Piston Engine Configurations

Kimberely Pipkin

First Edition, 2012

ISBN 978-81-323-4391-2

© All rights reserved.

Published by:
White Word Publications
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1 - Engine Configuration

Chapter 2 - Connecting Rod

Chapter 3 - Napier Deltic

Chapter 4 - Crank (Mechanism)

Chapter 5 - Flat Engine

Chapter 6 - Monobloc Engine

Chapter 7 - Opposed-Piston Engine

Chapter 8 - Piston Valve & H Engine

Chapter 9 - Controlled Combustion Engine

Chapter 10 - Corliss Steam Engine

Chapter 11 - Sleeve Valve

Chapter 12 - Scotch Yoke & Slide Valve

Chapter 13 - Wankel Engine

Chapter 14 - Poppet Valve

Chapter 1

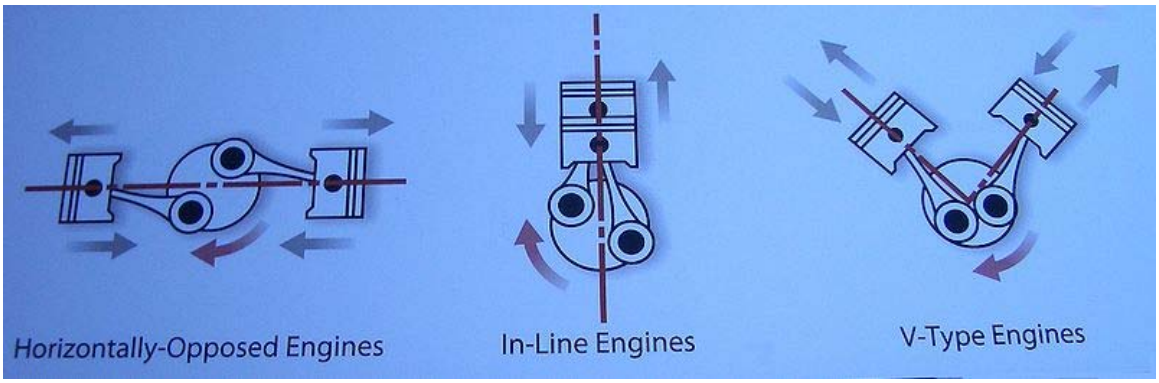
Engine Configuration

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.

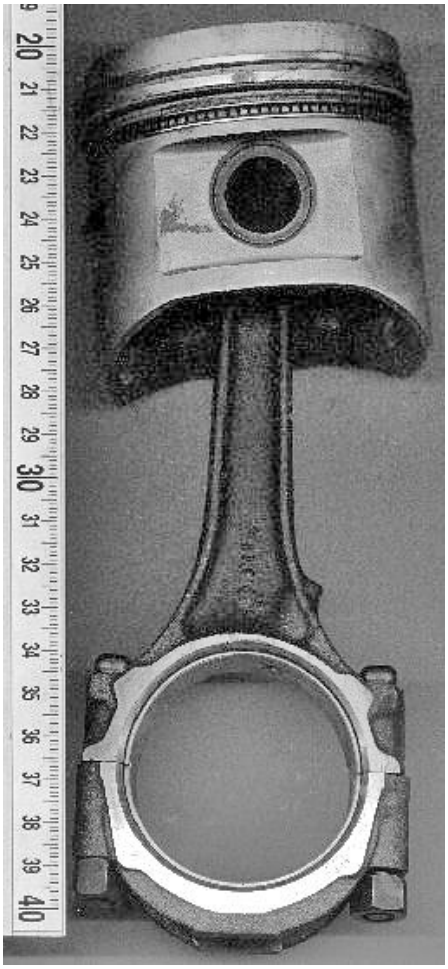
If there are two camshafts in the cylinder head, the cams can sometimes bear directly on cam followers on the valve stems. This is the usual arrangement for a four-valves-per-cylinder design. This latter arrangement is the most inertia free, allows the most unimpeded gas flows in the engine and is the 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 2

Connecting Rod



piston (top) and connecting rod from typical automotive engine (scale is in centimetres)

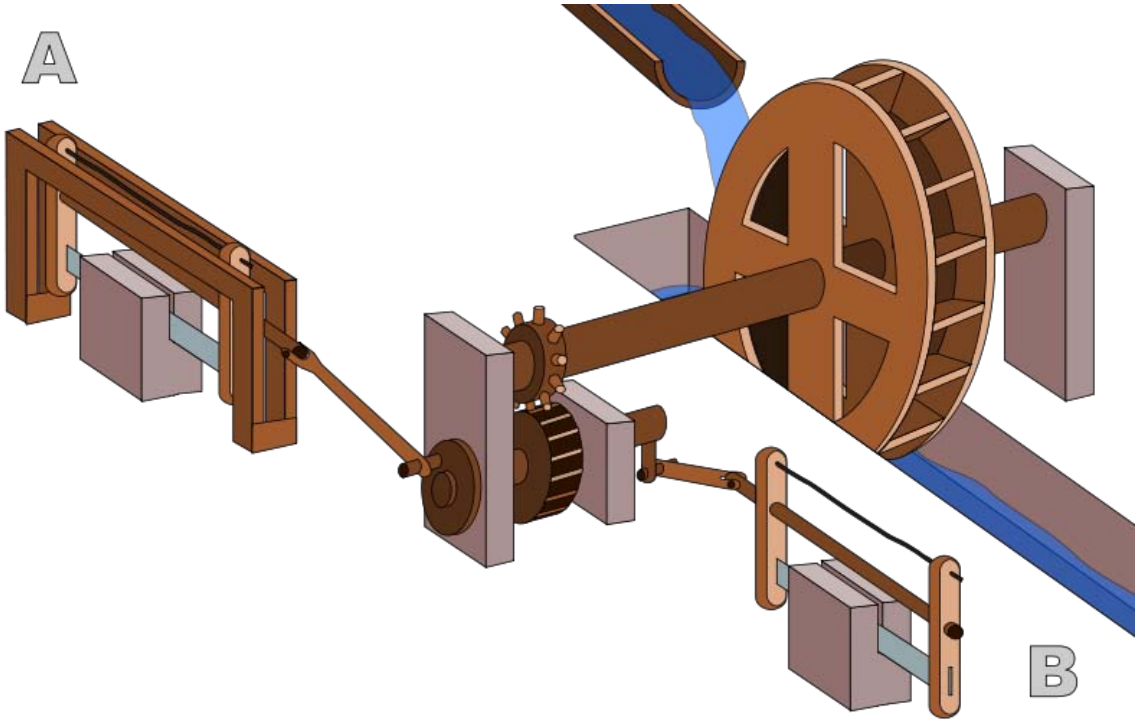
In a reciprocating piston engine, the **connecting rod** or **conrod** connects the piston to the crank or crankshaft. Together with the crank, they form a simple mechanism that converts linear motion into rotating motion.

