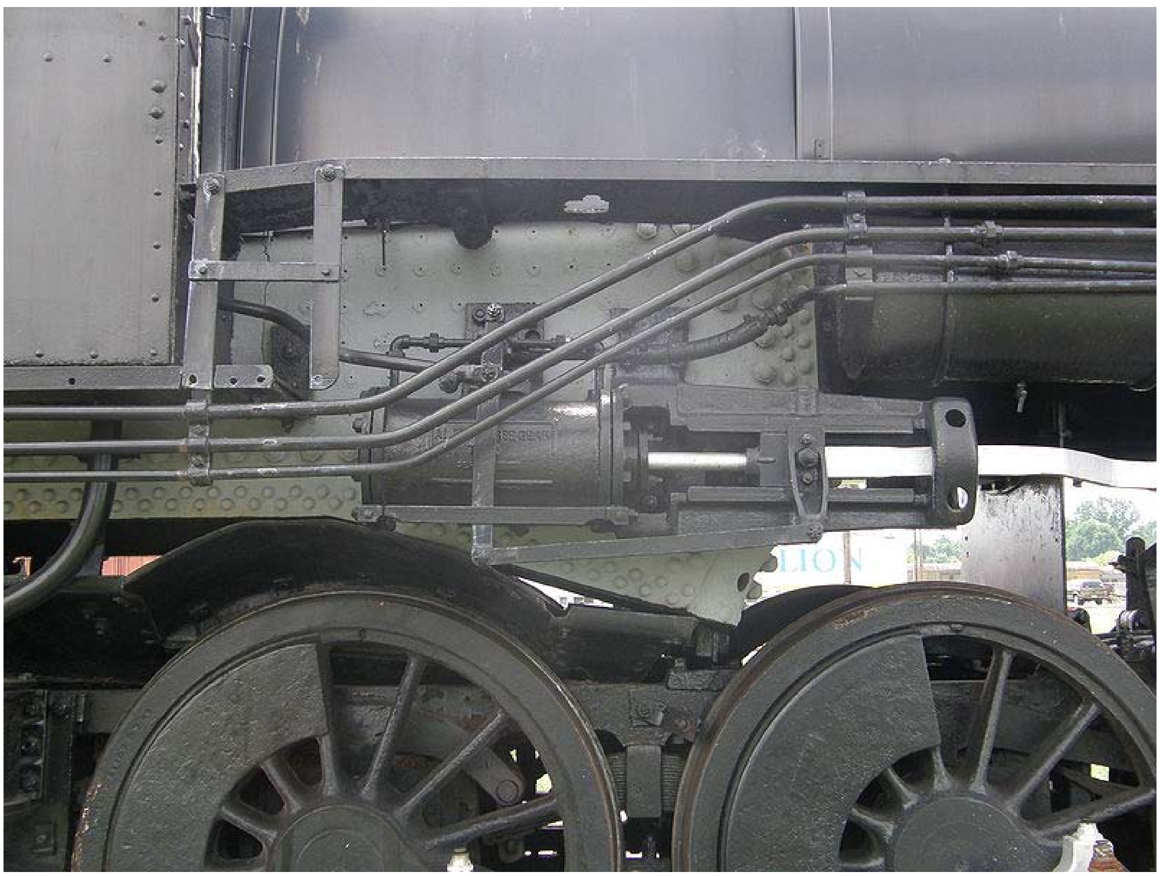
The two pistons of the steam reverser can be seen at the extreme left on this Bulleid *Merchant Navy* class

Power reverse gear

With larger engines, the linkages involved in controlling cutoff and direction grew progressively heavier and there was a need for power assistance in adjusting them. Steam (or later, compressed air) powered reversing gear were developed in the late 19th and early 20th centuries.

In smaller engines, the screw or lever used to control the cutoff and reversing linkages directly indicated the position of those linkages. The first power reversing gear separated the control and indicator functions. Typically, the operator worked a valve that admitted steam to one side or the other of a cylinder until the indicator showed the intended position. A second mechanism was required to lock the linkages in position.

Henszey's reversing gear, patented in 1882, illustrates a typical early solution. Henszey's device consists of two pistons mounted on a single piston rod. Both pistons are double-ended. One is a steam piston to move the rod as required. The other, containing oil, holds the rod in a fixed position when the steam is turned off. Control is by a small three-way steam valve (“forward”, “stop”, “back”) and a separate indicator showing the position of the rod and thus the percentage of cutoff in use. When the steam valve is at “stop”, an oil cock connecting the two ends of the locking piston is also closed, thus holding the mechanism in position. The piston rod connects by levers to the reversing gear, which operates in the usual way, according to the type of valve gear in use.



Steam reverser on a Southern Railway 2-8-0.

The first locomotive engineer to fit such a device was James Stirling of the South Eastern Railway in 1876. Several engineers then tried them, including William Dean of the GWR and Vincent Raven of the North Eastern Railway, but they found them little to their liking, mainly because of maintenance difficulties: any oil leakage from the locking cylinder, either through the piston gland or the cock, allowed the mechanism to creep, or worse “nose-dive”, into full forward gear while running. However Harry Wainwright of the SER's successor company the South Eastern and Chatham Railway incorporated them into most of his designs, which were in production about thirty years after Stirling's innovation. Later still the forward-looking Southern Railway engineer Oliver Bulleid fitted them to his famous Merchant Navy Class of locomotives, but they were mostly removed at rebuild.

The Ragonnet power reverse, patented in 1909, was a true feedback controlled servomechanism. The power reverse amplified small motions of reversing lever in the locomotive cab made with modest force into much larger and more forceful motions of the reach rod that controlled the engine cutoff and direction. It was usually air powered, but could also be steam powered. The term *servomotor* was explicitly used by the developers of some later power reverse mechanisms. The use of feedback control in these later power reverse mechanisms eliminated the need for a second cylinder for a hydraulic locking mechanism, and it restored the simplicity of a single operating lever that both controlled the reversing linkage and indicated its position.

The development of articulated locomotives was a major impetus to the development of power reverse systems, because these typically had two or even three sets of reverse gear, instead of just one on a simple locomotive. The Baldwin Locomotive Works used the Ragonnet reversing gear, and other American builders generally abandoned positive locking features. In British use, locking cylinders remained in use. The Hadfield reversing gear, patented in 1950, was in most particulars a Ragonnet reversing gear with added locking cylinder. Most Beyer Garratt locomotives used the Hadfield system.

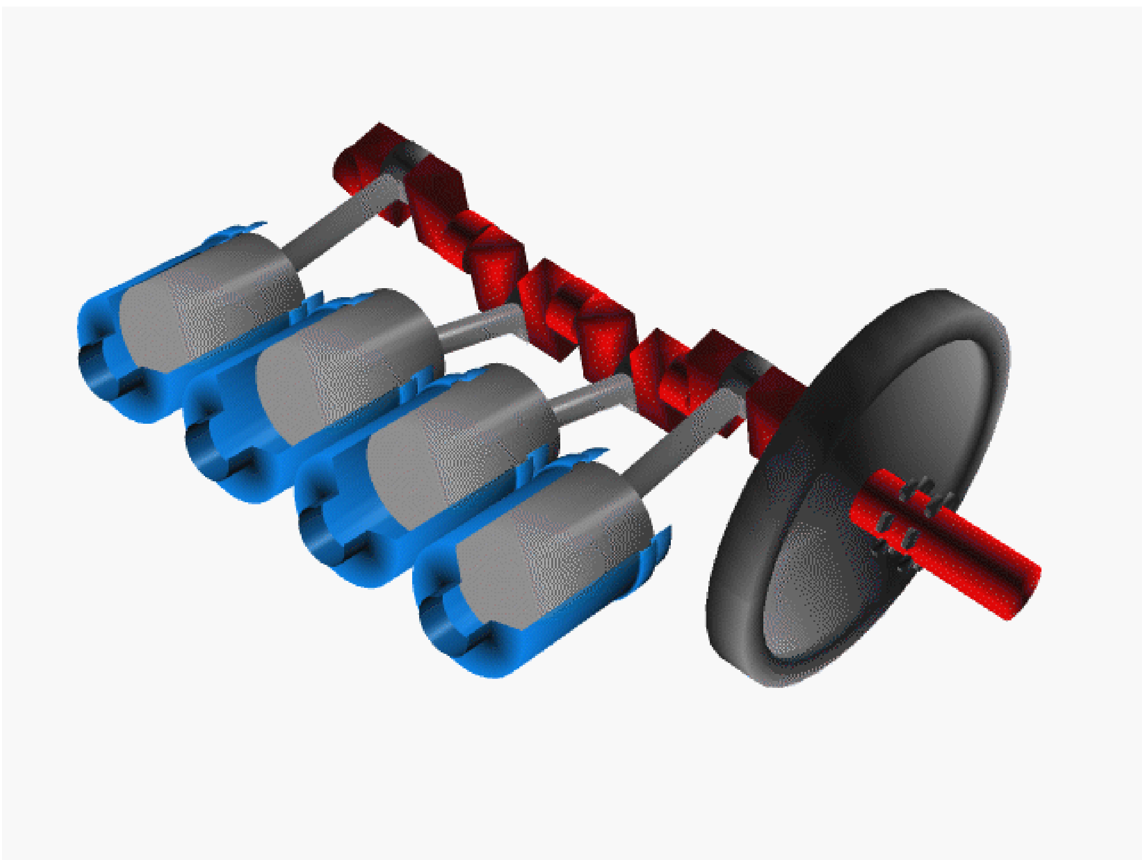
Many American locomotives were built, or retro-fitted, with power reverse, e.g. PRR K4s, PRR N1s, PRR B6, PRR L1s.

Enginemen's terminology

In the UK, a screw reverser is sometimes called a "bacon slicer", particularly the type fitted to BR Standard locomotives. In the US, a reversing lever is called a "Johnson bar".

Chapter 7

Crankshaft



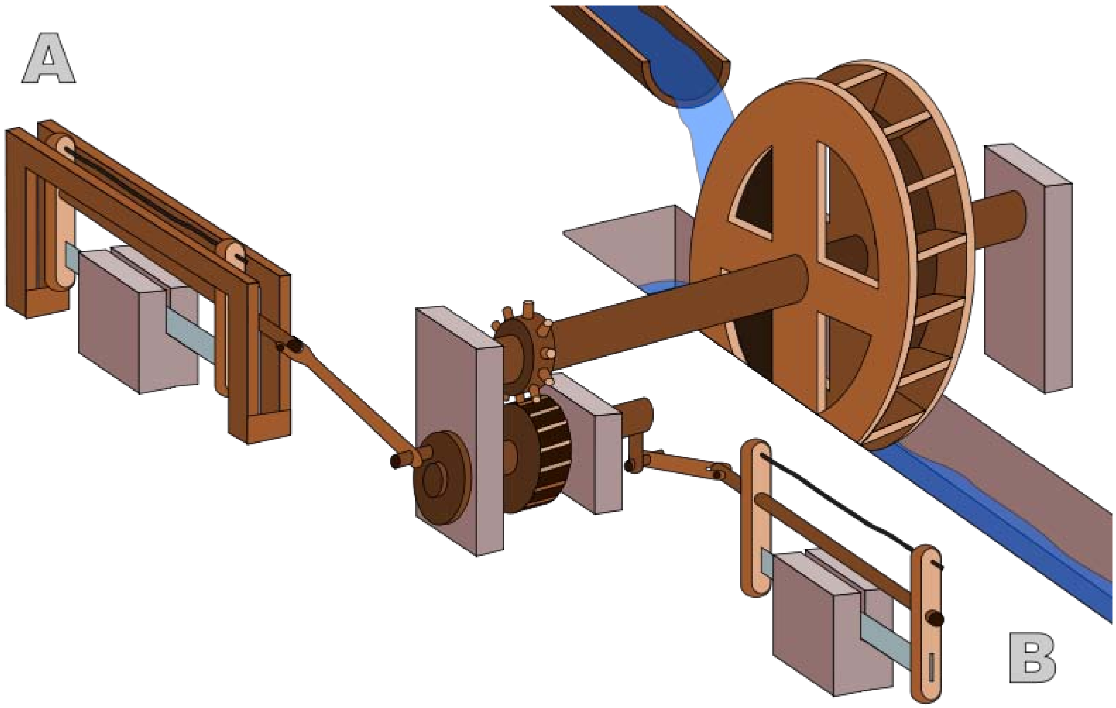
Crankshaft (red), pistons (gray) in their cylinders (blue), and flywheel (black)

The **crankshaft**, sometimes casually abbreviated to *crank*, is the part of an engine which translates reciprocating linear piston motion into rotation. To convert the reciprocating motion into rotation, the crankshaft has "crank throws" or "crankpins", additional bearing surfaces whose axis is offset from that of the crank, to which the "big ends" of the connecting rods from each cylinder attach.

It typically connects to a flywheel, to reduce the pulsation characteristic of the four-stroke cycle, and sometimes a torsional or vibrational damper at the opposite end, to reduce the torsion vibrations often caused along the length of the crankshaft by the cylinders farthest from the output end acting on the torsional elasticity of the metal.

History

Classical Antiquity



Roman Hierapolis sawmill from the 3rd century AD, the earliest known machine to combine a crank with a connecting rod.

The earliest evidence for the crank as part of a machine, that is in combination with a connecting rod, anywhere in the world appears in the late Roman Hierapolis sawmill from the 3rd century AD and two Roman stone sawmills at Gerasa, Roman Syria, and Ephesus, Asia Minor (both 6th century AD). On the pediment of the Hierapolis mill, a waterwheel fed by a mill race is shown powering via a gear train two frame saws which cut rectangular blocks by the way of some kind of connecting rods and, through mechanical necessity, cranks. The accompanying inscription is in Greek.

The crank and connecting rod mechanisms of the other two archaeologically attested sawmills worked without a gear train. In ancient literature, we find a reference to the workings of water-powered marble saws close to Trier, now Germany, by the late 4th century poet Ausonius; about the same time, these mill types seem also to be indicated by the Christian saint Gregory of Nyssa from Anatolia, demonstrating a diversified use of water-power in many parts of the Roman Empire. The three finds push back the date of the invention of the crank and connecting rod back by a full millennium; for the first time, all essential components of the much later steam engine were assembled by one technological culture:

With the crank and connecting rod system, all elements for constructing a steam engine (invented in 1712) — Hero's aeolipile (generating steam power), the cylinder and piston (in metal force pumps), non-return valves (in water pumps), gearing (in water mills and clocks) — were known in Roman times.

Middle Ages

In the 9th century, the non-manual crank appears in several of the hydraulic machines described by the Banu Musa brothers in their *Book of Ingenious Devices*. Two of them contain an action which approximates to that of a crankshaft and only a small modification would have required to convert it to a crankshaft.

In reality, however, these devices made only partial rotations and could only be lightly loaded, while the historian of technology Lynn White did not classify them even as the simplest application of a crank.

The first known use of a crankshaft in a chain pump was in one of Al-Jazari's (1136–1206) saqiya machines. The concept of minimizing intermittent working is also first implied in one of al-Jazari's *saqiya* chain pumps, which was for the purpose of maximising the efficiency of the saqiya chain pump Al-Jazari also constructed a water-raising saqiya chain pump which was run by hydropower rather than manual labour, though the Chinese were also using hydropower for chain pumps prior to him. Saqiya machines like the ones he described have been supplying water in Damascus since the 13th century up until modern times, and were in everyday use throughout the medieval Islamic world. Al-Jazari described a crank and connecting rod system in a rotating machine in two of his water-raising machines. His twin-cylinder pump incorporated a crankshaft, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion. Citing the Byzantine siphon used for discharging Greek fire as an inspiration, Al-Jazari went on to describe the first suction pipes, suction pump, double-action pump, and made early uses of valves and a crankshaft-connecting rod mechanism, when he invented a twin-cylinder reciprocating piston suction pump. This pump is driven by a water wheel, which drives, through a system of gears, an oscillating slot-rod to which the rods of two pistons are attached. The pistons work in horizontally opposed cylinders, each provided with valve-operated suction and delivery pipes. The delivery pipes are joined above the centre of the machine to form a single outlet into the irrigation system. This water-raising machine had a direct significance for the development of modern engineering. This pump is remarkable for three reasons:

- The first known use of a true suction pipe (which sucks fluids into a partial vacuum) in a pump.
- The first application of the double-acting principle.

- The conversion of rotary to reciprocating motion, via the crank-connecting rod mechanism.

Al-Jazari's suction piston pump could lift 13.6 m (45 ft) of water, with the help of delivery pipes. This was more advanced than the suction pumps that appeared in 15th-century Europe, which lacked delivery pipes. It was not, however, any more efficient than a noria commonly used by the Muslim world at the time.

The Italian physician Guido da Vigevano (c. 1280−1349), planning for a new crusade, made illustrations for a paddle boat and war carriages that were propelled by manually turned compound cranks and gear wheels (center of image). The Luttrell Psalter, dating to around 1340, describes a grindstone which was rotated by two cranks, one at each end of its axle; the geared hand-mill, operated either with one or two cranks, appeared later in the 15th century;

Taqi al-Din incorporated a crankshaft in a six-cylinder pump in 1551.

In China, the potential of the crank of converting circular motion into reciprocal one never seems to have been fully realized, and the crank was typically absent from such machines until the turn of the 20th century.

Renaissance

The first depictions of the compound crank in the carpenter's brace appear between 1420 and 1430 in various northern European artwork. The rapid adoption of the compound crank can be traced in the works of the Anonymous of the Hussite Wars, an unknown German engineer writing on the state of the military technology of his day: first, the connecting-rod, applied to cranks, reappeared, second, double compound cranks also began to be equipped with connecting-rods and third, the flywheel was employed for these cranks to get them over the 'dead-spot'.

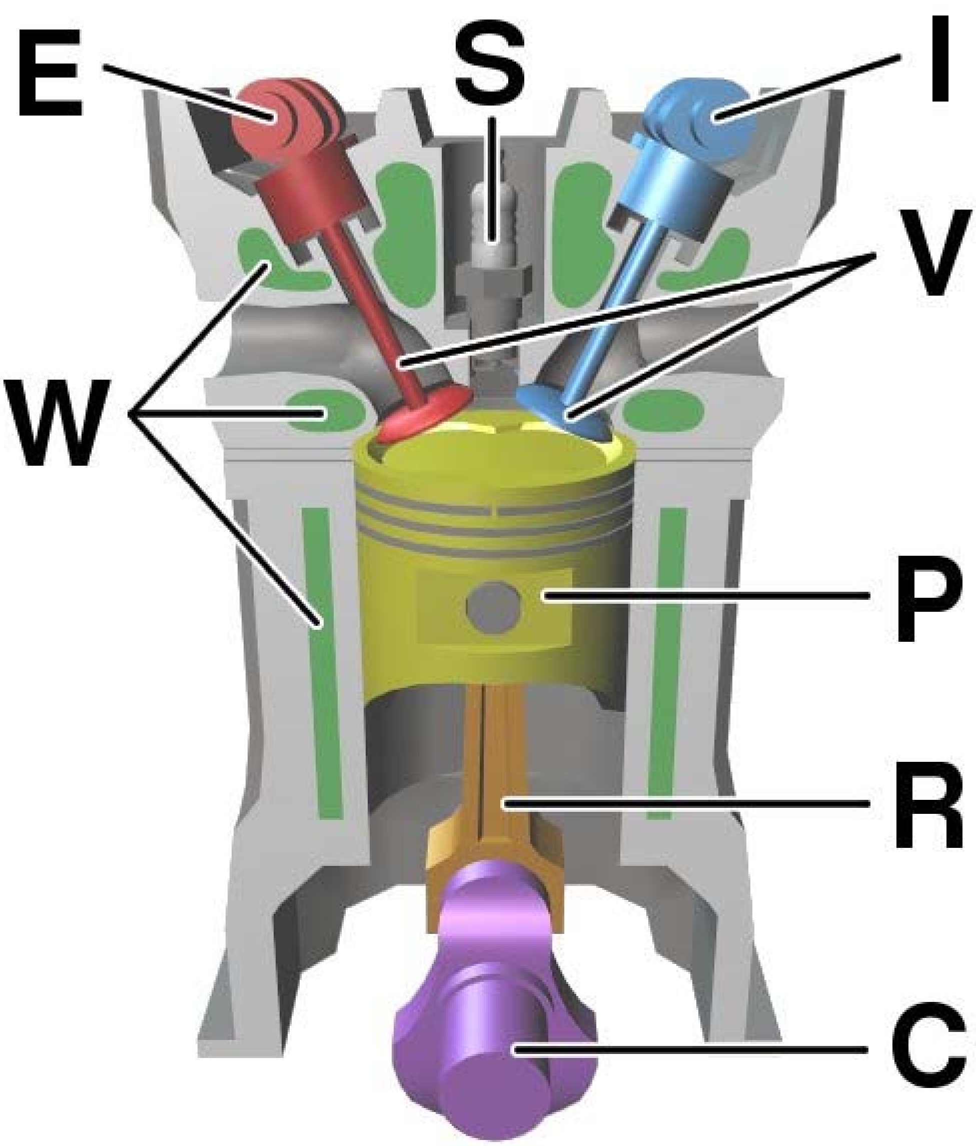
In Renaissance Italy, the earliest evidence of a compound crank and connecting-rod is found in the sketch books of Taccola, but the device is still mechanically misunderstood. A sound grasp of the crank motion involved demonstrates a little later Pisanello who painted a piston-pump driven by a water-wheel and operated by two simple cranks and two connecting-rods.

One of the drawings of the Anonymous of the Hussite Wars shows a boat with a pair of paddle-wheels at each end turned by men operating compound cranks. The concept was much improved by the Italian Roberto Valturio in 1463, who devised a boat with five sets, where the parallel cranks are all joined to a single power source by one connecting-rod, an idea also taken up by his compatriot Francesco di Giorgio.

Crankshafts were also described by Konrad Kyeser (d. 1405), Leonardo da Vinci (1452–1519) and a Dutch "farmer" by the name Cornelis Corneliszoon van Uitgeest in 1592. His wind-powered sawmill used a crankshaft to convert a windmill's circular motion into a back-and-forward motion powering the saw. Corneliszoon was granted a patent for his crankshaft in 1597.

From the 16th century onwards, evidence of cranks and connecting rods integrated into machine design becomes abundant in the technological treatises of the period: Agostino Ramelli's *The Diverse and Artifactitious Machines* of 1588 alone depicts eighteen examples, a number which rises in the *Theatrum Machinarum Novum* by Georg Andreas Böckler to 45 different machines, one third of the total.

Design



Components of a typical, four stroke cycle, DOHC piston engine. (E) Exhaust camshaft, (I) Intake camshaft, (S) Spark plug, (V) Valves, (P) Piston, (R) Connecting rod, (C) Crankshaft, (W) Water jacket for coolant flow.

Large engines are usually multicylinder to reduce pulsations from individual firing strokes, with more than one piston attached to a complex crankshaft. Many small engines, such as those found in mopeds or garden machinery, are single cylinder and use only a single piston, simplifying crankshaft design. This engine can also be built with no riveted seam.

Bearings

The crankshaft has a linear axis about which it rotates, typically with several bearing journals riding on replaceable bearings (the main bearings) held in the engine block. As the crankshaft undergoes a great deal of sideways load from each cylinder in a multicylinder engine, it must be supported by several such bearings, not just one at each end. This was a factor in the rise of V8 engines, with their shorter crankshafts, in preference to straight-8 engines. The long crankshafts of the latter suffered from an unacceptable amount of flex when engine designers began using higher compression ratios and higher rotational speeds. High performance engines often have more main bearings than their lower performance cousins for this reason.

Piston stroke

The distance the axis of the crank throws from the axis of the crankshaft determines the piston stroke measurement, and thus engine displacement. A common way to increase the low-speed torque of an engine is to increase the stroke, sometimes known as "shaft-stroking." This also increases the reciprocating vibration, however, limiting the high speed capability of the engine. In compensation, it improves the low speed operation of the engine, as the longer intake stroke through smaller valve(s) results in greater turbulence and mixing of the intake charge. For this reason, even such high speed production engines as current Honda engines are classified as "under square" or long-stroke, in that the stroke is longer than the diameter of the cylinder bore. As such, finding the proper balance between shaft-stroking speed and length will lead to more optimal results.

Engine configuration

The configuration and number of pistons in relation to each other and the crank leads to straight, V or flat engines. The same basic engine block can be used with different crankshafts, however, to alter the firing order; for instance, the 90° V6 engine configuration, in older days sometimes derived by using six cylinders of a V8 engine with what is basically a shortened version of the V8 crankshaft, produces an engine with an inherent pulsation in the power flow due to the "missing" two cylinders. The same engine, however, can be made to provide evenly spaced power pulses by using a crankshaft with an individual crank throw for each cylinder, spaced so that the pistons are actually phased 120° apart, as in the GM 3800 engine. While production V8 engines use four crank throws spaced 90° apart, high-performance V8 engines often use a "flat" crankshaft with throws spaced 180° apart. The difference can be heard as the flat-plane crankshafts result in the engine having a smoother, higher-pitched sound than cross-plane (for example, IRL IndyCar Series compared to NASCAR Nextel Cup, or a Ferrari 355 compared to a Chevrolet Corvette).

Engine balance

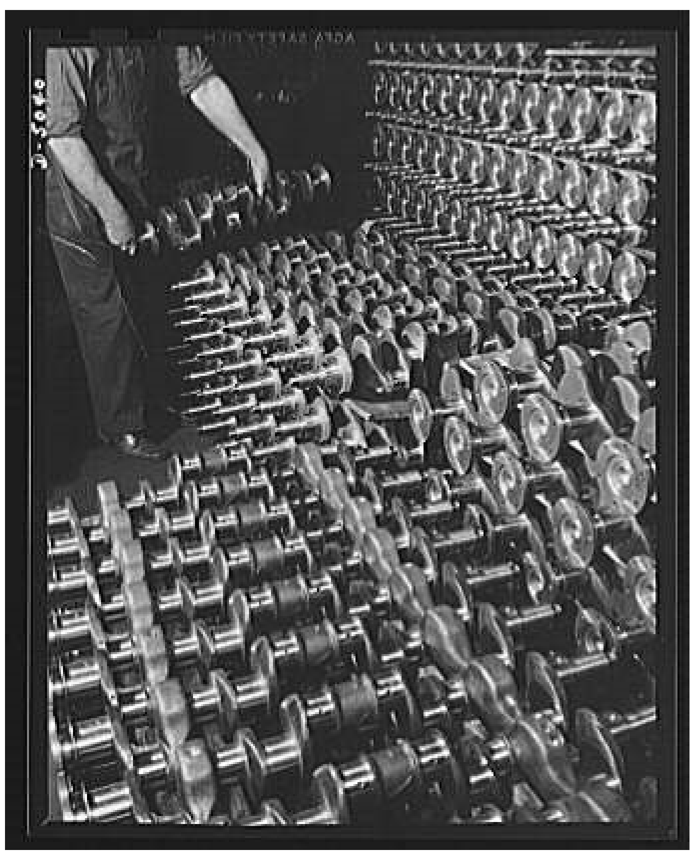
For some engines it is necessary to provide counterweights for the reciprocating mass of each piston and connecting rod to improve engine balance. These are typically cast as part of the crankshaft but, occasionally, are bolt-on pieces. While counter weights add a considerable amount of weight to the crankshaft, it provides a smoother running engine and allows higher RPMs to be reached.

Rotary engines

Many early aircraft engines (and a few in other applications) had the crankshaft fixed to the airframe and instead the cylinders rotated, known as a rotary engine design. Rotary engines such as the Wankel engine are referred to as pistonless rotary engines.

In the Wankel engine, also called a rotary engine, the rotors drive the eccentric shaft, which could be considered the equivalent of the crankshaft in a piston engine.

Construction



Continental engine marine crankshafts, 1942

Crankshafts can be monolithic (made in a single piece) or assembled from several pieces. Monolithic crankshafts are most common, but some smaller and larger engines use assembled crankshafts.

Forging and casting

Crankshafts can be forged from a steel bar usually through roll forging or cast in ductile steel. Today more and more manufacturers tend to favor the use of forged crankshafts due to their lighter weight, more compact dimensions and better inherent dampening. With forged crankshafts, vanadium microalloyed steels are mostly used as these steels can be air cooled after reaching high strengths without additional heat treatment, with exception to the surface hardening of the bearing surfaces. The low alloy content also makes the material cheaper than high alloy steels. Carbon steels are also used, but these require additional heat treatment to reach the desired properties. Iron crankshafts are today mostly found in cheaper production engines (such as those found in the Ford Focus diesel engines) where the loads are lower. Some engines also use cast iron crankshafts for low output versions while the more expensive high output version use forged steel.

Machining

Crankshafts can also be machined out of a billet, often using a bar of high quality vacuum remelted steel. Even though the fiber flow (local inhomogeneities of the material's chemical composition generated during casting) doesn’t follow the shape of the crankshaft (which is undesirable), this is usually not a problem since higher quality steels which normally are difficult to forge can be used. These crankshafts tend to be very expensive due to the large amount of material removal which needs to be done by using lathes and milling machines, the high material cost and the additional heat treatment required. However, since no expensive tooling is required, this production method allows small production runs of crankshafts to be made without high costs.

Fatigue strength

The fatigue strength of crankshafts is usually increased by using a radius at the ends of each main and crankpin bearing. The radius itself reduces the stress in these critical areas, but since the radii in most cases are rolled, this also leaves some compressive residual stress in the surface which prevents cracks from forming.

Hardening

Most production crankshafts use induction hardened bearing surfaces since that method gives good results with low costs. It also allows the crankshaft to be reground without having to redo the hardening. But high performance crankshafts, billet crankshafts in particular, tend to use nitridization instead. Nitridization is slower and thereby more costly, and in addition it puts certain demands on the alloying metals in the steel, in order to be able to create stable nitrides. The advantage with nitridization is that it can be done at low temperatures, it produces a very hard surface and the process will leave some compressive residual stress in the surface which is good for the fatigue properties of the crankshaft. The low temperature during treatment is advantageous in that it doesn't have any negative effects on the steel, such as annealing. With crankshafts that operate on roller bearings, the use of carburization tends to be favored due to the high Hertzian contact stresses in such an application. Like nitriding, carburization also leaves some compressive residual stresses in the surface.

Counterweights

Some expensive, high performance crankshafts also use heavy-metal counterweights to make the crankshaft more compact. The heavy-metal used is most often a tungsten alloy but depleted uranium has also been used. A cheaper option is to use lead, but compared with tungsten its density is much lower.

Stress on crankshafts

The shaft is subjected to various forces but generally needs to be analysed in two positions. Firstly, failure may occur at the position of maximum bending; this may be at the centre of the crank or at either end. In such a condition the failure is due to bending and the pressure in the cylinder is maximal. Second, the crank may fail due to twisting, so the conrod needs to be checked for shear at the position of maximal twisting. The pressure at this position is the maximal pressure, but only a fraction of maximal pressure.

Chapter 8

Bourke Engine

The **Bourke Engine** was designed by Russell Bourke in the 1920s, as an improved two stroke engine. Despite finishing his design and building several working engines, the onset of World War II, lack of test results, and the poor health of his wife compounded to prevent his engine from ever coming successfully to market. The main claimed virtues of the design are that it has only two moving parts, is light weight, powerful, has two power pulses per revolution, and does not need oil mixed into the fuel.

Overview

The Bourke engine is basically a two stroke design, with one horizontally opposed piston assembly using two pistons that move in the same direction at the same time, so that their operations are 180 degrees out of phase. The pistons are connected to a Scotch Yoke mechanism in place of the more usual crankshaft mechanism, which slightly reduces the acceleration of the pistons so that the hydrogen will detonate. The incoming charge is compressed in a chamber under the pistons, as in a conventional crankcase-charged two stroke engine. The connecting-rod seal prevents the fuel from contaminating the bottom-end lubricating oil.

Operation

The operating cycle is very similar to that of a current production spark ignition two-stroke with crankcase compression, with two modifications:

1. The fuel is injected directly into the air as it moves through the transfer port.
2. The engine is designed to run without using spark ignition once it is warmed up. This is known as auto-ignition or dieseling, and the air/fuel mixture starts to burn due to the high temperature of the compressed gas, and/or the presence of hot metal in the combustion chamber.

Design features

The following design features have been identified

Mechanical features

- Scotch yoke instead of connecting rods to translate linear motion to rotary motion
- Fewer moving parts (only 2 moving assemblies per opposed cylinder pair) and the opposed cylinders are combinable to make 2, 4, 6, 8, 10, 12 or any even number of cylinders
- Smoother operation due to elimination of crank and slider mechanism
- The piston is connected to the Scotch yoke through a slipper bearing (a type of hydrodynamic tilting-pad fluid bearing)
- Mechanical fuel injection.
- Ports rather than valves.
- Easy maintenance (top overhauling) with simple tools.
- The Scotch yoke does not create lateral forces on the piston, reducing friction, vibration and piston wear.
- O-rings are used to seal joints rather than gaskets.
- The use of the Scotch Yoke reduces vibration from the motions of the connecting rod—for example, the peak acceleration in a Scotch yoke is 25% less than the acceleration in a conventional crank and slider arrangement.
- The Scotch Yoke makes the pistons dwell very slightly longer at top dead center, so the fuel burns more completely in a smaller volume.