Connecting rods may also convert rotating motion into linear motion. Historically, before the development of engines, they were first used in this way.

As a connecting rod is rigid, it may transmit either a push or a pull and so the rod may rotate the crank through both halves of a revolution, i.e. piston pushing and piston pulling. Earlier mechanisms, such as chains, could only pull. In a few two-stroke engines, the connecting rod is only required to push.

Today, connecting rods are best known through their use in internal combustion piston engines, such as car engines. These are of a distinctly different design from earlier forms of connecting rods, used in steam engines and steam locomotives.

History



Scheme of the Roman Hierapolis sawmill, the earliest known machine to combine a connecting rod with a crank.

The earliest evidence for a connecting rod appears in the late 3rd century AD Roman Hierapolis sawmill. It also appears in two 6th century Eastern Roman saw mills excavated at Ephesus respectively Gerasa. The crank and connecting rod mechanism of these Roman watermills converted the rotary motion of the waterwheel into the linear movement of the saw blades.

Sometime between 1174 and 1206, the Arab inventor and engineer Al-Jazari described a machine which incorporated the connecting rod with a crankshaft to pump water as part

of a water-raising machine, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion.

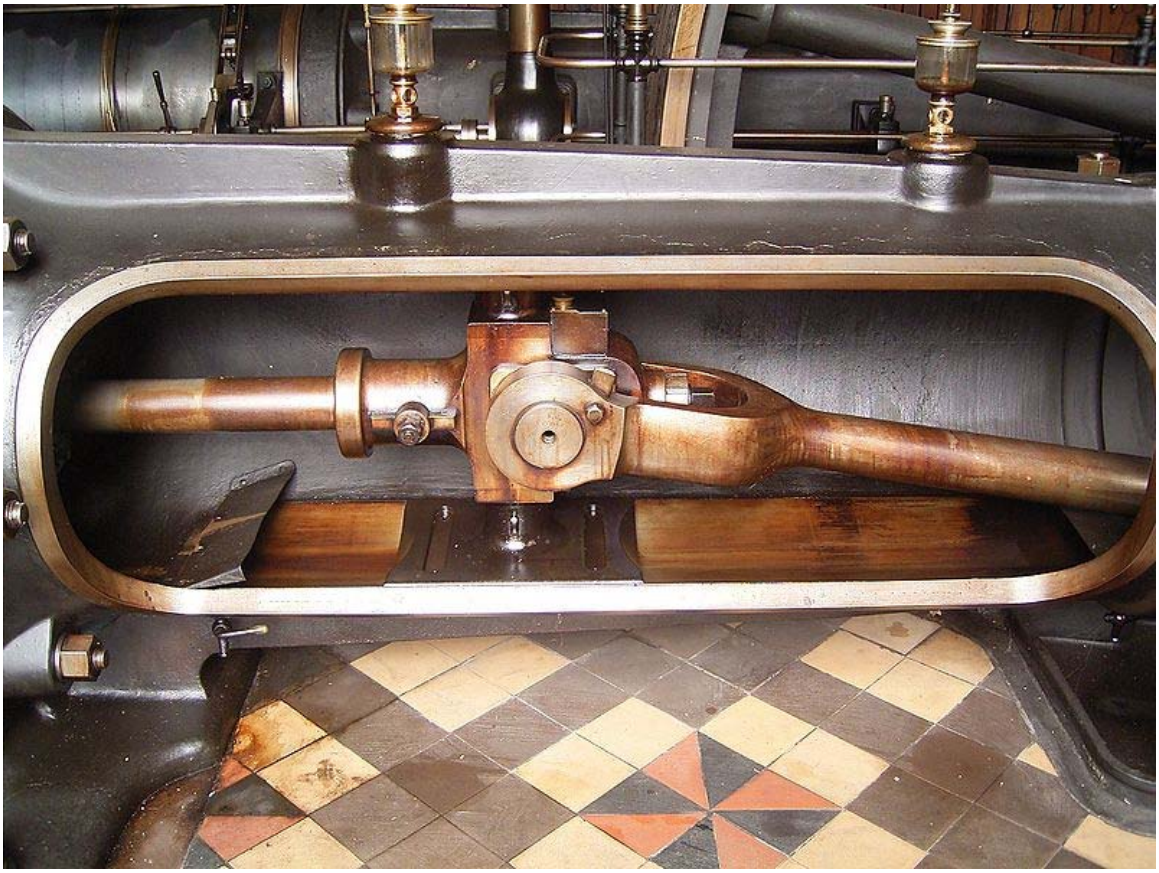
In Renaissance Italy, the earliest evidence of a − albeit mechanically misunderstood − compound crank and connecting-rod is found in the sketch books of Taccola. A sound understanding of the motion involved displays the painter Pisanello (d. 1455) who showed a piston-pump driven by a water-wheel and operated by two simple cranks and two connecting-rods.

By the 16th century, evidence of cranks and connecting rods in the technological treatises and artwork of Renaissance Europe becomes abundant; 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.

Steam engines

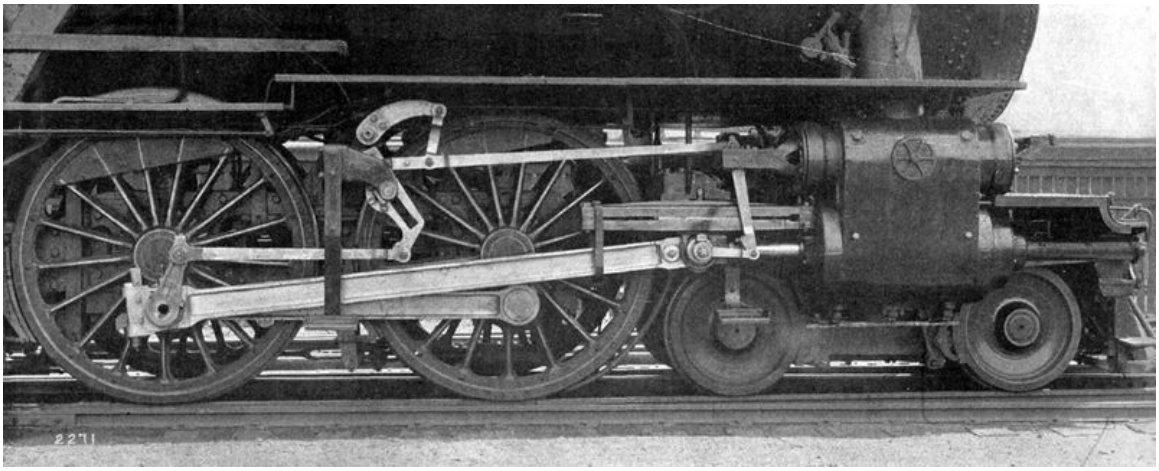
Beam engine, with twin connecting rods (almost vertical) between the horizontal beam and the flywheel cranks

The first steam engines, Newcomen's atmospheric engine, was single-acting: its piston only did work in one direction, and so these used a chain rather than a connecting rod. Their output rocked back and forth, rather than rotating continuously.