Gas flow and thermodynamic features

- Low exhaust temperature (below that of boiling water) so metal exhaust components are not required, plastic ones can be used if strength is not required from exhaust system
- Extremely fast hydrogen detonation burn time of the lean mixture so the engine can be considered to be a hydrogen detonation (i.e., explosion not deflagration) engine.
- 15:1 to 24:1 compression ratio for high efficiency and it can be easily changed as required by different fuels and operation requirements.
- Fuel is vaporised when it is injected into the transfer ports, and the turbulence in the intake manifolds and the piston shape above the rings stratifies the fuel air mixture into the combustion chamber.
- Lean burn for increased efficiency and reduced emissions.

Lubrication

- This design uses oil seals to prevent the pollution from the combustion chamber (created by piston ring blow-by in four-strokes and just combustion in two-strokes) from polluting the crankcase oil, extending the life of the oil as it is used slowly for keeping the rings full of oil to hold and use to lubricate. Oil was shown to be used slowly by the dropfull as needed, but checking the quantity and cleanness of it was still recommended by Russell Bourke, its creator.
- The lubricating oil in the base is protected from combustion chamber pollution by an oil seal over the connecting rod.

- The piston rings are supplied with oil from a small supply hole in the cylinder wall at bottom dead center.

Claimed and measured performance

- **Efficiency** 0.25 (lb/h)/hp is claimed - about the same as the best diesel engine, or roughly twice as efficient as the best two strokes. This is equivalent to a thermodynamic efficiency of 55.4%, which is an exceedingly high figure for a small internal combustion engine. In a test witnessed by a third party, the **actual** fuel consumption was 1.1 hp/(lb/h), or 0.9 (lb/h)/hp, equivalent to a thermodynamic efficiency of about 12.5%, which is typical of a 1920s steam engine.

- **Power to weight** 0.9 to 2.5 hp/lb is claimed, although no independently witnessed test to support this has been documented. The upper range of this is roughly twice as good as the best four stroke production engine shown here, or 0.1 hp/lb better than a Graupner G58 two stroke. The lower claim is unremarkable, easily exceeded by production four stroke engines, never mind two strokes.

- **Emissions** Achieved virtually no hydrocarbons (80 ppm) or carbon monoxide (less than 10 ppm) in published test results, however no power output was given for these results, and NOx was not measured.

- **Low Emissions** The engine is claimed to be able to operate on hydrogen or any hydro-carbon fuel without any modifications, producing only water vapor and carbon dioxide as emissions.

Engineering critique of the Bourke engine

The Bourke Engine has some interesting features, but the extravagant claims for its performance are unlikely to be borne out by real tests. Many of the claims are contradictory.

1) Seal friction from the seal between the air compressor chamber and the crankcase, against the connecting rod, will reduce the efficiency.

2) Efficiency will be reduced due to pumping losses, as the air charge is compressed and expanded twice but energy is only extracted for power in one of the expansions per piston stroke.

3) Engine weight is likely to be high because it will have to be very strongly built to cope with the high peak pressures seen as a result of the rapid high temperature combustion.

4) Each piston pair is highly imbalanced as the two pistons move in the same direction at the same time, unlike in a boxer engine. This will limit the speed range and hence the

power of the engine, and increase its weight due to the strong construction necessary to react the high forces in the components.

5) High speed two-stroke engines tend to be inefficient compared with four-strokes because some of the intake charge escapes unburnt with the exhaust.

6) When the charge is transferred from the compressor chamber to the combustion chamber it will cool down, reducing the efficiency of the engine.

7) Use of excess air will reduce the torque available for a given engine size.

8) Forcing the exhaust out rapidly through small ports will incur a further efficiency loss.

9) Operating an internal combustion engine in detonation reduces efficiency due to heat lost from the combustion gases being scrubbed against the combustion chamber walls by the shock waves.

10) Emissions - although some tests have shown low emissions in some circumstances, these were not necessarily at full power. As the scavenge ratio (i.e. engine torque) is increased more HC and CO will be emitted.

11) Increased dwell time at TDC will allow more heat to be transferred to the cylinder walls, reducing the efficiency.

12) When running in auto-ignition mode the timing of the start of the burn is controlled by the operating state of the engine, rather than directly as in a spark ignition or diesel engine. As such it may be possible to optimize it for one operating condition, but not for the wide range of torques and speeds that an engine typically sees. The result will be reduced efficiency and higher emissions.

13) If the efficiency is high, then combustion temperatures must be high, as required by the Carnot cycle, and the air fuel mixture must be lean. High combustion temperatures and lean mixtures cause nitrogen dioxide to be formed.

Chapter 9

Flathead Engine

Harley-Davidson flathead engine

A **flathead engine** or **sidevalve engine** (sometimes called a **flatty**) is an internal combustion engine with valves placed in the engine block beside the piston, instead of in the cylinder head, as in an overhead valve engine. The design was common on early engine designs, but has since fallen from favor.

Advantages

Generally the flathead's valves are carried on one side of the cylinder. A chamber is recessed into the underside of the head to allow the poppet valves to alternately rise from their seats to admit the fuel-air mixture and for the exhaust gases to escape the combustion chamber. This has a number of advantages, primarily making the valve gear simpler, without either long push rods and rocker arms to work overhead valves from a cam shaft mounted near the crank shaft or a long chain, belt or gear train to drive one or more overhead cam shafts. The head of a flathead engine commonly consists of only a single piece of cast metal.

Each valve is operated by pushing directly up on it, as opposed to needing some sort of mechanical arrangement to transfer the motion from the crank case to the cylinder head, as in an overhead valve engine. The line of intakes along the side of the engine leads to the alternate name **L-block** (or **L-head**), due to the cylinders having the shape of an upside-down L. This configuration is also known as (Ford) sidevalve engine. A great advantage to this design was that limited damage occurred if a valve dropped, unlike the overhead design in which serious damage could occur. One could still continue to travel even with a broken valve.

Because the intake and exhaust pass through the same small passage between the block and head, and because the light valve gear allows the valves to open and close quickly, flatheads are designed with very little "overlap", part of the cycle when both intake and exhaust valves are open. This gives better low rotation speed performance than is typical of push rod overhead valve engines or overhead cam engines tuned for high speed power. On the other hand, the light valve gear allows the engine to function at high speed, though with little power. The torque and power curves are therefore broad, making it easier for the manual transmission and driver or for the automatic transmission. This flexibility is returning to cars in the form of electric motors.

Disadvantages

The flathead configuration requires the intake and exhaust gases to make at least a 90-degree turn and to pass between the block and head to enter and leave the cylinder, which makes it less efficient, colloquially called poorer "breathing". Breathing was not greatly important for early production cars because engines could not run long and reliably at high speed, and few roads allowed sustained high speeds, so this was a minor concern given the benefits in simplicity. The maximum compression ratio is also low at only about 7:1, further reducing efficiency (although it means the engine can run well on low-octane fuel.) This is mainly because the combustion chamber must include the space for the valve movement and the space for the gas flow.

A compromise used by Willys (Jeep),Rover and Rolls-Royce in the mid 20th century was the F-head or intake over exhaust configuration, in which there is one side valve and one overhead valve per cylinder.

The greatest advancements to flathead engine technology were developed in the 1920s through experimentation by Sir Harry Ricardo of Great Britain, who improved the performance and efficiency by intently studying their flow characteristics. He published his findings, and obtained patents, in 1927. Primarily, his **Ricardo head** can be recognized on sight, because he moved the exhaust valve farther from the center of the cylinder than the intake valve (they had previously been symmetrical). He also paid careful attention to the form of the intake and exhaust tracts cast into the cylinder block as regarded turbulence in the intake stream and within the combustion chamber.

Another concern is that because the exhaust follows a more complicated path to leave the engine, there is increased tendency for the engine to overheat under sustained heavy use. This is especially true if the exhaust is routed between the cylinders, as in the Ford flathead. It is possible to arrange the sidevalve engine layout so exhaust will be taken away through a valve and an exhaust tract located on the opposite side of the cylinder from the intake valve, in which case the layout is referred to as a **T-block** or **T-head**. American LaFrance famously powered their production fire engines with T-head engines from the 1920s to the 1950s. The Cleveland Motorcycle Company produced a four-cylinder in-line motorcycle engine using the T-head configuration in the 1920s. Very early Stutz engines were T heads. This requires two passages between the block and head, within the combustion chamber, and it loses some of the simplicity.

The flathead design also greatly reduced the ability to overbore the engine for performance purposes. Since the piston, exhaust valve, and intake valve were all next to each other, the piston cylinder bore could only be slightly increased, if at all, or it would encroach upon the radii of the intake and exhaust valves, and also cause thin and weak cylinder walls.

History and applications

Although flathead in-line 4 and 6 cylinder engines were frequently used for automobiles, tractors, and other products, the best known flathead automotive engine is the early 20th century Ford V-8, which has both sets of valves (intake and exhaust) located on the inside of the "Vee," and which are all operated by a single camshaft located above the crankshaft. Other common configurations included in-line ("straight") eights and a V 12 Lincoln version of the Ford V 8.

Due to cooling and efficiency problems, flathead engines fell out of favor in "high power" applications, such as aircraft engines, prior to World War I. However they lived on for some time in the automotive world and were used on the Jeep for instance. Flatheads are no longer in common use for automobiles (except in some rodding and customizing circles), although they are still used for some small-engine applications like lawnmowers. Because of their design, the size of valves and the compression ratio are limited, which in turn reduces available power and economy.

Harley-Davidson motorcycle flathead engines

The flathead engine saw service in Harley-Davidson motorcycles beginning with the "Sport Model" opposed twin produced from 1919 to 1923, and continuing in 1924 with single cylinder export-model 21 cubic inches (340 cc) and 30.5 cubic inches (500 cc) singles and continued in the Servi-Cars until 1973. In the domestic U.S. market, the 45 cubic inches (740 cc) DL model (1929 to 1931) and its technical descendant, the RL model (1932 to 1936), started Harley's side valve tradition in the 45 cubic inch displacement class. The DL and RL models featured a total loss oiling system and were succeeded in 1937 by the WL 45, which had recirculating oil lubrication. The WL went on to serve in WWII as the U.S. and Canadian Army's primary two-wheeled mount and subsequently as a civilian middleweight through 1952. The engine continued virtually unchanged with various G-based designations in the three wheeled "Servi-Car" until production ceased in 1973.

In 1952, the K series flatheads was introduced, selling in parallel with the W series (which was discontinued after 1952), designed to compete with British sporting motorcycles of the time, as the American motorcycle Association allowed the 750 cc sidevalves to compete against 500 cc overhead-valve bikes. The K models featured a unit construction engine and transmission case, right side foot shift and left side foot brake, and evolved from 45 cubic inch (1952 to 1953) to 55 cubic inches by a 0.75 inches (19 mm) increase in stroke length (1954 to 1956) over its five year retail market run. The K series was replaced by the overhead valve Sportster series in the retail market in 1957. However, racing versions of the 750 cc K model, designated KR, continued to be produced in very limited numbers for some time after, winning both roadraces and dirt track events against overhead valve bikes limited to 500 cc through 1969, when the American Motorcycle Association finally decided to change the rules and make the venerable flatheads uncompetitive. The K racers were replaced first by the iron-head XR 750cc overhead valve engine, and two years later by the alloy-head XR, which continues in service in flat track racing to this day.

In 1930, the 74 cubic inches (1,210 cc) VL flathead replaced the JD Big Twin, which had featured intake-over-exhaust (IoE) valve configuration. The VL had a single downtube frame and total loss oiling, culminating in an 80 cubic inches (1,300 cc) version (VLH) in 1935. In 1937, that engine was redesigned to include a recirculating lubrication system, and designated the model U, and it went into the same frame and running gear configuration as the model E Knucklehead, which had originated in 1936. The U continued to be produced in varying configurations as a 74& cubic inch U & UL (1937 to 1948), and 80 cubic inch UH & ULH engine (1937 to 1941). By that time, the first year of the aluminum-head Panhead, it had been thoroughly superseded and outsold in the marketplace by the superior performance of the overhead valve model Big Twins.

Chapter 10

Oil Burner (Engine) and Fluidyne Engine

Oil burner

Darjeeling Himalayan Railway Locomotive No.787 after conversion to oil firing.

An **oil burner engine** is a steam engine that uses oil as its fuel. The term is often used with reference to a locomotive or ship engine that burns oil, to heat water, to produce steam which drives the pistons, or turbines, from which the power is derived. Some engines of this form were originally designed to be coal powered and were converted. An early pioneer of this form of engine was James Holden.

This is mechanically very different from a diesel engine that is a form of internal combustion engine, which is sometimes colloquially referred to as an oil burner .

Conversion

When a coal-burning steam locomotive is converted to oil-burning, various modifications are usual:

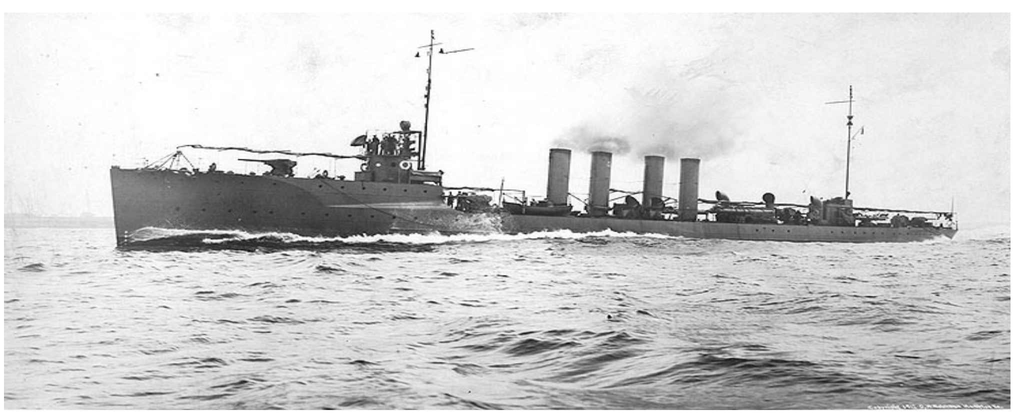
1. the grate is covered with broken firebrick to act as a reservoir of heat. If the oil flame is blown out (e.g. by a downdraft when entering a tunnel) the hot firebrick will re-ignite it
2. the lower part of the inner firebox is lined with firebrick
3. shorter superheater elements are fitted

Changes 2 & 3 are needed because oil firing produces higher temperatures than coal firing and can cause rapid erosion of metal. For a similar reason, the smokebox is sometimes painted with silver-coloured heat-resisting paint.