Crosshead of a stationary steam engine: piston rod to the left, connecting rod to the right

Steam engines after this are usually double-acting: their internal pressure works on each side of the piston in turn. This requires a seal around the piston rod and so the hinge between the piston and connecting rod is placed outside the cylinder, in a large sliding bearing block called a crosshead.



Steam locomotive rods, the large angled rod being the connecting rod

In a steam locomotive, the crank pins are usually mounted directly on one or more pairs of driving wheels, and the axle of these wheels serves as the crankshaft. The connecting rods, also called the **main rods** (*in US practice*), run between the crank pins and crossheads, where they connect to the piston rods. Crossheads or trunk guides are also used on large diesel engines manufactured for marine service. The similar rods between driving wheels are called **coupling rods** (*in British practice*).

The connecting rods of smaller steam locomotives are usually of rectangular cross-section but, on small locomotives, marine-type rods of circular cross-section have occasionally been used. Stephen Lewin, who built both locomotive and marine engines, was a frequent user of round rods. Gresley's A4 Pacifics, such as *Mallard, had an alloy steel connecting rod with a web that was only 3/8" thick.*

On Western Rivers steamboats, the connecting rods are properly called **pitmans**, and are sometimes incorrectly referred to as pitman arms.

Internal combustion engines

Failure of a connecting rod is one of the most common causes of catastrophic engine failure.

In modern automotive internal combustion engines, the connecting rods are most usually made of steel for production engines, but can be made of T6-2024 and T651-7075

aluminum alloys (for lightness and the ability to absorb high impact at the expense of durability) or titanium (for a combination of lightness with strength, at higher cost) for high performance engines, or of cast iron for applications such as motor scooters. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. Connecting rods, especially in racing engines, may be called "billet" rods, if they are machined out of a solid billet of metal, rather than being cast.

The **small end** attaches to the piston pin, gudgeon pin or wrist pin, which is currently most often press fit into the connecting rod but can swivel in the piston, a "floating wrist pin" design. The **big end** connects to the bearing journal on the crank throw, in most engines running on replaceable bearing shells accessible via the *connecting rod bolts* which hold the bearing "cap" onto the big end. Typically there is a pinhole bored through the bearing and the big end of the connecting rod so that pressurized lubricating motor oil squirts out onto the thrust side of the cylinder wall to lubricate the travel of the pistons and piston rings. Most small two-stroke engines and some single cylinder four-stroke engines avoid the need for a pumped lubrication system by using a rolling-element bearing instead, however this requires the crankshaft to be pressed apart and then back together in order to replace a connecting rod.

The connecting rod is under tremendous stress from the reciprocating load represented by the piston, actually stretching and being compressed with every rotation, and the load increases to the square of the engine speed increase. Failure of a connecting rod, usually called "throwing a rod" is one of the most common causes of catastrophic engine failure in cars, frequently putting the broken rod through the side of the crankcase and thereby rendering the engine irreparable; it can result from fatigue near a physical defect in the rod, lubrication failure in a bearing due to faulty maintenance, or from failure of the rod bolts from a defect, improper tightening. Re-use of rod bolts is a common practice as long as the bolts meet manufacturer specifications. Despite their frequent occurrence on televised competitive automobile events, such failures are quite rare on production cars during normal daily driving. This is because production auto parts have a much larger factor of safety, and often more systematic quality control.

When building a high performance engine, great attention is paid to the connecting rods, eliminating stress risers by such techniques as grinding the edges of the rod to a smooth radius, shot peening to induce compressive surface stresses (to prevent crack initiation), balancing all connecting rod/piston assemblies to the same weight and Magnafluxing to reveal otherwise invisible small cracks which would cause the rod to fail under stress. In addition, great care is taken to torque the connecting rod bolts to the exact value specified; often these bolts must be replaced rather than reused. The big end of the rod is fabricated as a unit and cut or cracked in two to establish precision fit around the big end bearing shell. Therefore, the big end "caps" are not interchangeable between connecting rods, and when rebuilding an engine, care must be taken to ensure that the caps of the different connecting rods are not mixed up. Both the connecting rod and its bearing cap are usually embossed with the corresponding position number in the engine block.

Recent engines such as the Ford 4.6 liter engine and the Chrysler 2.0 liter engine, have connecting rods made using powder metallurgy, which allows more precise control of size and weight with less machining and less excess mass to be machined off for balancing. The cap is then separated from the rod by a fracturing process, which results in an uneven mating surface due to the grain of the powdered metal. This ensures that upon reassembly, the cap will be perfectly positioned with respect to the rod, compared to the minor misalignments which can occur if the mating surfaces are both flat.

A major source of engine wear is the sideways force exerted on the piston through the connecting rod by the crankshaft, which typically wears the cylinder into an oval cross-section rather than circular, making it impossible for piston rings to correctly seal against the cylinder walls. Geometrically, it can be seen that longer connecting rods will reduce the amount of this sideways force, and therefore lead to longer engine life. However, for a given engine block, the sum of the length of the connecting rod plus the piston stroke is a fixed number, determined by the fixed distance between the crankshaft axis and the top of the cylinder block where the cylinder head fastens; thus, for a given cylinder block longer stroke, giving greater engine displacement and power, requires a shorter connecting rod (or a piston with smaller compression height), resulting in accelerated cylinder wear.