Oil-fired steam locomotives

- Darjeeling Himalayan Railway
- LNER Class U1
- Snowdon Mountain Railway
- Union Pacific 737
- Mount Washington Cog Railway
- most cab forward locomotives
- some Fairlie locomotives
- Advanced steam technology locomotives

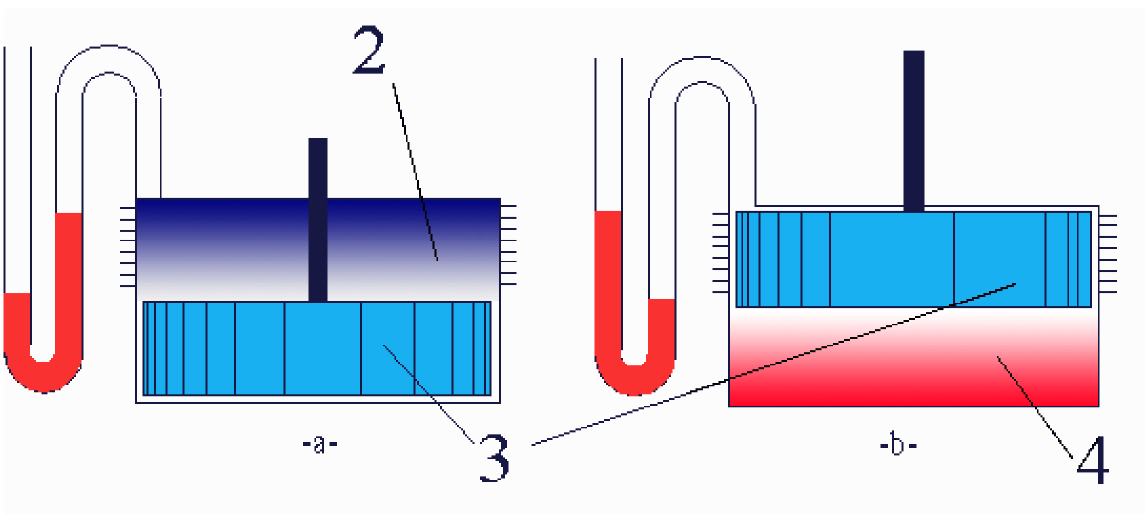
Oil-fired steamships



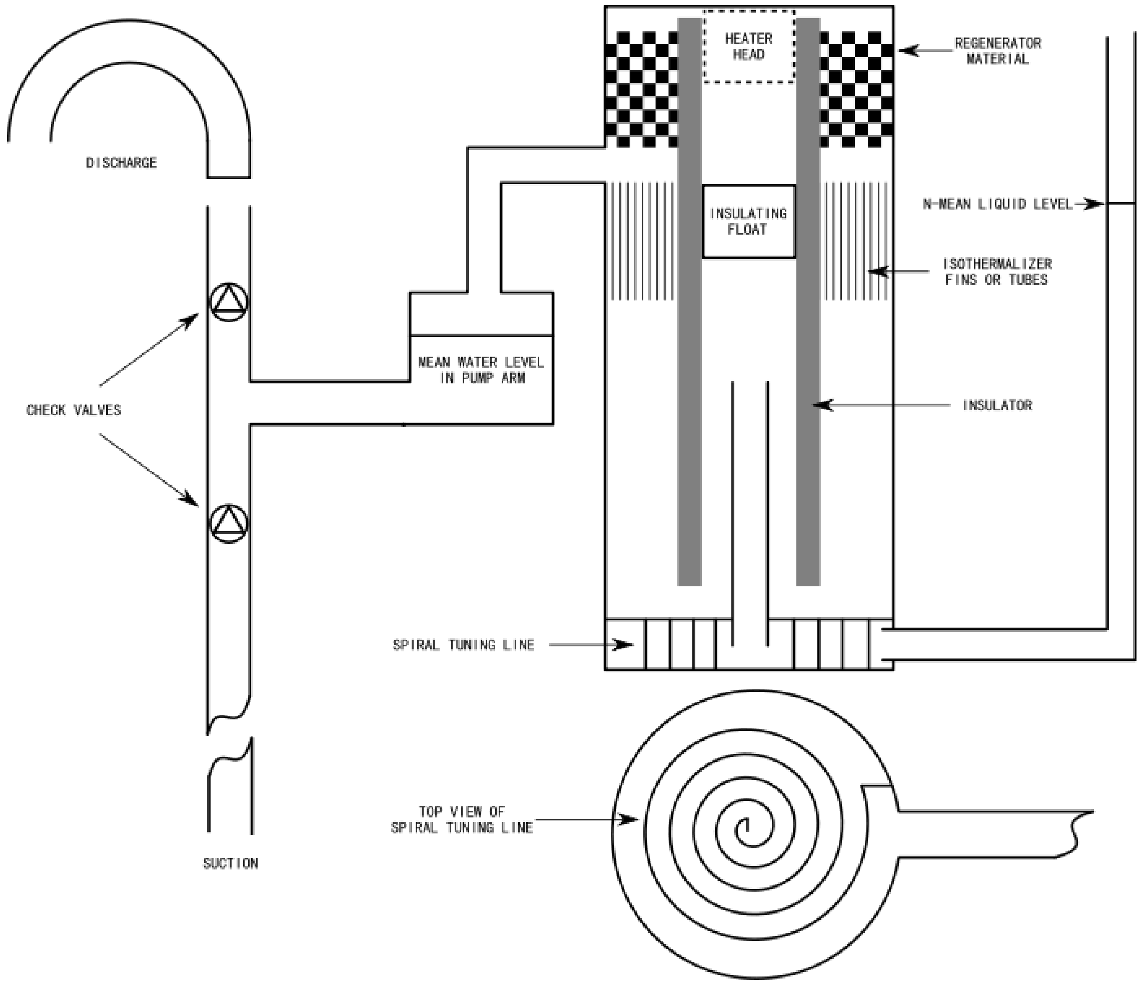
USS Trippe, an oil burner powered ship

- USS Drayton (DD-23)
- USS Terry (DD-25)
- USS Perkins (DD-26)
- USS Sterett (DD-27)
- USS McCall (DD-28)
- USS Warrington (DD-30)
- USS Burrows (DD-29)
- USS Monaghan (DD-32)
- USS Trippe (DD-33)
- USS Walke (DD-34)
- USS Ammen (DD-35)
- USS Jarvis (DD-38)
- USS Henley (DD-39)
- USS Jouett (DD-41)
- USS Jenkins (DD-42)
- USS George Washington (1908)

Fluidyne Engine



This is a Fluidyne variant with a solid displacer piston (3). In figure -a-, as the displacer moves from the cold compression space (2), to the hot expansion space (4) in figure -b-, the temperature of the gaseous working fluid is increased. This increases the pressure of the gaseous working fluid, and as it expands, work is done on the (red) liquid piston as it is pushed through the tube.



A Concentric-cylinder Fluidyne Pumping engine

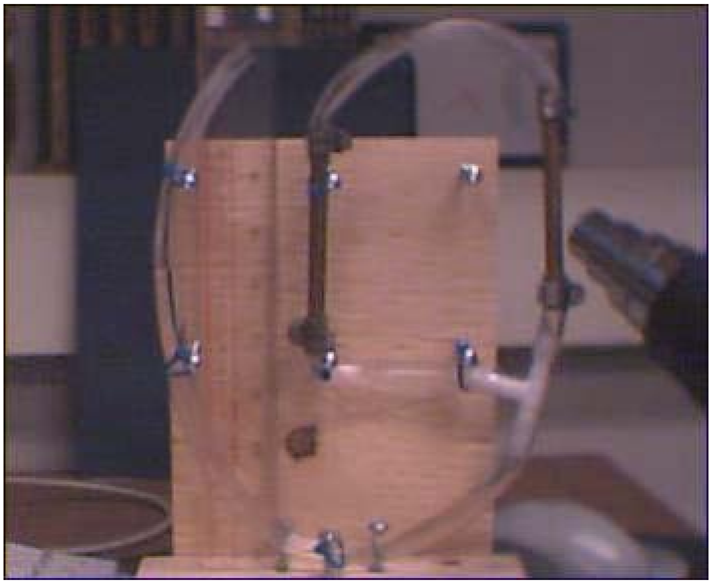
A **Fluidyne engine** is an alpha or gamma type Stirling engine with one or more liquid pistons. It contains a working gas (often air), and either two liquid pistons or one liquid piston and a displacer.

Engine operation

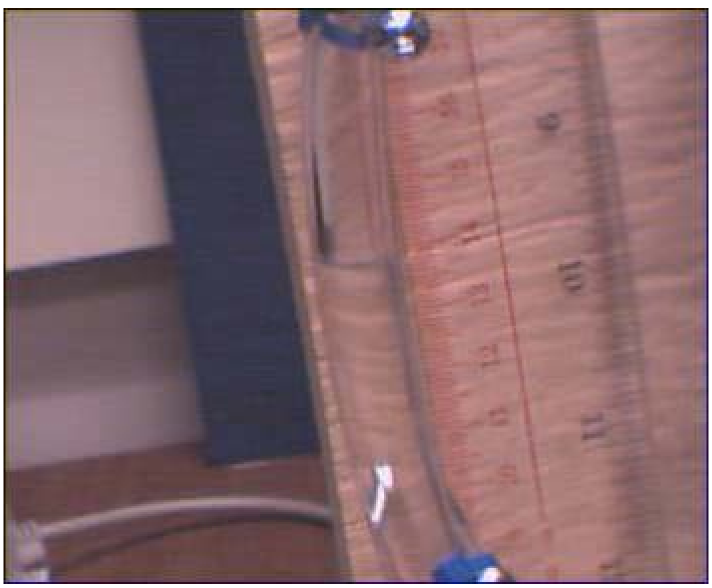
Working gas in the engine is heated, and this causes it to expand and push on the water column. This expansion cools the air which contracts, at the same time being pushed back by the weight of the displaced water column. Cycle then repeats.

Engine as a pump

In the classic configuration, the work produced via the water pistons is integrated with a water pump. The simple pump is external to the engine, and consists of two check valves, one on the intake and one on the outlet. In the engine, the loop of oscillating liquid can be thought of as acting as a displacer piston. The liquid in the single tube extending to the pump acts as the power piston. Traditionally the pump is open to the atmosphere, and the hydraulic head is small, so that the absolute engine pressure is close to atmospheric pressure.



Test of a model fluidyne engine.

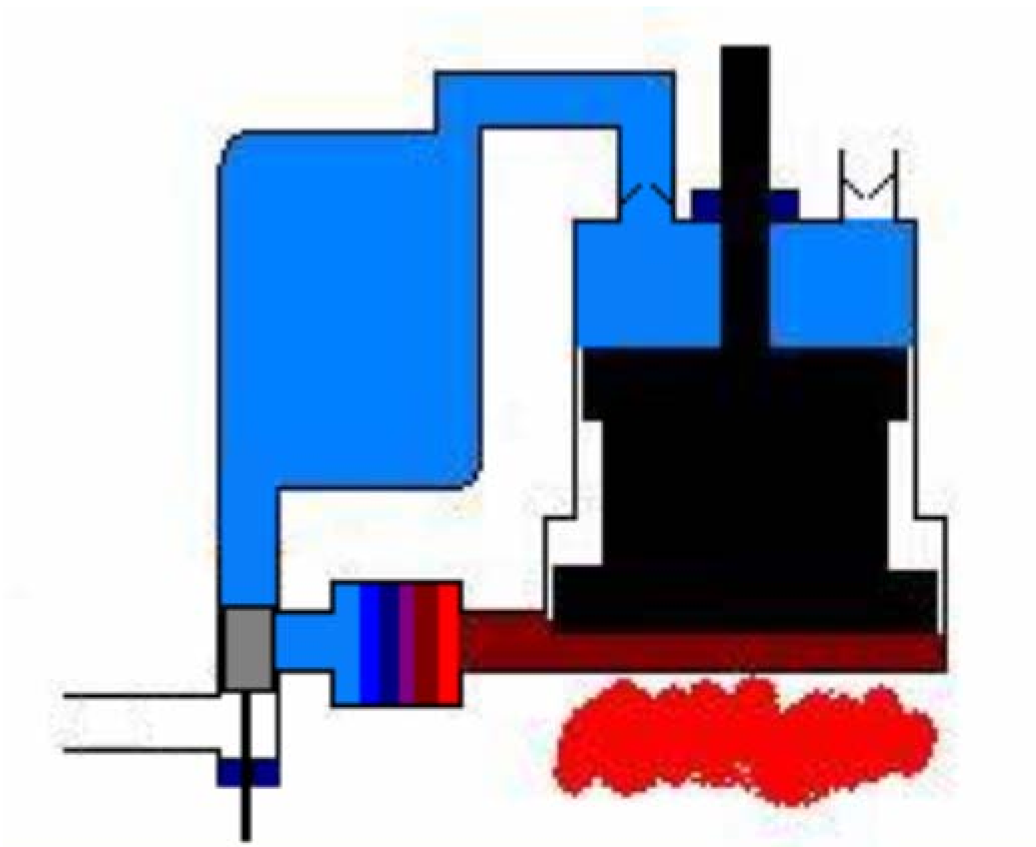


Detail of a water level displacement in a leftmost vertical tube.

This shows operation of a model fluidyne engine. Hot pipe is heated by a heat gun, and water column oscillation builds up to a steady-state level. Second image shows a detail of the actual water displacement.

Chapter 11

Ericsson Cycle



Rendering of an Ericsson engine

The **Ericsson cycle** is named after inventor John Ericsson, who designed and built many unique heat engines based on various thermodynamic cycles. He is credited with inventing two unique heat engine cycles and developing practical engines based on these cycles. His *first* cycle is very similar to what is now called the "Brayton cycle", with the exception that it uses external combustion. His second cycle is now called the Ericsson cycle.

Ideal Ericsson cycle

The following is a list of the four processes that occur between the four stages of the ideal Ericsson cycle:

- Process 1 -> 2: Isothermal compression. The compression space is assumed to be intercooled, so the gas undergoes isothermal compression. The compressed air flows into a storage tank at constant pressure. In the ideal cycle, there is no heat transfer across the tank walls.
- Process 2 -> 3: Isobaric heat addition. From the tank, the compressed air flows through the regenerator and picks up heat at a high constant-pressure on the way to the heated power-cylinder.
- Process 3 -> 4: Isothermal expansion. The power-cylinder expansion-space is heated externally, and the gas undergoes isothermal expansion.
- Process 4 -> 1: Isobaric heat removal. Before the air is released as exhaust, it is passed back through the regenerator, thus cooling the gas at a low constant pressure, and heating the regenerator for the next cycle.

Comparison with Stirling and Carnot cycles

The Ericsson cycle is often compared to the Stirling cycle, since the engine designs based on these respective cycles are both external combustion engines with regenerators. The Ericsson is perhaps most similar to the so called "double-acting" type of Stirling engine, in which the displacer piston also acts as the power piston. Theoretically, both of these cycles have so called *ideal* efficiency, which is the highest allowed by the second law of thermodynamics. The most well known ideal cycle is the Carnot cycle, although a real *Carnot engine* is not known to have been invented. The theoretical efficiencies for both, Ericsson and Stirling cycles acting in the same limits are equal to the Carnot Efficiency for same limits.

Comparison with the Brayton cycle

The first cycle Ericsson developed is now called the "Brayton cycle", commonly applied to the rotary jet engines for airplanes.

The second Ericsson cycle is the cycle most commonly referred to as simply the "Ericsson cycle". The (second) Ericsson cycle is also the limit of an ideal gas-turbine Brayton cycle, operating with multistage intercooled compression, and multistage expansion with reheat and regeneration. Compared to the Brayton cycle which uses adiabatic compression and expansion, the second Ericsson cycle uses isothermal compression and expansion, thus producing more net work per stroke. Also the use of regeneration in the Ericsson cycle increases efficiency by reducing the required heat input.

Cycle/Process	Compression	Heat addition	Expansion	Heat rejection
Ericsson (First, 1833)	adiabatic	isobaric	adiabatic	isobaric
Ericsson (Second, 1853)	isothermal	isobaric	isothermal	isobaric
Brayton (Turbine)	adiabatic	isobaric	adiabatic	isobaric

Ericsson engine

The Ericsson engine is based on the Ericsson cycle, and is known as an "external combustion engine", because it is externally heated. To improve efficiency, the engine has a regenerator or recuperator between the compressor and the expander. The engine can be run open- or closed-cycle. Expansion occurs simultaneously with compression, on opposite sides of the piston.

Regenerator

Ericsson coined the term "regenerator" for his independent invention of the mixed-flow counter-current heat exchanger. However, Rev. Robert Stirling had invented the same device, prior to Ericsson, so the invention is credited to Stirling. Stirling called it an "economiser" or "economizer", because it increased the fuel economy of various types of heat processes. The invention was found to be useful, in many other devices and systems, where it became more widely used, since other types of engines became favored over the Stirling engine. The term "regenerator" is now the name given to the component in the Stirling engine.

The term "recuperator" refers to a separated-flow, counter-current heat exchanger. As if this weren't confusing enough, a mixed-flow regenerator is sometimes used as a quasi-separated-flow recuperator. This can be done through the use of moving valves, or by a rotating regenerator with fixed baffles, or by the use of other moving parts. When heat is recovered from exhaust gases and used to preheat combustion air, typically the term recuperator is used, because the two flows are separate.

History

In 1791, before Ericsson, Barber proposed a similar engine. The Barber engine used a bellows compressor and a turbine expander, but it lacked a regenerator/recuperator. There are no records of a working Barber engine. Ericsson invented and patented his first engine using an external version of the Brayton cycle in 1833 (number 6409/1833 British). This was 18 years before Joule and 43 years before Brayton. Brayton engines were all piston engines and for the most part, internal combustion versions of the un-recuperated Ericsson engine. The "Brayton Cycle" is now known as the gas turbine cycle, which differs from the original "Brayton Cycle" in the use of a turbine compressor and expander. The gas turbine cycle is used for all modern gas turbine and turbojet engines, however simple cycle turbines are often recuperated to improve efficiency and these recuperated turbines more closely resemble Ericsson's work.

Ericsson eventually abandoned the open cycle in favor of the traditional closed Stirling cycle.

Ericsson's engine can easily be modified to operate in a closed-cycle mode, using a second, lower-pressure, cooled container between the original exhaust and intake. In closed cycle, the lower pressure can be significantly above ambient pressure, and He or H2 working gas can be used. Because of the higher pressure difference between the upward and downward movement of the work-piston, specific output can be greater than of a valveless Stirling engine. The added cost is the valve. Ericsson's engine also minimizes mechanical losses: the power necessary for compression does not go through crank-bearing frictional losses, but is applied directly from the expansion force. The piston-type Ericsson engine can potentially be the highest efficiency heat engine arrangement ever constructed. Admittedly, this has yet to be proven in practical applications.