Compound rods

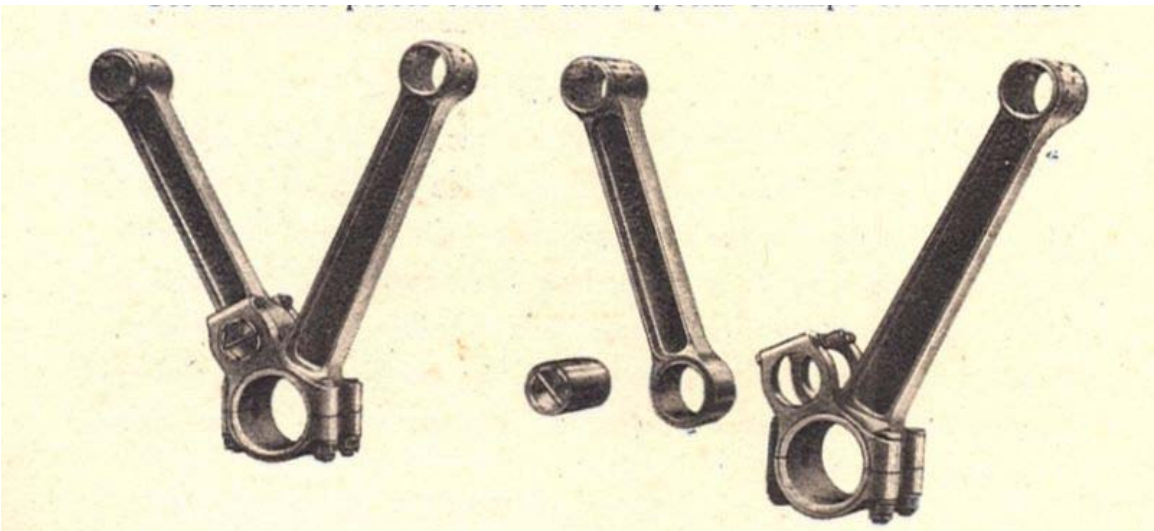


Fig. 5. — Bielles et Biellettes.

Articulated connecting rods

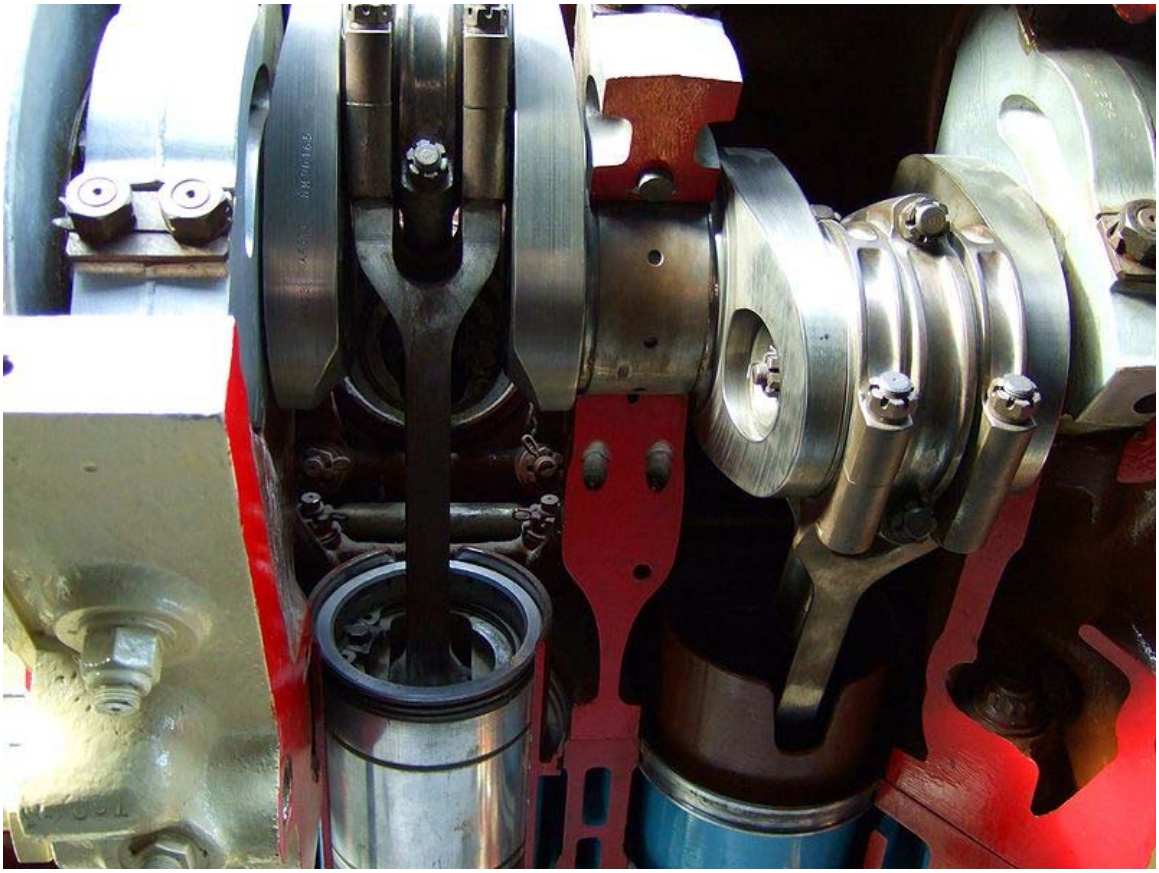
Many-cylinder multi-bank engines such as a V12 layout have little space available for many connecting rod journals on a limited length of crankshaft. This is a difficult compromise to solve and its consequence has often led to engines being regarded as failures (Sunbeam Arab, Rolls-Royce Vulture).

The simplest solution, almost universal in road car engines, is to use simple rods where cylinders from both banks share a journal. This requires the rod bearings to be *narrower*, increasing bearing load and the risk of failure in a high-performance engine. This also means the opposing cylinders are not exactly in line with each other.

In certain engine types, master/slave rods are used rather than the simple type shown in the picture above. The master rod carries one or more ring pins to which are bolted the much smaller big ends of slave rods on other cylinders. Certain designs of V engines use a master/slave rod for each pair of opposite cylinders. A drawback of this is that the stroke of the subsidiary rod is slightly shorter than the master, which increases vibration in a vee engine, catastrophically so for the Sunbeam Arab.

BMW 132 radial aero engine rods

Radial engines typically have a master rod for one cylinder and multiple slave rods for all the other cylinders in the same bank.

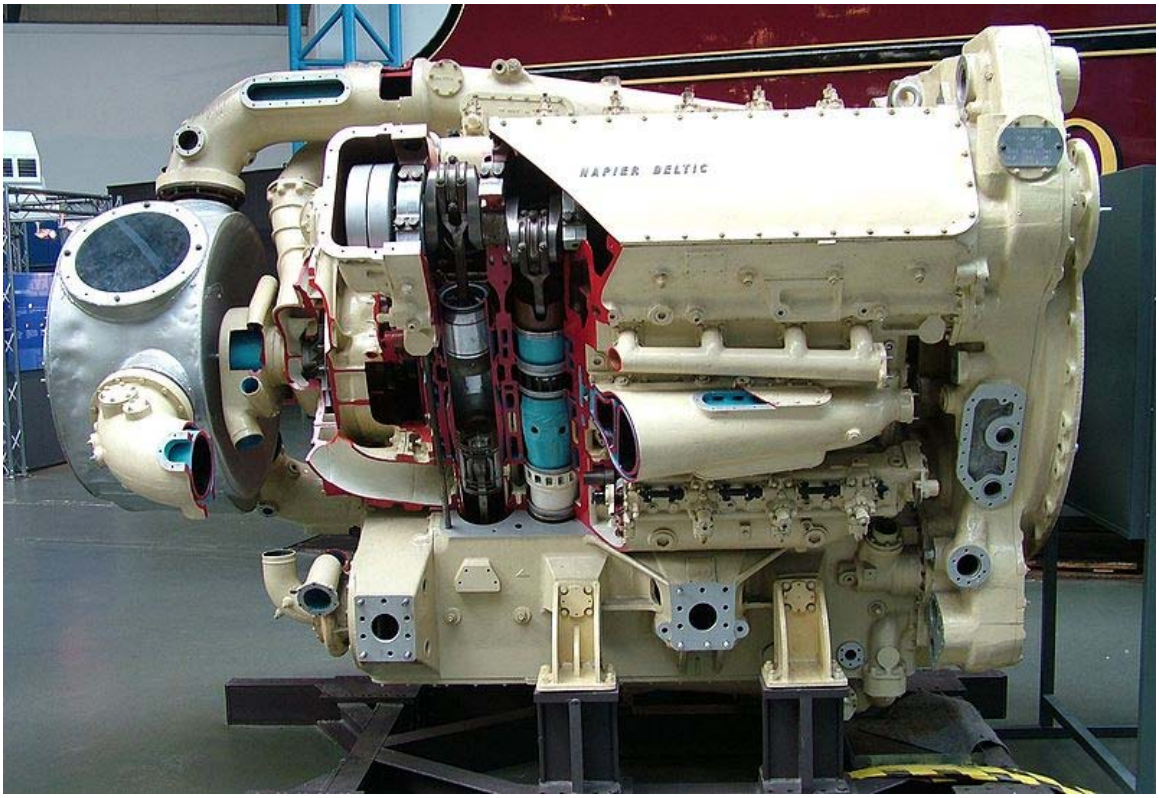


Fork and blade rods of a Napier Deltic

The usual solution for high-performance aero-engines is a "forked" connecting rod. One rod is split in two at the big end and the other is thinned to fit into this fork. The journal is still shared between cylinders. The Rolls-Royce Merlin used this "fork-and-blade" style.

Chapter 3

Napier Deltic



Napier Deltic engine at the National Railway Museum, York, UK

The **Napier Deltic** engine was a British opposed-piston valveless, two-stroke diesel engine used in marine and locomotive applications, designed and produced by Napier & Son. The cylinders were divided in three blocks in a triangular arrangement, the blocks forming sides with crankcases located in each apex of the triangle.

The term Deltic (meaning in the form of the Greek letter Delta) is used to refer to both the *Deltic E.130* opposed-piston high-speed diesel engine and the locomotives produced by English Electric using these engines, including their demonstrator locomotive named

DELTIC and the production version for British Railways, who designated these as (TOPS) Class 55.

A single half-sized, turbocharged Deltic power unit also featured in the English Electric-built Type 2 locomotive, designated as the Class 23. Both locomotive and engine became better known as the "Baby Deltic".

History and design

The Deltic story began in 1943 when the British Admiralty set up a committee to develop a high-power, lightweight diesel engine for Motor Torpedo Boats. Hitherto in the Royal Navy, such boats had been driven by petrol engines but this fuel is highly flammable, making them vulnerable to fire, and at a disadvantage compared with the German diesel-powered E-boats.

Until this time, diesel engines had poor power-to-weight ratio and low speed. Before the war, Napier had been working on an aviation diesel design known as the Culverin after licensing versions of the Junkers Jumo 204. The Culverin was an opposed-piston two-stroke design. Instead of each cylinder having a single piston and being closed at one end with a cylinder head, the Jumo-based design used an elongated cylinder containing two pistons moving in opposite directions towards the centre. This negates the need for a heavy cylinder head, as the opposing piston filled this role. On the downside, the layout required separate crankshafts on either end of the engine, and some form of gearing to take off power and combine it back into a single shaft. The primary advantage of the design was that it led to a rather "flat" engine, intended to be buried in the wings of large aircraft.

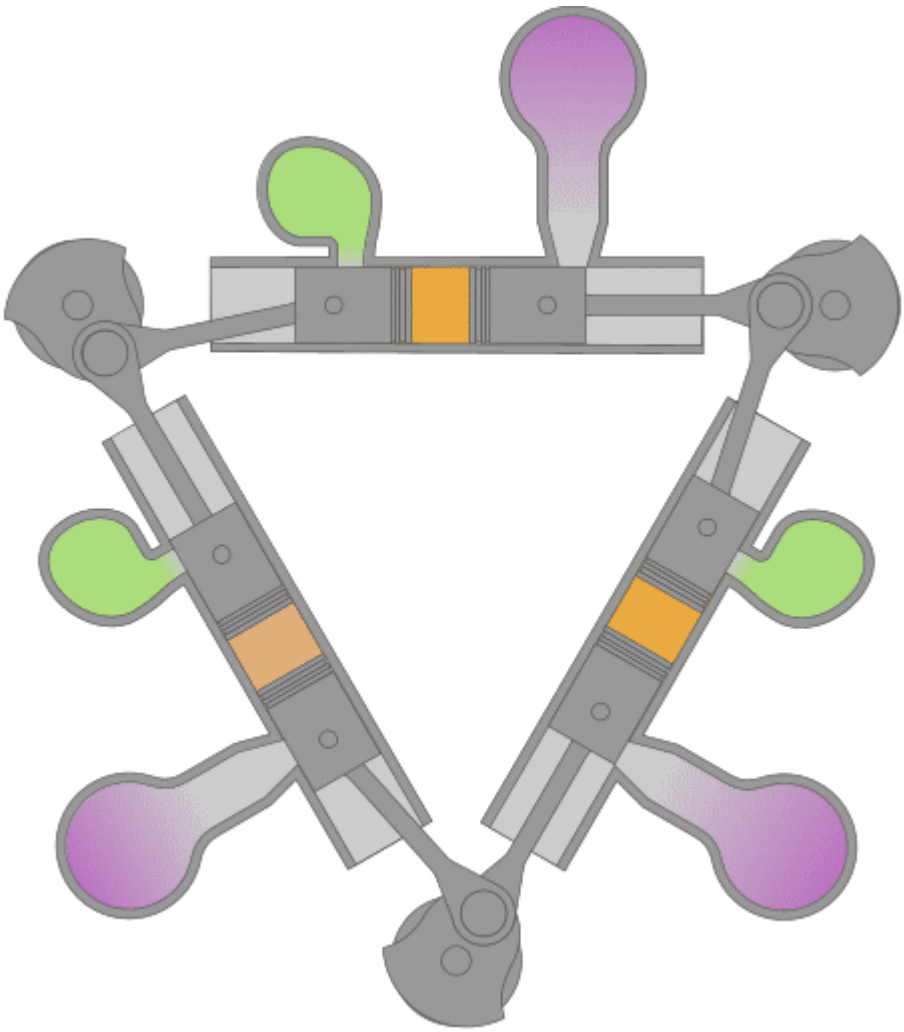


Diagram of Deltic engine layout
Note: The bottom left input and output ports are shown incorrectly as reversed