The Ericsson-cycle engine (the second of the two discussed here) was used to power a 2,000-ton ship, the caloric ship *Ericsson*, and ran flawlessly for 73 hours. The combination engine produced about 300 horsepower (220 kW). It had a combination of four dual-piston engines; the larger expansion piston/cylinder, at 14 feet (4.3 m) in diameter, was perhaps the largest piston ever built. Rumor has it that tables were placed on top of those pistons (obviously in the cool compression chamber, not the hot power chamber) and dinner was served and eaten, while the engine was running at full power. At 6.5 RPM the pressure was limited to 8 psi (55 kPa). According to the official report it only consumed 4200 kg coal per 24 hours (original target was 8000 kg, which is still better than contemporary steam engines). The one sea trial proved that even though the engine ran well, the ship was underpowered. Sometime after the trials, the *Ericsson* sank. When it was raised, the Ericsson-cycle engine was removed and a steam engine took its place.

Ericsson designed and built a very great number of engines running on various cycles including steam, Stirling, Brayton, externally heated diesel air fluid cycle. He ran his engines on a great variety of fuels including coal and solar heat.

Ericsson was also responsible for an early use of the screw propeller for ship propulsion, in the USS *Princeton*, built in 1842–43.

Today's potential

The Ericsson cycle (and the similar Brayton cycle) receives renewed interest today to extract power from the exhaust heat of gas (and producer gas) engines and solar concentrators. An important advantage of the Ericsson cycle over the widely known Stirling engine is often not recognized: the volume of the heat exchanger does not adversely effect the efficiency. For medium and large engines the cost of valves can be small compared to this advantage. Turbocompressor plus turbine implementations seem favorable in the MWe range, positive displacement compressor plus turbine for Nx100 kWe power, and positive displacement compressor+expander below 100 kW.

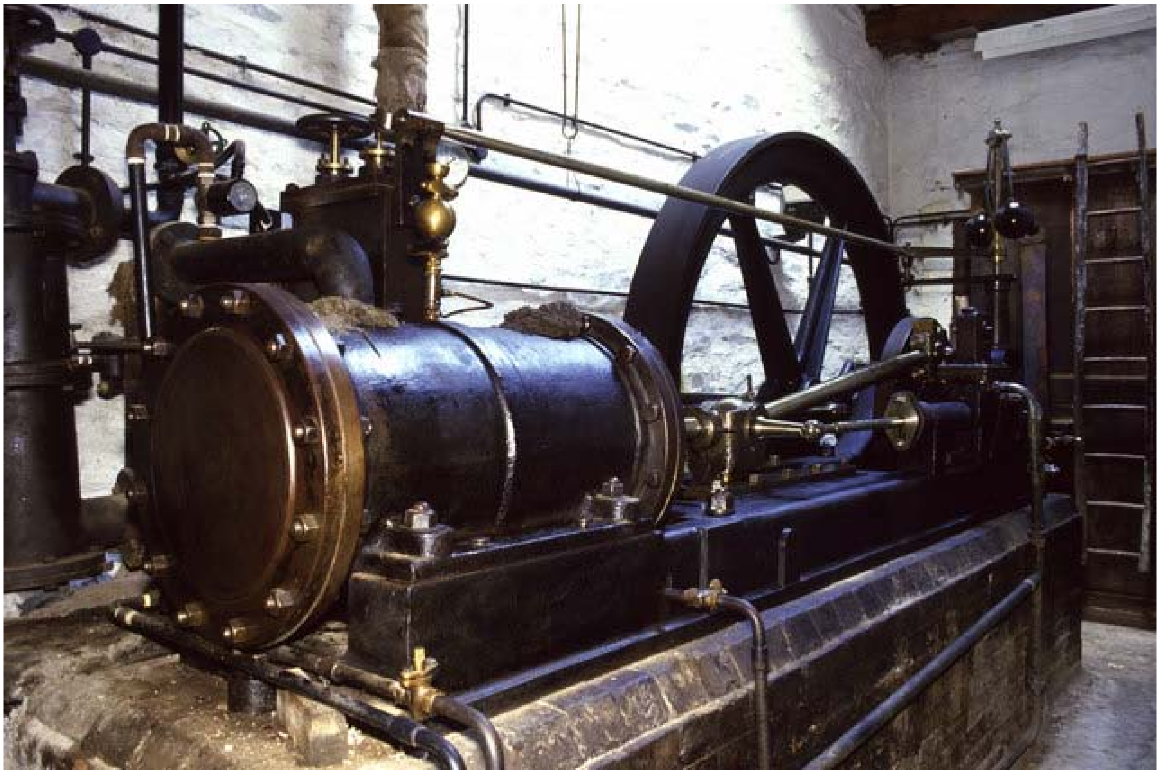
With high temperature hydraulic fluid, both the compressor and the expander can be liquid ring pump even up to 400°C, with rotating casing for best efficiency.

Chapter 12

Steam Engine

A 1817 Boulton & Watt beam blowing engine, used in Netherton at the ironworks of M W Grazebrook, re-erected on the A38(M) in Birmingham, UK

Preserved British steam-powered fire engine – an example of a mobile steam engine. This is a horse-drawn vehicle: the steam engine drives the water pump



A mill engine from Stott Park Bobbin Mill, Cumbria, England

A **steam engine** is a heat engine that performs mechanical work using steam as its working fluid.

The idea of using boiling water to produce mechanical motion has a long history, going back about 2,000 years. Early devices were not practical power producers, but more advanced designs producing usable power have become a major source of mechanical power over the last 300 years, beginning with applications for removing water from mines using vacuum engines. Subsequent developments using pressurized steam and converting linear to rotational motion enabled the powering of a wide range of manufacturing machinery. This could be sited anywhere that water and coal or wood fuel could be obtained, whereas previous installations were limited to locations where water wheels or windmills could be used. Significantly, this power source would later be applied to prime movers, mobile devices such as steam tractors and railway locomotives. Modern steam turbines generate about 80% of the electric power in the world using a variety of heat sources.

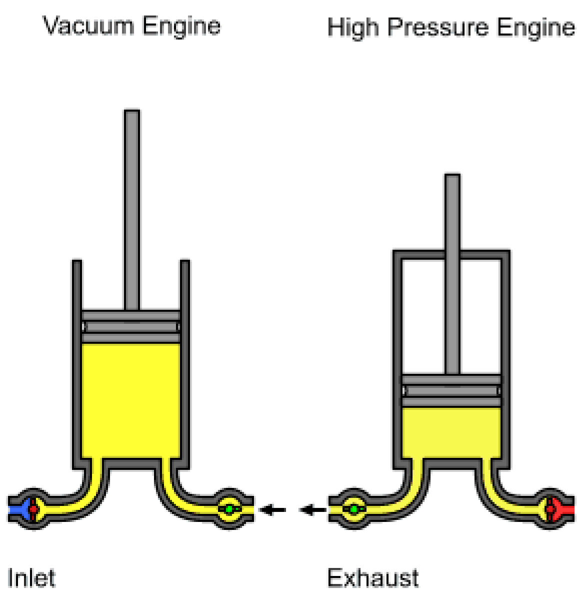
Steam engines are typically external combustion engines, although other external sources of heat such as solar power, nuclear power or geothermal energy may be used. The heat cycle is known as the Rankine cycle.

In general usage, the term 'steam engine' can refer to integrated steam plants such as railway steam locomotives and portable engines, or may refer to the machinery alone, as in the beam engine and stationary steam engine. Specialized devices such as steam hammers and steam pile drivers are dependent on steam supplied from a separate boiler.

History

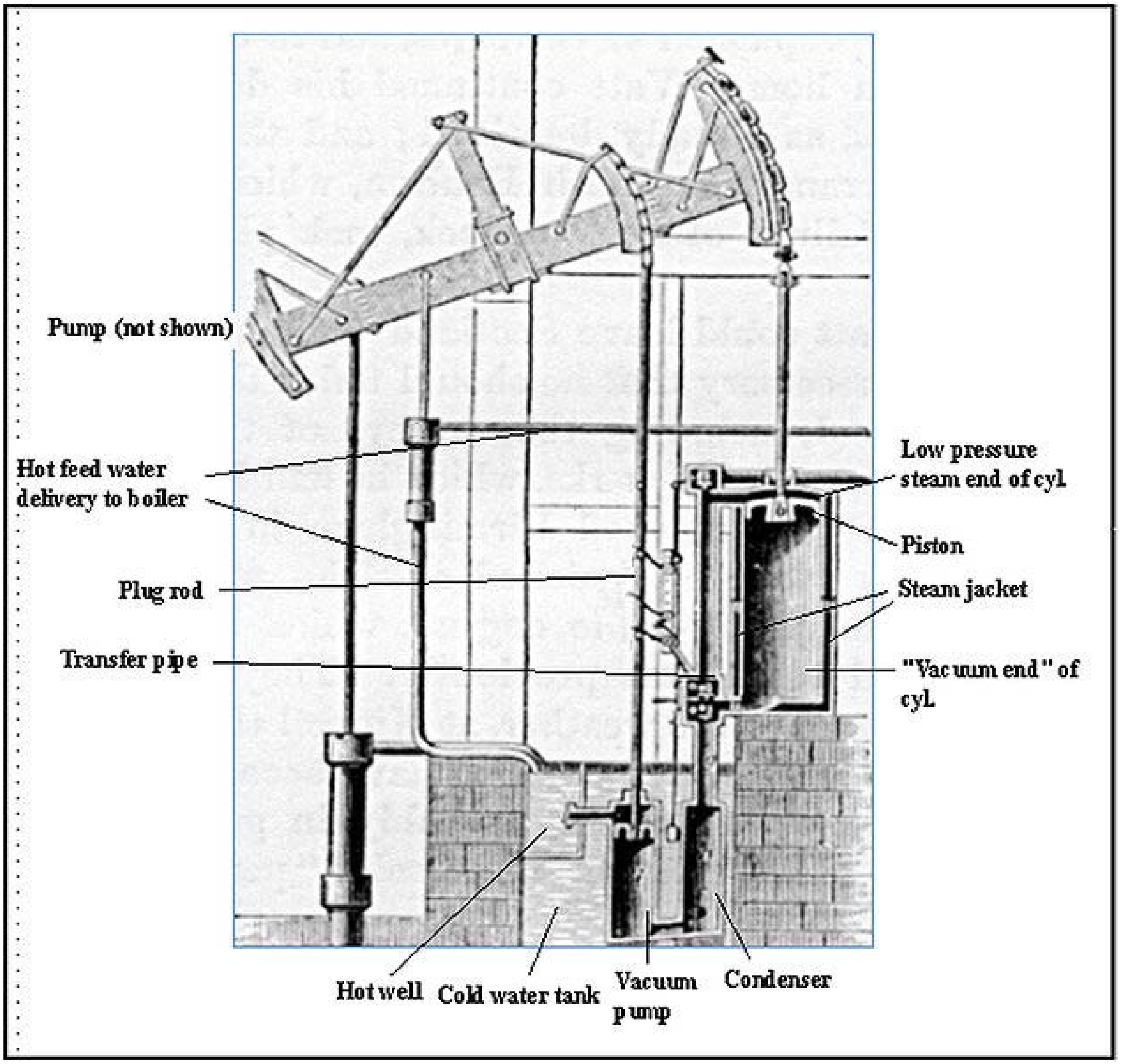
The history of the steam engine stretches back as far as the first century AD; the first recorded rudimentary steam engine being the aeolipile described by Greek mathematician Hero of Alexandria. In the following centuries, the few steam-powered 'engines' known about were essentially experimental devices used by inventors to demonstrate the properties of steam. A rudimentary steam turbine device was described by Taqi al-Din in 1551 and by Giovanni Branca in 1629.

Following the invention by Denis Papin of the steam digester in 1679, and a first piston steam engine in 1690, the first practical steam-powered 'engine' was a water pump, developed in 1698 by Thomas Savery. It proved only to have a limited lift height and was prone to boiler explosions, but it still received some use for mines and pumping stations.



The operation of "vacuum" and high pressure steam engines

The first commercially successful engine did not appear until around 1712. Incorporating technologies discovered by Savery and Denis Papin, the atmospheric engine, invented by Thomas Newcomen, paved the way for the Industrial Revolution. Newcomen's engine was relatively inefficient, and in most cases was only used for pumping water. It worked by using the vacuum from condensing steam in a cylinder and was mainly employed for draining mine workings at depths hitherto impossible, but also for providing a reusable water supply for driving waterwheels at factories sited away from a suitable 'head'.



Early Watt pumping engine

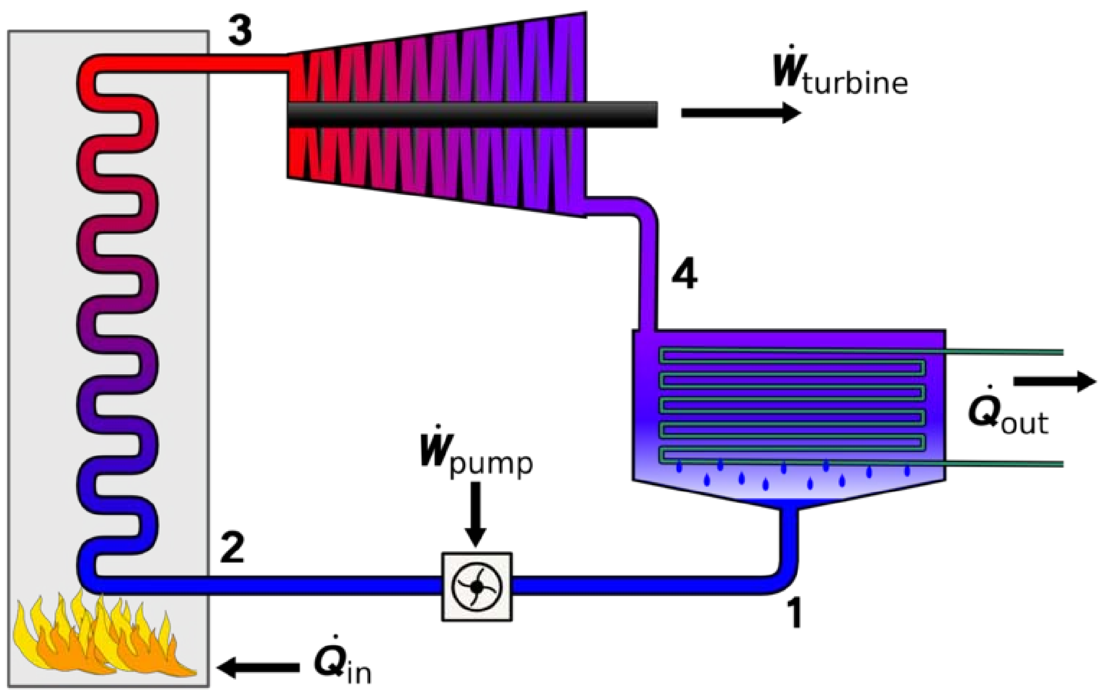
The next major step occurred when James Watt developed (1763–75) an improved version of Newcomen's engine, with a separate condenser. Watt's engine used 75% less coal than Newcomen's, and was hence much cheaper to run. Watt proceeded to develop his engine further, modifying it to provide a rotary motion suitable for driving factory machinery. This enabled factories to be sited away from rivers, and further accelerated the pace of the Industrial Revolution.

Newcomen's and Watt's early engines were "atmospheric", meaning that they were powered by the vacuum generated by condensing steam instead of the pressure of expanding steam. Cylinders had to be large, as the only usable force acting on them was atmospheric pressure. Steam was only used to compensate for the atmosphere allowing the piston to move back to its starting position.

Around 1800, Richard Trevithick introduced engines using high-pressure steam. These were much more powerful than previous engines and could be made small enough for transport applications. Thereafter, technological developments and improvements in manufacturing techniques (partly brought about by the adoption of the steam engine as a power source) resulted in the design of more efficient engines that could be smaller, faster, or more powerful, depending on the intended application.

Steam engines remained the dominant source of power well into the 20th century, when advances in the design of electric motors and internal combustion engines gradually resulted in the vast majority of reciprocating steam engines being replaced in commercial usage, and the ascendancy of steam turbines in power generation.

The steam cycle



Physical layout of the four main devices used in the Rankine cycle. Other components that perform the same or similar functions are often used, the turbine is often replaced with a steam driven piston.

The Rankine cycle is the fundamental thermodynamic underpinning of the steam engine. The Rankine cycle is a cycle that converts heat into work. The heat is supplied externally to a closed loop, which in steam engines contains water and steam. This cycle generates about 80% of all electric power used throughout the world, including virtually all solar thermal, biomass, coal and nuclear power plants. It is named after William John Macquorn Rankine, a Scottish polymath.