The Admiralty required a much more powerful engine, and knew about Junkers' designs for multi-crankshaft engines of triangular- and diamond-form. The Admiralty felt these would be a reasonable starting point for the larger design it required. The result was a triangle, the cylinder banks forming the sides, and tipped by three crankshafts, one at each apex. The crankshafts were connected with phasing gears to drive one output shaft. In this arrangement, there were six banks of pistons driving three crankshafts, the same as three separate V-engines of the same overall size. Various models of Deltic engine could be produced with varying numbers of cylinders, though nine and eighteen cylinders were the most common, having three and six cylinders per bank respectively. In 1946, the Admiralty placed a contract with the English Electric Company, parent of Napier, to develop this engine.

One feature of the engine was the way the crankshaft-phasing was arranged to allow for exhaust port lead and inlet port lag. These engines are called 'uniflow' designs because

the flow of gas into and out of the cylinder is one way, assisted by mild supercharging to improve cylinder exhaust scavenging. The inlet/outlet port order is In/Out/In/Out/In/Out going around the triangular ring (i.e. the inlet and outlet manifold arrangements have C_3 rotational symmetry).

Earlier attempts at designing such an engine failed because of the difficulty in arranging the pistons to move in the correct manner, for all three cylinders in one delta, and this was the problem which caused Junkers Motorenbau to leave behind work on the delta-form while continuing to prototype of a diamond-form four-crankshaft 24-cylinder Junkers Jumo 223. Mr. N. Penwarden of the Admiralty Engineering Laboratory solved this problem by suggesting that one crankshaft needed to revolve anti-clockwise to achieve the correct piston-phasing, so Napier designers produced the necessary gearing in order that one of them rotated in the opposite direction to the other two.

In an opposed-piston design with no inlet or exhaust valves, and no ability to vary the port positions, the Deltic design arranged each crankshaft to connect two adjacent pistons operating in different cylinders in the same plane, using "fork and blade" connecting rods, the latter an 'inlet' piston used to open and close the inlet port, and the former an 'exhaust' piston in the adjacent cylinder to open and close the exhaust port.

Crankshaft connecting-rod journals were arranged so that each cylinder's exhaust piston 'led' its inlet piston by 20 degrees of crankshaft rotation. This allowed the exhaust port to be opened well before the inlet port, and allowed the inlet port to be closed after the exhaust port, which led to both good scavenging of exhaust gas, and good volumetric efficiency for the fresh air charge. It also led to Deltics' even, buzzing exhaust note, with a charge ignition every 20 degrees of crankshaft revolution, and a lack of torsional vibration, ideal for use in mine-hunting vessels.

Although the engine was cylinder-ported and required no poppet valves, it did still have camshafts, with each bank having a separate camshaft, driven at crankshaft speed. This was used solely to drive the fuel injection pumps, each cylinder having its own injector and pump, driven by its own cam lobe.

Uses

Naval service

The Deltic-powered Hunt class Mine Countermeasures Vessel HMS *Ledbury*

Development began in 1947 and the first Deltic unit was produced in 1950. By January 1952 six engines were available, enough for full development and endurance trials. S212, a captured ex-German E-Boat powered by three Mercedes-Benz diesel engines, was selected for these trials, since its power units were of approximately equal power to the new 18-cylinder Deltic engines. Two of the three Mercedes-Benz engines were replaced with Napier Deltics, the compactness of the Deltic being graphically illustrated: they were half the size of the original engines. The Deltic weighed one fifth of its contemporaries of equivalent power.

Proving successful, Deltic diesel engines became a common powerplant in small and fast naval craft. The Royal Navy used them first in the Dark class fast attack craft. Subsequently they were used in a number of other smaller attack craft. The low magnetic signature lent itself to use in mine countermeasures vessels and the Deltic was selected to power the Ton class minesweeper. The Deltic engine is still in service in the Hunt class. These versions are de-rated to reduce engine stress.

Deltic diesels served in MTBs and PT Boats built for other navies. Particularly notable was the Norwegian *Tjeld* or *Nasty* class, which was also sold to Germany, Greece, and the United States Navy. *Nasty* class boats served in the Vietnam War, largely for covert operations.

Smaller nine-cylinder *Deltic 9* engines were used as marine engines, notably by minesweepers. The Ton class vessels were powered by a pair of Deltic 18s and used an additional Deltic 9 for power generation for their magnetic influence sweep. The Hunt class used three Deltic 9s, two for propulsion and again one for power generation, but this time with a hydraulic pump integrated as well to power bow-thrusters for slow-speed manœuvring.

Railway use

Napier Deltic powered British Rail Class 55 *Alycidon*, at the National Railway Museum, York, UK

The 'Deltic' engines were used in two types of British rail locomotive: classes 55 and 23, built in the 1960s—both earned the *nom-de-plume* or nickname from the type of engines—"Deltics" and "Baby Deltics" respectively.

The Class 55 used two deltic engines: mechanically-blown 18-cylinder engines, the Class 23 used a single less powerful nine-cylinder turbocharged T9-29 Deltic of 1,100 hp (820 kW).

Reliability in service

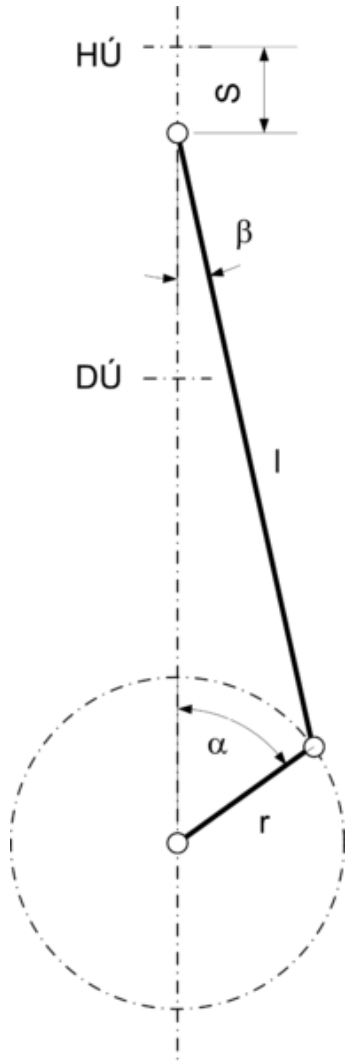
While the Deltic engine was successful and very powerful for its size and weight, it was a highly-strung unit, requiring careful maintenance. This led to a policy of unit replacement rather than repair in situ. Deltic engines were easily removed after breakdown, generally being sent back to the manufacturer for repair, although after initial contracts expired both the Royal Navy and British Railways set up their own workshops for overhauls.