The Rankine cycle is sometimes referred to as a practical Carnot cycle because, when an efficient turbine is used, the TS diagram begins to resemble the Carnot cycle. The main difference is that heat addition (in the boiler) and rejection (in the condenser) are isobaric (constant pressure) in the Rankine cycle and isentropic (constant entropy) in the theoretical Carnot cycle. In this cycle a pump is also used to pressurize the working fluid received from the condenser as a liquid instead of as a gas. Pumping the working fluid through the cycle as a liquid requires a very small fraction of the energy needed to transport it as compared to compressing the working fluid as a gas in a compressor (as in the Carnot cycle).

The working fluid in a Rankine cycle follows a closed loop and is reused constantly. While many substances could be used in the Rankine cycle, water is usually the fluid of choice due to its favorable properties, such as nontoxic and unreactive chemistry, abundance, and low cost, as well as its thermodynamic properties.

Components of steam engines

There are two fundamental components of a steam plant: the boiler or steam generator, and the "motor unit", referred to itself as a "steam engine". Stationary steam engines in fixed buildings may have the two parts in separate buildings some distance apart. For portable or mobile use, such as steam locomotives, the two are mounted together.

Other components are often present; pumps (such as an injector) to supply water to the boiler during operation, condensers to recirculate the water and recover the latent heat of vaporisation, and superheaters to raise the temperature of the steam above its saturated vapour point, and various mechanisms to increase the draft for fireboxes. When coal is used, a chain or screw stoking mechanism and its drive engine or motor may be included to move the fuel from a supply bin (bunker) to the firebox.

Heat source

The heat required for boiling the water and supplying the steam can be derived from various sources, most commonly from burning combustible materials with an appropriate supply of air in a closed space (called variously combustion chamber, firebox). In some cases the heat source is a nuclear reactor or geothermal energy.

Boilers

An industrial boiler used for a stationary steam engine

Boilers are pressure vessels that contain water to be boiled, and some kind of mechanism for transferring the heat to the water so as to boil it.

The two most common methods of transferring heat to the water according are:

1. water-tube boiler - water is contained in or run through one or several tubes surrounded by hot gases
2. fire-tube boiler - the water partially fills a vessel below or inside which is a combustion chamber or furnace and fire tubes through which the hot gases flow

Once turned to steam, many boilers raise the temperature of the steam further, turning 'wet steam' into 'superheated steam'. This use of superheating prevents the steam condensing within the engine, and allows significantly greater efficiency.

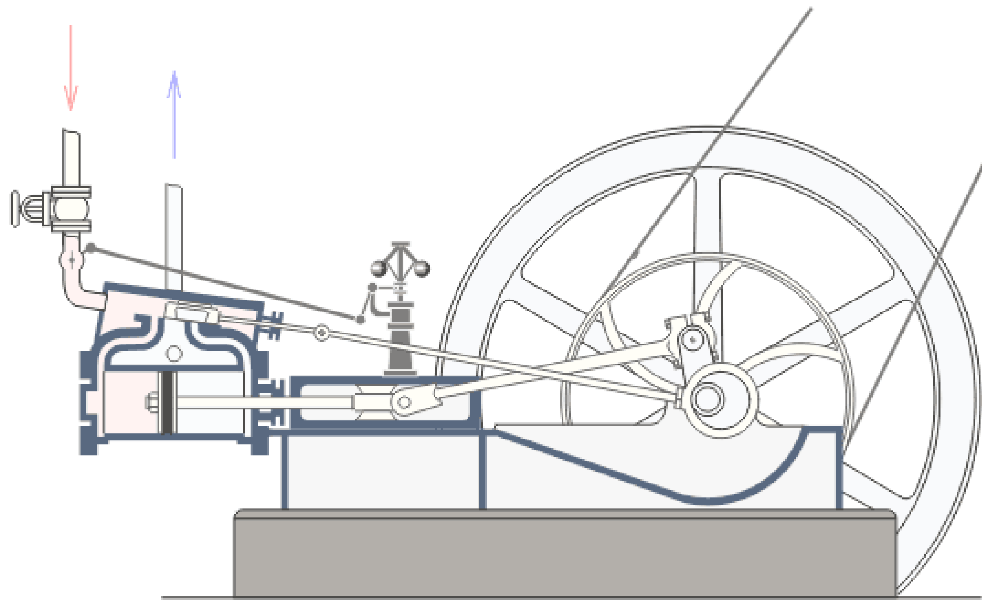
Motor units

A motor unit takes a supply of steam at high pressure and temperature and gives out a supply of steam at lower pressure and temperature, using as much of the difference in steam energy as possible to do mechanical work.

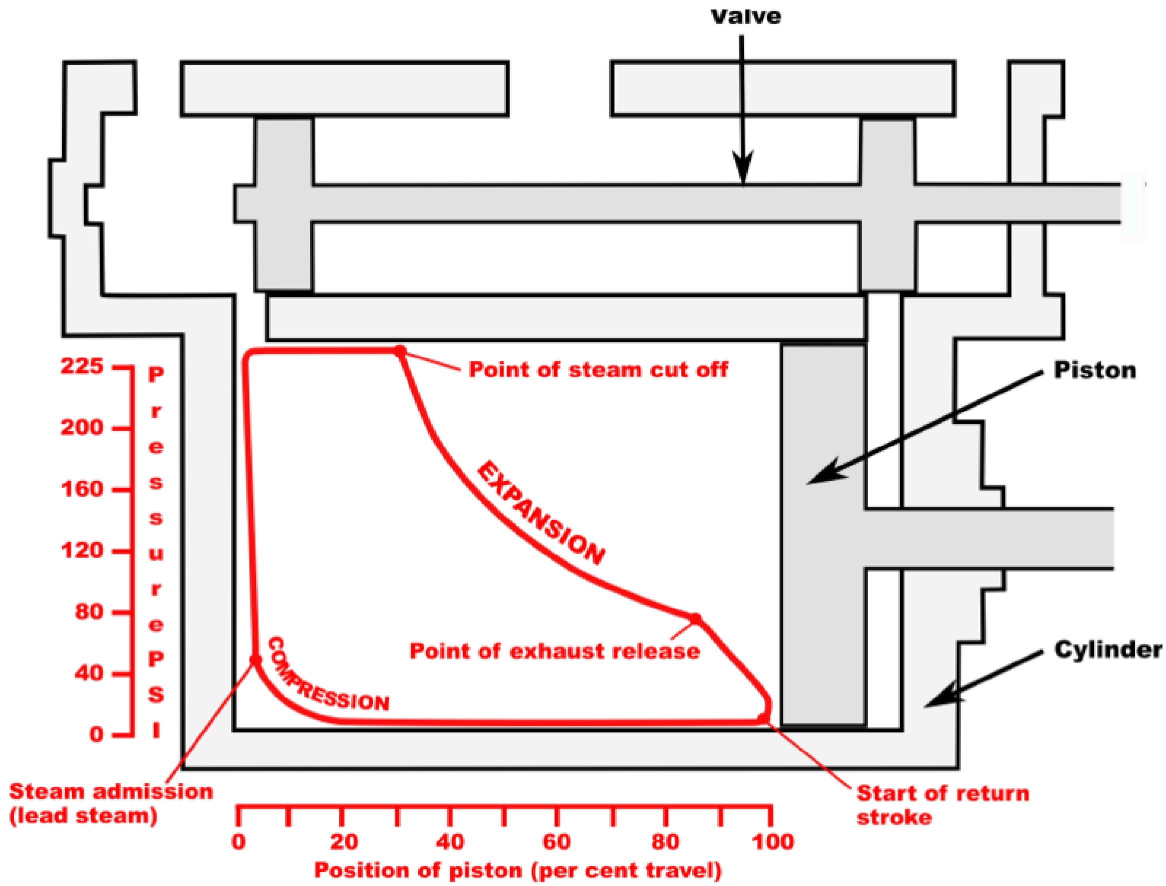
A motor unit is often called 'steam engine' in its own right. They will also operate on compressed air or other gas.

Simple expansion

This means that a charge of steam works only once in the cylinder. It is then exhausted directly into the atmosphere or into a condenser, but remaining heat can be utilized if needed to heat a living space, or to provide warm feedwater for the boiler.



Double acting stationary engine



Schematic Indicator diagram showing the four events in a double piston stroke

In most reciprocating piston engines, the steam reverses its direction of flow at each stroke (counterflow), entering and exhausting from the cylinder by the same port. The complete engine cycle occupies one rotation of the crank and two piston strokes; the cycle also comprises four *events — admission, expansion, exhaust, compression*. These events are controlled by valves often working inside a *steam chest* adjacent to the cylinder; the valves distribute the steam by opening and closing steam *ports* communicating with the cylinder end(s) and are driven by valve gear, of which there are many types. The simplest valve gears give events of fixed length during the engine cycle and often make the engine rotate in only one direction. Most however have a reversing mechanism which additionally can provide means for saving steam as speed and momentum are gained by gradually "shortening the cutoff" or rather, shortening the admission event; this in turn proportionately lengthens the expansion period. However, as one and the same valve usually controls both steam flows, a short cutoff at admission adversely affects the exhaust and compression periods which should ideally always be kept fairly constant; if the exhaust event is too brief, the totality of the exhaust steam cannot evacuate the cylinder, choking it and giving excessive compression (*"kick back"*).

In the 1840s and 50s, there were attempts to overcome this problem by means of various patent valve gears with a separate, variable cutoff expansion valve riding on the back of the main slide valve; the latter usually had fixed or limited cutoff. The combined setup gave a fair approximation of the ideal events, at the expense of increased friction and wear, and the mechanism tended to be complicated. The usual compromise solution has been to provide *lap* by lengthening rubbing surfaces of the valve in such a way as to overlap the port on the admission side, with the effect that the exhaust side remains open for a longer period after cut-off on the admission side has occurred. This expedient has since been generally considered satisfactory for most purposes and makes possible the use of the simpler Stephenson, Joy and Walschaerts motions. Corliss, and later, poppet valve gears had separate admission and exhaust valves driven by trip mechanisms or cams profiled so as to give ideal events; most of these gears never succeeded outside of the stationary marketplace due to various other issues including leakage and more delicate mechanisms.

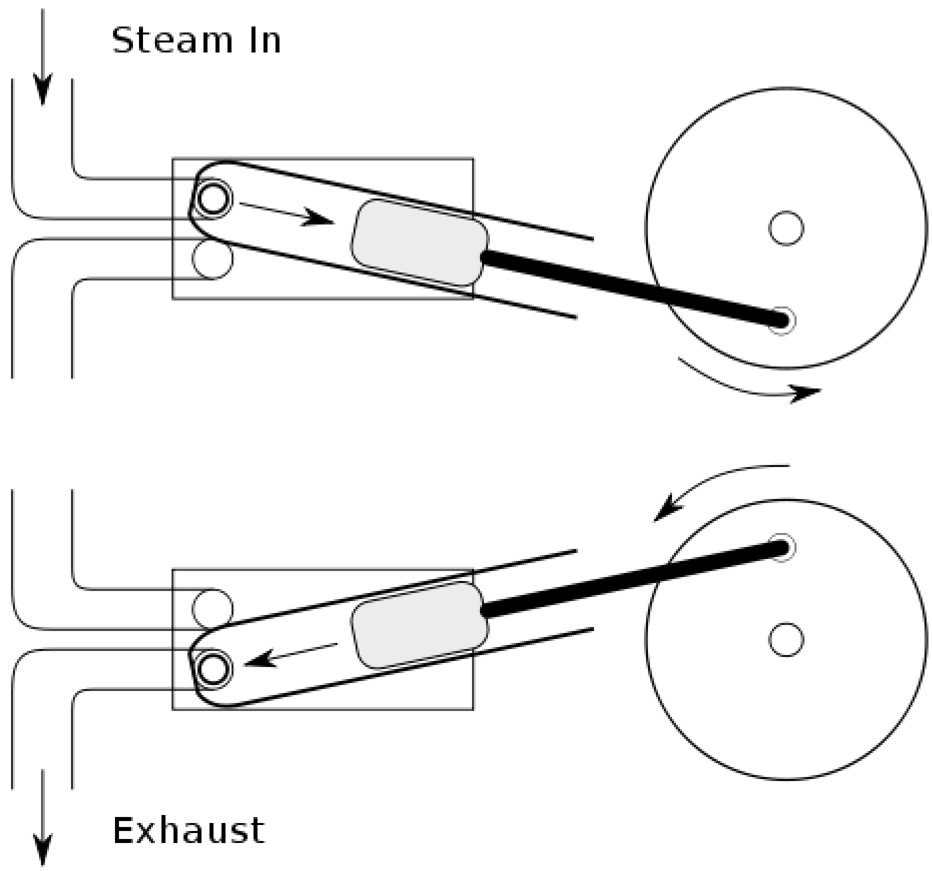
Compression

Before the exhaust phase is quite complete, the exhaust side of the valve closes, shutting a portion of the exhaust steam inside the cylinder. This determines the compression phase where a cushion of steam is formed against which the piston does work whilst its velocity is rapidly decreasing; it moreover obviates the pressure and temperature shock, which would otherwise be caused by the sudden admission of the high pressure steam at the beginning of the following cycle.

Lead

The above effects are further enhanced by providing *lead*: as was later discovered with the internal combustion engine, it has been found advantageous since the late 1830s to advance the admission phase, giving the valve *lead* so that admission occurs a little before the end of the exhaust stroke in order to fill the *clearance volume* comprising the ports and the cylinder ends (not part of the piston-swept volume) before the steam begins to exert effort on the piston.

Oscillating cylinder steam engines



Operation of a simple oscillating cylinder steam engine

An oscillating cylinder steam engine is a variant of the simple expansion steam engine which does not require valves to direct steam into and out of the cylinder. Instead of valves, the entire cylinder rocks, or oscillates, such that one or more holes in the cylinder line up with holes in a fixed port face or in the pivot mounting (trunnion). These engines are mainly used in toys and models, because of their simplicity, but have also been used in full size working engines, mainly on ships where their compactness is valued.

Compounding engines

As steam expands in a high pressure engine its temperature drops; because no heat is released from the system, this is known as adiabatic expansion and results in steam entering the cylinder at high temperature and leaving at low temperature. This causes a cycle of heating and cooling of the cylinder with every stroke which is a source of inefficiency.

A method to lessen the magnitude of this heating and cooling was invented in 1804 by British engineer Arthur Woolf, who patented his *Woolf high pressure* ***compound engine*** in 1805. In the compound engine, high pressure steam from the boiler expands in a high pressure (HP) cylinder and then enters one or more subsequent lower pressure (LP) cylinders. The complete expansion of the steam now occurs across multiple cylinders and as less expansion now occurs in each cylinder so less heat is lost by the steam in each. This reduces the magnitude of cylinder heating and cooling, increasing the efficiency of the engine. To derive equal work from lower pressure steam requires a larger cylinder volume as this steam occupies a greater volume. Therefore the bore, and often the stroke, are increased in low pressure cylinders resulting in larger cylinders.

Double expansion (usually known as **compound**) engines expanded the steam in two stages. The pairs may be duplicated or the work of the large LP cylinder can be split with one HP cylinder exhausting into one or the other, giving a 3-cylinder layout where cylinder and piston diameter are about the same making the reciprocating masses easier to balance.

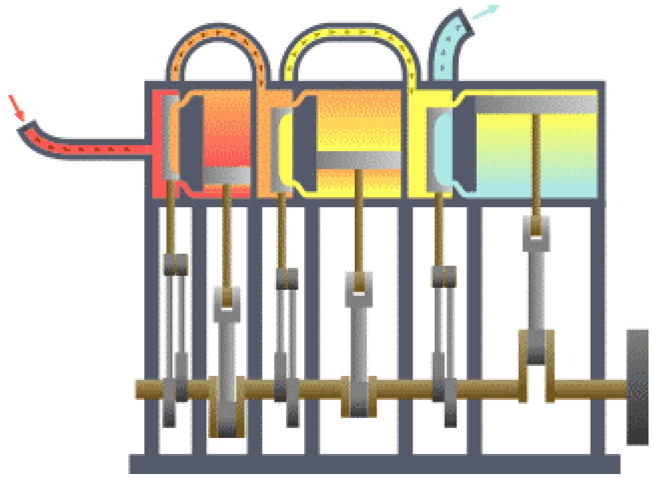
Two-cylinder compounds can be arranged as:

- **Cross compounds** - The cylinders are side by side.
- **Tandem compounds** - The cylinders are end to end, driving a common connecting rod
- **Angle compounds** - The cylinders are arranged in a vee (usually at a 90° angle) and drive a common crank.