Turbo-compound Deltic

The *E.185* or *Compound Deltic* turbo-compound variant was planned and a single protoype was built in 1956 and tested in 1957. This capitalised on Napier's experience with both the *Nomad* and their increasing involvement with gas turbines. It used the Deltic as the gas generator inside a gas turbine, with both a twelve-stage axial compressor and a three stage gas turbine. Unlike the Nomad, this turbine was not mechanically coupled to the crankshaft but merely drove the compressor. It was hoped to produce 6,000 horsepower, with fuel economy and power-to-weight ratio "second to none". Predictions by the engineers closely connected with it were that connecting rod failure would be the limit on this power, failing at around 5,300 bhp. On test it actually produced 5,600 bhp, before throwing a connecting rod through the crankcase just as predicted. Naval interest had waned by 1958 in favour of the pure gas turbine, despite its heavier fuel consumption, and no further development was carried out.

Chapter 4

Crank (Mechanism)

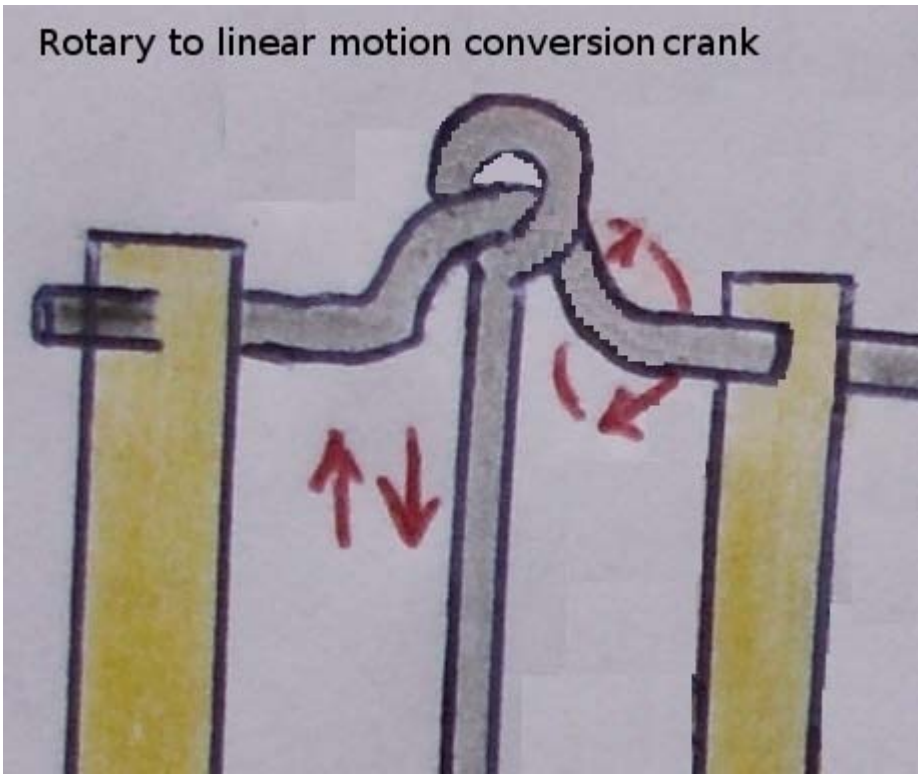


A **crank** is an arm attached at right angles to a rotating shaft by which reciprocating motion is imparted to or received from the shaft. It is used to change circular into reciprocating motion, or reciprocating into circular motion. The arm may be a bent

portion of the shaft, or a separate arm attached to it. Attached to the end of the crank by a pivot is a rod, usually called a connecting rod. The end of the rod attached to the crank moves in a circular motion, while the other end is usually constrained to move in a linear sliding motion, in and out.

The term often refers to a human-powered crank which is used to manually turn an axle, as in a bicycle crankset or a brace and bit drill. In this case a person's arm or leg serves as the connecting rod, applying reciprocating force to the crank. Often there is a bar perpendicular to the other end of the arm, often with a freely rotatable handle on it to hold in the hand, or in the case of operation by a foot (usually with a second arm for the other foot), with a freely rotatable pedal.

Examples



A crank

Hand crank on a pencil sharpener

Familiar examples include:

Hand-powered cranks

- Mechanical pencil sharpener
- Fishing reel and other reels for cables, wires, ropes, etc.
- Manually operated car window
- The crank set that drives a trikke through its handles.

Foot-powered cranks

- The crankset that drives a bicycle via the pedals.
- Treadle sewing machine

Engines

Almost all reciprocating engines use cranks to transform the back-and-forth motion of the pistons into rotary motion. The cranks are incorporated into a crankshaft.

Mechanics

The displacement of the end of the connecting rod is approximately proportional to the cosine of the angle of rotation of the crank, when it is measured from top dead center (TDC). So the reciprocating motion created by a steadily rotating crank and connecting rod is approximately simple harmonic motion:

$$x = l + r\cos\alpha$$

where x is the distance of the end of the connecting rod from the crank axle, l is the length of the connecting rod, r is the length of the crank, and α is the angle of the crank measured from top dead center (TDC). Technically, the reciprocating motion of the connecting rod departs slightly from sinusoidal motion due to the changing angle of the connecting rod during the cycle.

The mechanical advantage of a crank, the ratio between the force on the connecting rod and the torque on the shaft, varies throughout the crank's cycle. The relationship between the two is approximately:

$$\tau = Fr\sin\alpha$$

where τ is the torque and F is the force on the connecting rod. For a given force on the crank, the torque is maximum at crank angles of $\alpha = 90°$ or $270°$ from TDC. When the crank is driven by the connecting rod, a problem arises when the crank is at top dead centre (0°) or bottom dead centre (180°). At these points in the crank's cycle, a force on the connecting rod causes no torque on the crank. Therefore if the crank is stationary and happens to be at one of these two points, it cannot be started moving by the connecting

rod. For this reason, in steam locomotives, whose wheels are driven by cranks, the two connecting rods are attached to the wheels at points 90° apart, so that regardless of the position of the wheels when the engine starts, at least one connecting rod will be able to exert torque to start the train.