With two-cylinder compounds used in railway work, the pistons are connected to the cranks as with a two-cylinder simple at 90° out of phase with each other (*quartered*). When the double expansion group is duplicated, producing a 4-cylinder compound, the individual pistons within the group are usually balanced at 180°, the groups being set at 90° to each other. In one case (the first type of Vauclain compound), the pistons worked in the same phase driving a common crosshead and crank, again set at 90° as for a two-cylinder engine. With the 3-cylinder compound arrangement, the LP cranks were either set at 90° with the HP one at 135° to the other two, or in some cases all three cranks were set at 120°.

The adoption of compounding was common for industrial units, for road engines and almost universal for marine engines after 1880; it was not universally popular in railway locomotives where it was often perceived as complicated. This is partly due to the harsh railway operating environment and limited space afforded by the loading gauge (particularly in Britain, where compounding was never common and not employed after 1930). However although never in the majority it was popular in many other countries.

Multiple expansion engines



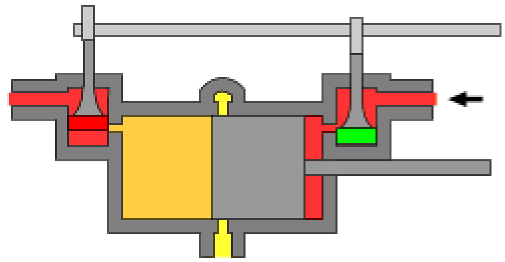
High-pressure steam (red) enters from the boiler and passes through the engine, exhausting as low-pressure steam (blue) to the condenser.

It is a logical extension of the compound engine (described above) to split the expansion into yet more stages to increase efficiency. The result is the **multiple expansion engine**. Such engines use either three or four expansion stages and are known as *triple* and *quadruple expansion engines* respectively. These engines use a series of double-acting cylinders of progressively increasing diameter and/or stroke and hence volume. These cylinders are designed to divide the work into three or four, as appropriate, equal portions for each expansion stage. As with the double expansion engine, where space is at a premium, two smaller cylinders of a large sum volume may be used for the low pressure stage. Multiple expansion engines typically had the cylinders arranged inline, but various other formations were used. In the late 19th century, the Yarrow-Schlick-Tweedy balancing 'system' was used on some marine triple expansion engines. Y-S-T engines divided the low pressure expansion stages between two cylinders, one at each end of the engine. This allowed the crankshaft to be better balanced, resulting in a smoother, faster-responding engine which ran with less vibration. This made the 4-cylinder triple-expansion engine popular with large passenger liners (such as the Olympic class), but was ultimately replaced by the virtually vibration-free turbine.

The image shows of a triple expansion engine. The steam travels through the engine from left to right. The valve chest for each of the cylinders is to the left of the corresponding cylinder.

Land-based steam engines could exhaust much of their steam, as feed water was usually readily available. Prior to and during World War I, the expansion engine dominated marine applications where high vessel speed was not essential. It was however superseded by the British invention steam turbine where speed was required, for instance in warships, such as the dreadnought battleships, and ocean liners. HMS *Dreadnought* of 1905 was the first major warship to replace the proven technology of the reciprocating engine with the then-novel steam turbine.

Uniflow (or unaflow) engine



Compression

The poppet valves are controlled by the rotating camshaft at the top. High pressure steam enters, red, and exhausts, yellow.

This is intended to remedy the difficulties arising from the usual counterflow cycle mentioned above which means that at each stroke the port and the cylinder walls will be cooled by the passing exhaust steam, whilst the hotter incoming admission steam will waste some of its energy in restoring working temperature. The aim of the uniflow is to remedy this defect by providing an additional port uncovered by the piston at the end of each stroke making the steam flow only in one direction. By this means, thermal efficiency is improved by having a steady temperature gradient along the cylinder bore. The simple-expansion uniflow engine is reported to give efficiency equivalent to that of classic compound systems with the added advantage of superior part-load performance. It is also readily adaptable to high-speed uses and was a common way to drive electricity generators towards the end of the 19th century before the coming of the steam turbine.

All common steam admission valves, such as slide valves, piston valves and rotary Corliss type valves, have been used on uniflow engines, usually actuated by common eccentrics. The most advanced uniflow engines used poppet valves, which allow high steam inlet temperatures. The inlet valves may be driven by a double cam system whose phasing and duration is controllable; this allows adjustments for high torque and power when needed with more restrained use of steam and greater expansion for economical cruising.

Uniflow engines have been produced in single-acting, double-acting, simple, and compound versions. Skinner 4-crank 8-cylinder single-acting tandem compound engines power two Great Lakes ships still trading today (2007). These are the *Saint Marys Challenger*, that in 2005 completed 100 years of continuous operation as a powered carrier (the Skinner engine was fitted in 1950) and the car ferry, SS *Badger*.

In the early 1950s, the Ultimax engine — a 2-crank 4-cylinder arrangement similar to Skinner's — was developed by Abner Doble for the Paxton car project with tandem opposed single-acting cylinders giving effective double-action.

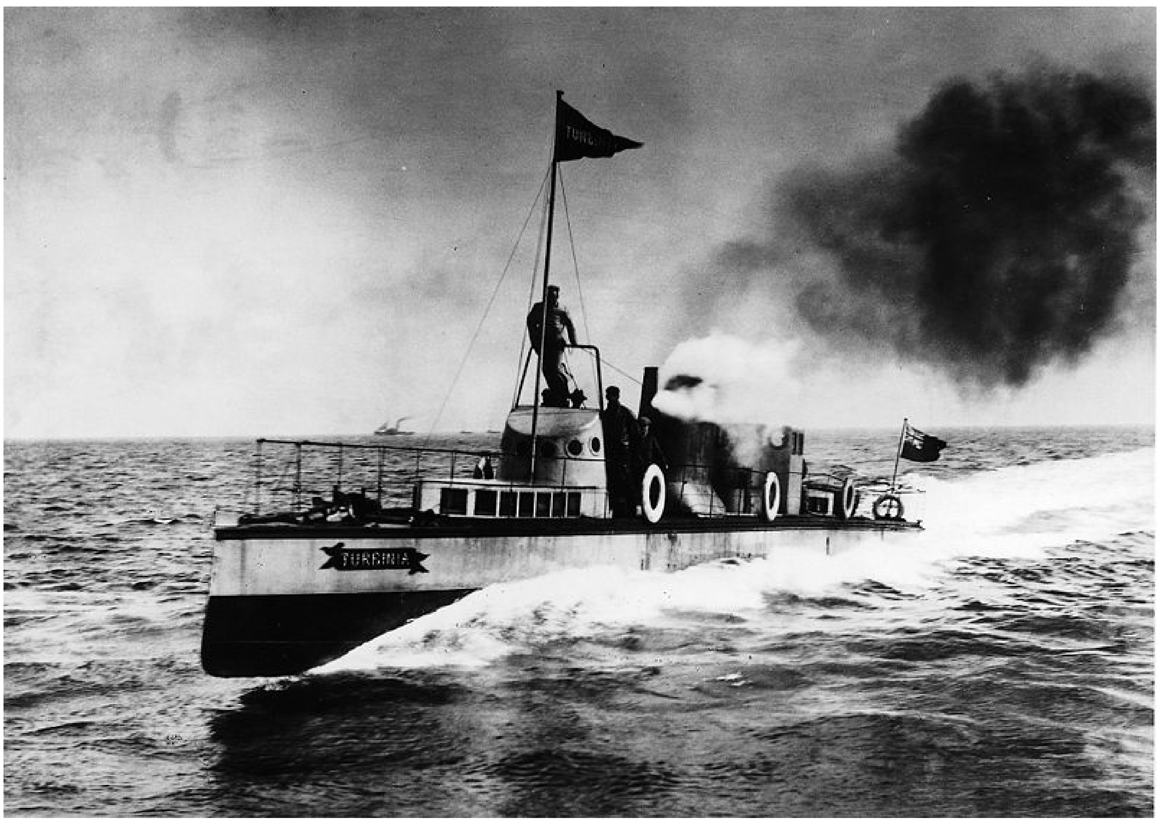
Small uniflow steam engines have been made as conversions of two-stroke internal combustion engines, by feeding the cylinder with steam via a "bash valve" in the spark plug hole which is knocked open by the piston reaching the top of its stroke.

Turbine engines

A rotor of a modern steam turbine, used in a power plant

A steam turbine consists of an alternating series of one or more rotating discs mounted on a drive shaft, *rotors*, and static discs fixed to the turbine casing, *stators*. The rotors have a propeller-like arrangement of blades at the outer edge. Steam acts upon these blades, producing rotary motion. The stator consists of a similar, but fixed, series of blades that serve to redirect the steam flow onto the next rotor stage. A steam turbine often exhausts into a surface condenser that provides a vacuum. The stages of a steam turbine are typically arranged to extract the maximum potential work from a specific velocity and pressure of steam, giving rise to a series of variably sized high and low pressure stages. Turbines are only effective if they rotate at very high speed, therefore they are usually connected to reduction gearing to drive another mechanism, such as a ship's propeller, at a lower speed. This gearbox can be mechanical but today it is more common to use an alternator/generator set to produce electricity that later is used to drive an electric motor. A turbine rotor is also only capable of providing power when rotating in one direction. Therefore a reversing stage or gearbox is usually required where power is required in the opposite direction.

Steam turbines provide direct rotational force and therefore do not require a linkage mechanism to convert reciprocating to rotary motion. Thus, they produce smoother rotational forces on the output shaft. This contributes to a lower maintenance requirement and less wear on the machinery they power than a comparable reciprocating engine.



The *Turbinia* - the first steam turbine-powered ship

The main use for steam turbines is in electricity generation (about 80% of the world's electric production is by use of steam turbines) and to a lesser extent as marine prime movers. In the former, the high speed of rotation is an advantage, and in both cases the relative bulk is not a disadvantage; in the latter (pioneered on the Turbinia), the light weight, high efficiency and high power are highly desirable.

Virtually all nuclear power plants generate electricity by heating water to provide steam that drives a turbine connected to an electrical generator. Nuclear-powered ships and submarines either use a steam turbine directly for main propulsion, with generators providing auxiliary power, or else employ turbo-electric propulsion, where the steam drives a turbine-generator set with propulsion provided by electric motors. A limited number of steam turbine railroad locomotives were manufactured. Some non-condensing direct-drive locomotives did meet with some success for long haul freight operations in Sweden and for express passenger work in Britain, but were not repeated. Elsewhere, notably in the U.S.A., more advanced designs with electric transmission were built experimentally, but not reproduced. It was found that steam turbines were not ideally suited to the railroad environment and these locomotives failed to oust the classic reciprocating steam unit in the way that modern diesel and electric traction has done.

Rotary steam engines

It is possible to use a mechanism based on a pistonless rotary engine such as the Wankel engine in place of the cylinders and valve gear of a conventional reciprocating steam engine.. The major problem is the difficulty of sealing the rotors to make them steam-tight in the face of wear and thermal expansion; the resulting leakage made them very inefficient. Lack of expansive working, or any means of control of the cutoff is also a serious problem with many such designs. By the 1840s, it was clear that the concept had inherent problems and rotary engines were treated with some derision in the technical press. However, the arrival of electricity on the scene, and the obvious advantages of driving a dynamo directly from a high-speed engine, led to something of a revival in interest in the 1880s and 1890s, and a few designs had some limited success.

Of the few designs that were manufactured in quantity, those of the Hult Brothers Rotary Steam Engine Company of Stockholm, Sweden, and the spherical engine of Beauchamp Tower are notable. Tower's engines were used by the Great Eastern Railway to drive lighting dynamos on their locomotives, and by the Admiralty for driving dynamos on board the ships of the Royal Navy. They were eventually replaced in these niche applications by steam turbines.

The Quasiturbine is an experimental uniflow rotary design.

Jet type

Invented by Australian engineer Alan Burns and developed in Britain by engineers at Pursuit Dynamics, this underwater jet engine uses high pressure steam to draw in water through an intake at the front and expel it at high speed through the rear. The engine can also serve as pump and mixer. This type of system is referred to as 'PDX Technology' by Pursuit Dynamics and has been applied to food technology problems.

Rocket type

The aeolipile represents the use of steam by the rocket-reaction principle, although not for direct propulsion.

In more modern times there has been limited use of steam for rocketry—particularly for rocket cars. The technique is simple in concept, simply fill a pressure vessel with hot water at high pressure, and open a valve leading to a suitable nozzle. The drop in pressure immediately boils some of the water and the steam leaves through a nozzle, giving a significant propulsive force.

There are even speculative plans for interplanetary use. Although steam rockets are relatively inefficient in their use of propellant, this very well may not matter as the solar system is believed to have extremely large stores of water ice which can be used as propellant. Extracting this water and using it in interplanetary rockets requires several orders of magnitude less equipment than breaking it down to hydrogen and oxygen for conventional rocketry.

Cold sink

A power station's cooling tower produces clouds from the low temperature waste-heat which has been transferred to air which rises and cools

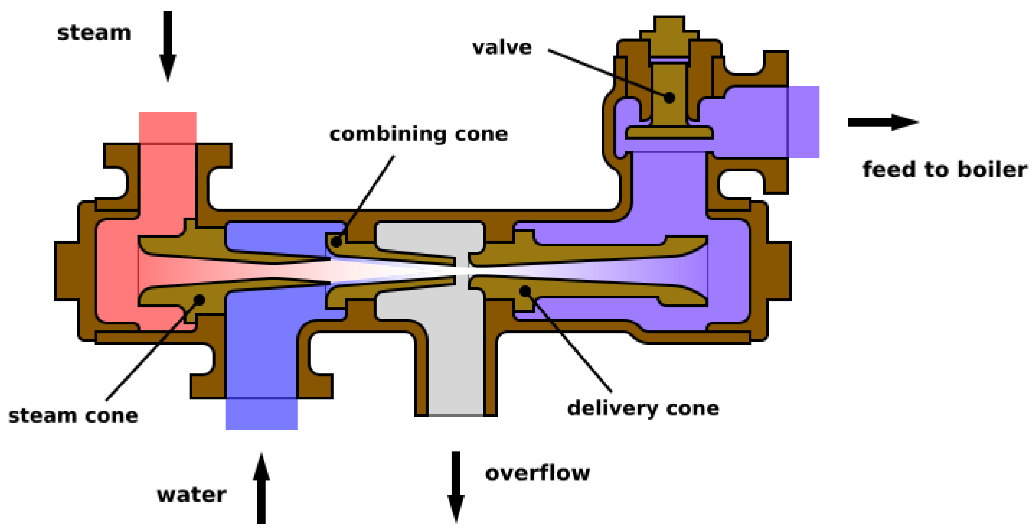
As with all heat engines, a considerable quantity of waste heat at relatively low temperature is produced and must be disposed of.

The simplest cold sink is to vent the steam to the environment. This is often used on steam locomotives, as the released steam is released in the chimney so as to increase the draw on the fire, which greatly increases engine power, but is inefficient. Steam locomotive condensing apparatus can be employed to improve efficiency.

Sometimes the waste heat is useful in and of itself, and in those cases very high overall efficiency can be obtained. For example, combined heat and power (CHP) systems use the waste steam for district heating.

Where CHP is not used, steam turbines in power stations use surface condensers as a cold sink. The condensers are cooled by water flow from oceans, rivers, lakes, and often by cooling towers which evaporate water to provide cooling energy removal. The resulting condensed hot water output from the condenser is then put back into the boiler via a pump. The water vapor with entrained droplets often seen billowing from power stations is generated by the cooling systems (not from the closed-loop Rankine power cycle) and represents the waste energy heat (pumping and vaporization) that could not be converted to useful work in the turbine. Note that cooling towers operate using the latent heat of vaporization of the cooling fluid. The white billowing clouds that form in cooling tower operation are the result of water droplets that are entrained in the cooling tower airflow; they are not, as commonly thought, released steam.

Water pump



An injector uses a jet of steam to force water into the boiler.

The Rankine cycle and most practical steam engines have a water pump to recycle or top up the boiler water, so that they may be run continuously. The water pump can be of almost any type although special types, such as an injector, which is a pump that uses a steam jet usually supplied from the boiler and is present on very many steam locomotives.

Monitoring equipment

For safety reasons, nearly all steam engines are equipped with mechanisms to monitor the boiler, such as a pressure gauge and a sight glass to monitor the water level.

Many engines, stationary and mobile, are also fitted with a governor to regulate the speed of the engine without the need for human interference (similar to cruise control in some cars).

Advantages

The strength of the steam engine for modern purposes is in its ability to convert heat from almost any source into mechanical work, unlike the internal combustion engine.

Similar advantages are found in a different type of external combustion engine, the Stirling engine, which can offer efficient power (with advanced regenerators and large radiators) at the cost of a much lower power-to-size/weight ratio than even modern steam engines with compact boilers. These Stirling engines are not commercially produced, although the concepts are promising.

Steam locomotives are especially advantageous at high elevations as they are not adversely affected by the lower atmospheric pressure. This was inadvertently discovered when steam locomotives operated at high altitudes in the mountains of South America were replaced by diesel-electric units of equivalent sea level power. These were quickly replaced by much more powerful locomotives capable of producing sufficient power at high altitude.

For road vehicles, steam propulsion has the advantage of having high torque from stationary, removing the need for a clutch and transmission, though start-up time and sufficiently compact packaging remain a problem.

In Switzerland (Brienz Rothhorn) and Austria (Schafberg Bahn) new rack steam locomotives have proved very successful. They were designed based on a 1930s design of Swiss Locomotive and Machine Works (SLM) but with all of today's possible improvements like roller bearings, heat insulation, light-oil firing, improved inner streamlining, one-man-driving and so on. These resulted in 60 percent lower fuel consumption per passenger and massively reduced costs for maintenance and handling. Economics now are similar or better than with most advanced diesel or electric systems. Also a steam train with similar speed and capacity is 50 percent lighter than an electric or diesel train, thus, especially on rack railways, significantly reducing wear and tear on the track. Also, a new steam engine for a paddle steam ship on Lake Geneva, the *Montreux*, was designed and built, being the world's first full-size ship steam engine with an electronic remote control. The steam group of SLM in 2000 created a wholly owned company called DLM to design modern steam engines and steam locomotives.

Safety

Steam engines possess boilers and other components that are pressure vessels that contain a great deal of potential energy. Steam escapes and boiler explosions (typically BLEVEs) can and have caused great loss of life in the past. While variations in standards may exist in different countries, stringent legal, testing, training, care with manufacture, operation and certification is applied to try to minimise or prevent such occurrences.

Failure modes may include:

- over-pressurisation of the boiler
- insufficient water in the boiler causing overheating and vessel failure
- pressure vessel failure of the boiler due to inadequate construction or maintenance.
- escape of steam from pipework/boiler causing scalding

Steam engines frequently possess two independent mechanisms for ensuring that the pressure in the boiler does not go too high; one may be adjusted by the user, the second is typically designed as an ultimate fail-safe.

Lead fusible plugs may be present in the crown of the firebox. If the water level drops, such that the temperature of the firebox crown increases significantly, the lead melts and the steam escapes warning the operators, who may then manually drop the fire. Except in the smallest of boilers the steam escape has little effect on dampening the fire. The plugs are also too small in area to lower steam pressure significantly, depressurizing the boiler. If they were any larger, the volume of escaping steam would itself endanger the crew.

Efficiency

The efficiency of an engine can be calculated by dividing the energy output of mechanical work that the engine produces by the energy input to the engine by the burning fuel.

No heat engine can be more efficient than the Carnot cycle, in which heat is moved from a high temperature reservoir to one at a low temperature, and the efficiency depends on the temperature difference. For the greatest efficiency, steam engines should be operated at the highest steam temperature possible (superheated steam), and release the waste heat at the lowest temperature possible.

The efficiency of a Rankine cycle is usually limited by the working fluid. Without the pressure reaching super critical levels for the working fluid, the temperature range the cycle can operate over is quite small; in steam turbines, turbine entry temperatures are typically 565°C (the creep limit of stainless steel) and condenser temperatures are around 30°C. This gives a theoretical Carnot efficiency of about 63% compared with an actual efficiency of 42% for a modern coal-fired power station. This low turbine entry temperature (compared with a gas turbine) is why the Rankine cycle is often used as a bottoming cycle in combined-cycle gas turbine power stations.

One of the principal advantages the Rankine cycle holds over others is that during the compression stage relatively little work is required to drive the pump, the working fluid being in its liquid phase at this point. By condensing the fluid, the work required by the pump consumes only 1% to 3% of the turbine power and contributes to a much higher efficiency for a real cycle. The benefit of this is lost somewhat due to the lower heat addition temperature. Gas turbines, for instance, have turbine entry temperatures approaching 1500°C. Nonetheless, the efficiencies of actual large steam cycles and large modern gas turbines are fairly well matched.

In practice, a steam engine exhausting the steam to atmosphere will typically have an efficiency (including the boiler) in the range of 1-10%, but with the addition of a condenser and multiple expansion, it may be greatly improved to 25% or better.

A megawatt electrical power station with steam reheat, economizer etc. will achieve up to 50% thermal efficiency.

It is also possible to capture the waste heat using cogeneration in which the waste heat is used for heating a lower boiling point working fluid or as a heat source for district heating via saturated low pressure steam. By this means it is possible to use as much as 85-90% of the input energy.

Applications

Since the early 18th century, steam power has been applied to a variety of practical uses. At first it was applied to reciprocating pumps, but from the 1780s rotative engines (i.e. those converting reciprocating motion into rotary motion) began to appear, driving factory machinery such as spinning mules and power looms. At the turn of the 19th century, steam-powered transport on both sea and land began to make its appearance becoming ever more dominant as the century progressed.

Steam engines can be said to have been the moving force behind the Industrial Revolution and saw widespread commercial use driving machinery in factories, mills and mines; powering pumping stations; and propelling transport appliances such as railway locomotives, ships and road vehicles. Their use in agriculture led to an increase in the land available for cultivation.

Very low power engines are used to power models and speciality applications such as the steam clock.

The presence of several phases between heat source and power delivery has meant that it has always been difficult to obtain a power-to-weight ratio anywhere near that obtainable from internal combustion engines; notably this has made steam aircraft extremely rare. Similar considerations have meant that for small and medium-scale applications steam has been largely superseded by internal combustion engines or electric motors, which has given the steam engine an out-dated image. However it is important to remember that the power supplied to the electric grid is predominantly generated using steam turbine plant, so that indirectly the world's industry is still dependent on steam power. Recent concerns about fuel sources and pollution have incited a renewed interest in steam both as a component of cogeneration processes and as a prime mover. This is becoming known as the Advanced Steam movement.

Steam engines can be classified by their application:

Stationary applications

Stationary steam engines can be classified into two main types:

1. Winding engines, rolling mill engines, steam donkeys, marine engines, and similar applications which need to frequently stop and reverse.
2. Engines providing power, which rarely stop and do not need to reverse. These include engines used in thermal power stations and those that were used in pumping stations, mills, factories and to power cable railways and cable tramways before the widespread use of electric power.

The steam donkey is technically a stationary engine but is mounted on skids to be semi-portable. It is designed for logging use and can drag itself to a new location. Having secured the winch cable to a sturdy tree at the desired destination, the machine will move towards the anchor point as the cable is winched in.

A portable engine is a stationary engine mounted on wheels so that it may be towed to a work-site by horses or a traction engine, rather than being fixed in a single location.

Transport applications

A steam locomotive- a GNR N2 Class No.1744 at Weybourne nr. Sheringham, Norfolk.

A steam-powered bicycle

Steam engines have been used to power a wide array of transport appliances:

- Marine: Steamboat, steamship, steam yacht
- Rail: Steam locomotive, fireless locomotive
- Agriculture: Traction engine, steam tractor
- Road: Steam wagon, steam bus, steam tricycle, steam car
- Construction: Steam roller, steam shovel
- Military: steam tank (tracked), steam tank (wheeled), steam catapult
- Space: Steam rocket

In these applications internal combustion engines are now used due to their higher power-to-weight ratio , lower maintenance and space requirements .

Modern applications

Although the reciprocating steam engine is no longer in widespread commercial use, various companies are exploring or exploiting the potential of the engine as an alternative to internal combustion engines.

The company Energiprojekt AB in Sweden has made progress in using modern materials for harnessing the power of steam. The efficiency of Energiprojekt's steam engine reaches some 27-30% on high-pressure engines. It is a single-step, 5-cylinder engine (no compound) with superheated steam and consumes approx. 4 kg (8.8 lb) of steam per kWh.

Steam museums

Australia

- Powerhouse Museum in Sydney

Canada

- Ontario Agricultural Museum in Milton, Ontario
- Steam Era in Milton, Ontario

UK

- Bolton Steam Museum
- Bressingham Steam and Gardens - Gardens, Steam railways and museum of steam vehicles
- Crofton Beam Engines ()
- Hollycombe Steam Collection
- Kempton Park Steam Engines
- Kew Bridge Steam Museum

US

- The New England Wireless and Steam Museum ()

Chapter 13

Swashplate Engine

Almen A-4 barrel engine

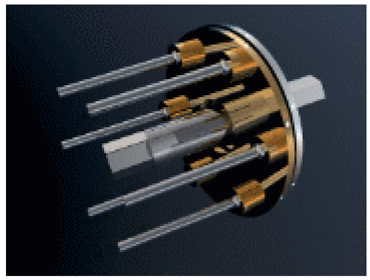
The **swashplate engine** (also sometimes called **axial engine** or **barrel engine**) is a type of reciprocating engine that replaces the common crankshaft with a circular plate (the swashplate). Pistons press down on the plate in sequence, forcing it to nutate around its center. This motion can be simulated by placing a CD on a ball bearing at its centre and pressing down at progressive places around its circumference. The plate, also known as a **wobble plate**, is typically geared to produce rotary motion. An alternate design replaces the plate with a sine-shaped cam, and is thus known as a **cam engine**.

The key advantage of the design is that the cylinders are arranged in parallel around the edge of the plate, and possibly on either side of it as well, and are aligned with the output shaft rather than at 90 degrees as in crankshaft engines. This results in a very compact, cylindrical engine, for which reason the design is also known as a **barrel engine**.

The arrangement also allows the compression ratio of the engine to be changed whilst running by adjusting the distance of the plate from the cylinders.

History

Macomber



Swashplate. Note that the swashplate is fastened to the shaft, so it rotates with it.

In 1911 the Macomber Rotary Engine Company of Los Angeles marketed one of the first axial internal-combustion engines, manufactured by the Avis Engine Company of Allston, Massachusetts. A four-stroke, air-cooled unit, it had seven cylinders and a variable compression ratio, altered by changing the wobble-plate angle and hence the length of piston stroke. It was called a "rotary engine" because the entire engine rotated apart from the end casings.

Ignition was supplied by a Bosch magneto directly driven from the cam gears. The high voltage current was then taken to a fixed electrode on the front bearing case, from which the sparks would jump to the spark plugs in the cylinder heads as they passed within 1/16 inch from it. According to Macomber's literature, it was "Guaranteed not to overheat".

The engine was claimed to be able to run at 150 to 1,500 rpm. At the normal speed of 1,000 rpm, it reportedly developed 50 hp. It weighed 230 pounds (100 kg) and it was 28 inches (710 mm) long by 19 inches (480 mm) in diameter.

Pioneer aviator Charles Francis Walsh flew an aircraft powered by a Macomber engine in May 1911, the "Walsh Silver Dart".

Statax

In 1913 Statax-Motor of Zurich, Switzerland introduced a swashplate engine design. Only a single prototype was produced, which is currently held in the Science Museum, London. In 1914 the company moved to London to become the Statax Engine Company and planned on introducing a series of rotary engines; a 3 cylinder of 10 hp, a 5 cyl of 40 hp, a 7 cyl of 80 hp, and a 10 cyl of 100 hp.

It appears only the 40 hp design was ever produced, which was installed in a Caudron G.II for the British 1914 Aerial Derby but was withdrawn before the flight. Hansen introduced an all-aluminum version of this design in 1922, but it is not clear if they produced it in any quantity. Much improved versions were introduced by Statax's German division in 1929, producing 42 hp in a new sleeve valve version known as the *29B*. Greenwood and Raymond of San Francisco acquired the patent rights for the US, Canada, and Japan, and planned a 5 cylinder of 100 hp and a 9 cylinder of 350 hp.

Michell

In 1917 Anthony Michell obtained patents for his swashplate engine design. Its unique feature was the means of transferring the load from the pistons to the swashplate, achieved using tilting slipper pads sliding on a film of oil. Another innovation by Michell was his mathematical analysis of the mechanical design, including the mass and motion of the components, so that his engines were in perfect dynamic balance at all speeds.

In 1920 Michell established the Crankless Engines Company in Fitzroy (Australia), and produced working prototypes of pumps, compressors, car engines and aero engines, all based on the same basic design.

The legendary Phil Irving worked for the Crankless Engine Company before his time at HRD.

A number of companies obtained a manufacturing licence for Michell's design. The most successful of these was the British company Waller and Son, who produced gas boosters.

The largest Michell crankless engine was the XB-4070, a diesel aircraft engine built for the US Navy. Consisting of 18 pistons, it was rated at 2000 horsepower and weighed 2150 pounds.

J.O. Almen

Experimental barrel engines for aircraft use were built and tested by Mr J.O. Almen of Seattle in the early 1920s, and by the mid-1920s the water-cooled *Almen A-4* (18 cylinders, two groups of nine each horizontally opposed) had passed its United States Air Corps acceptance tests. It however never entered production, reportedly due to limited funds and the Air Corps' growing emphasis on air-cooled radial engines. The A-4 had much smaller frontal area than water-cooled engines of comparable power output, and thereby offered better streamlining possibilities. It was rated at 425 horsepower (317 kW), and weighed only 749 pounds (340 kg), thus giving a power/weight ratio of better than 1:2, a considerable design achievement at the time.

Heraclio Alfaro

Heraclio Alfaro was a Spanish aviator who was knighted at the age of 18 by King Alfonso XIII of Spain for designing, building, and flying Spain's first airplane. He developed a barrel engine for aircraft use which was later produced by the Indian Motorcycle Company as the *Alfaro*. It was a perfect example of the "put in everything" design, as it included a sleeve valve system based on a rotating cylinder head, a design that never entered production on any engine. It was later developed further for use in the Doman helicopter by Stephen duPont, son of the president of the Indian Motorcycle Company, who had been one of Alfaro's students at MIT.

Bristol

The Bristol Axial Engine of the mid 1930s was designed by Charles Benjamin Redrup for the Bristol Tramways and Carriage Company; it was a 7 litre, 9 cylinder, wobble-plate type engine. It was originally conceived as a power unit for buses, possibly because its compact format would allow it to be installed beneath the vehicle's floor. The engine had a single rotary valve to control induction and exhaust. Several variants were used in Bristol buses during the late 1930s, the engine going through several versions from RR1 to RR4, which had a power output of 145 hp at 2900 rpm. Development was halted in 1936 following a change of management at the Bristol company.

Wooler

Perhaps the most refined of the designs was the British Wooler wobble-plate engine of 1947. This 6 cylinder engine was designed by John Wooler, better known as a motorcycle engine designer, for aircraft use. It was similar to the Bristol axial engine but had two wobble-plates, driven by 12 opposed pistons in 6 cylinders. The engine is often incorrectly referred to as a swashplate engine. A single example is preserved in the Aeroplane Gallery of The Science Museum, London.

H.L.F Trebert

Some small barrel engines were produced by the H.L.F. Trebert Engine Works of Rochester, New York for marine usage.

Present day

Dyna-Cam

The Dyna-Cam engine originally came from a design by the Blazer brothers, who worked for Studebaker in 1916. They sold the rights to Karl Herrmann, Studebaker's head of engineering, who developed the concept over many years, eventually taking out US patent 2237989 in 1941. It has 6 double-ended pistons working in 6 cylinders, and its 12 combustion chambers are fired every revolution of the drive shaft. The pistons drive a sine-shaped cam, as opposed to a swashplate or wobble-plate, hence its name.

In 1961, at the age of 80, Herrmann sold the rights to one of his employees, Dennis Palmer, who set up the Dyna-Cam Engine Corp. The engine was flown for 7 hours in a Piper Arrow in 1987, after which little or nothing happened until 2006 when the assets of the Dyna-Cam Engine Corp were acquired by Axial Vector Engine Corporation. Their engine, like many of the others on this list, suffers from the "put in everything" problem, including piezoelectric valves and ignition, ceramic cylinder liners with no piston rings, and a variety of other advanced features.

Fairdiesel

UK company FairDiesel Limited is designing two stroke diesel opposed piston barrel engines which use non-sinusoidal cams, for industrial applications and aviation use. Their designs range from a 2-cylinder, 80mm bore engine to a 32-cylinder, 160mm bore one.

Honda

After introducing a hydrostatic drive in 2001 for their FourTrax Rubicon ATV, in the DN-01 motorcycle was announced in 2005, and began selling in 2008. It is the first production, road-going vehicle with hydrostatic drive.

Applications

- The most well-known application is in torpedoes, where the cylindrical shape is desirable. The modern Mark 48 torpedo is powered by a 500 hp swashplate engine geared to a pump-jet propulsor. It is fueled by Otto fuel II, a monopropellant that requires no oxygen supply and can propel the torpedo at up to 65 knots (120 km/h) (74.56 mph).

- Other applications include pneumatic and hydraulic motors, hydrostatic transmissions such as Honda's Hondamatic CVT, and air conditioner pumps. Also, some Stirling engines use a swashplate arrangement, e.g. Stirling Thermal Motors' STM 4-120 engine.