History

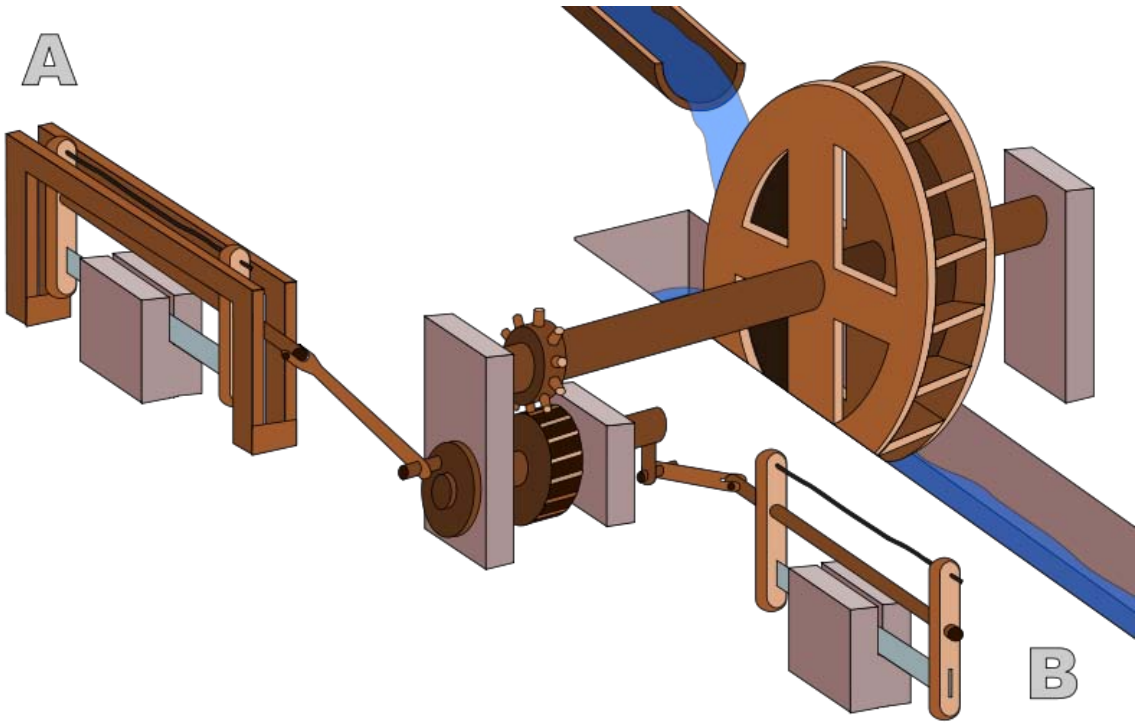
Western World

Classical Antiquity

Roman crank handle from Augusta Raurica, from before 250 AD

The eccentrically mounted handle of the rotary handmill which appeared in 5th century BC Celtiberian Spain and ultimately spread across the Roman Empire constitutes a crank. A ca. 40 cm long true iron crank was excavated, along with a pair of shattered mill-stones of 50−65 cm diameter and diverse iron items, in Aschheim, close to Munich. The crank-operated Roman mill is dated to the late 2nd century AD.

A Roman iron crank handle was excavated in Augusta Raurica, Switzerland. The 82.5 cm long piece with a 15 cm long handle is of yet unknown purpose and dates to no later than ca. 250 AD. An often cited modern reconstruction of a bucket-chain pump driven by hand-cranked flywheels from the Nemi ships has been dismissed though as "archaeological fantasy".



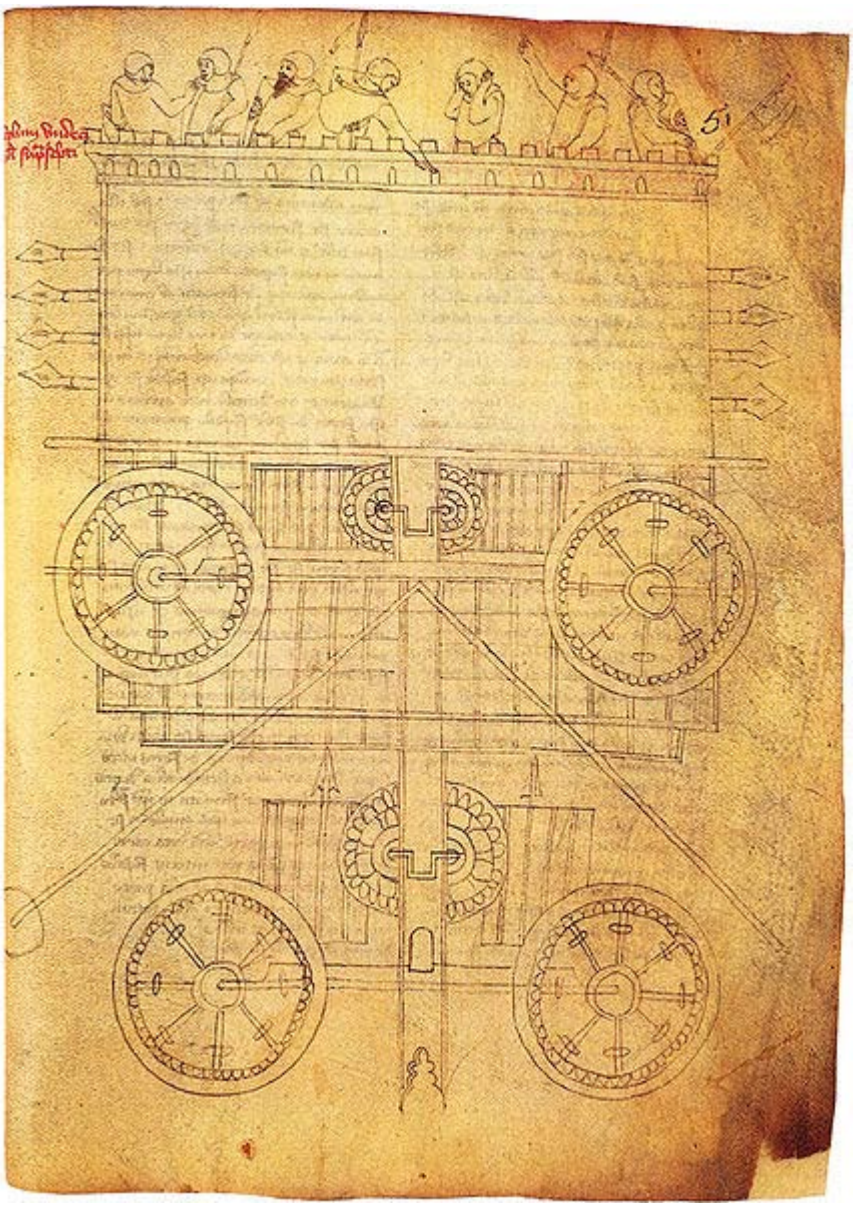
Roman Hierapolis sawmill from the 3rd century AD, the earliest known machine to combine a crank with a connecting rod.

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



Vigevano's war carriage

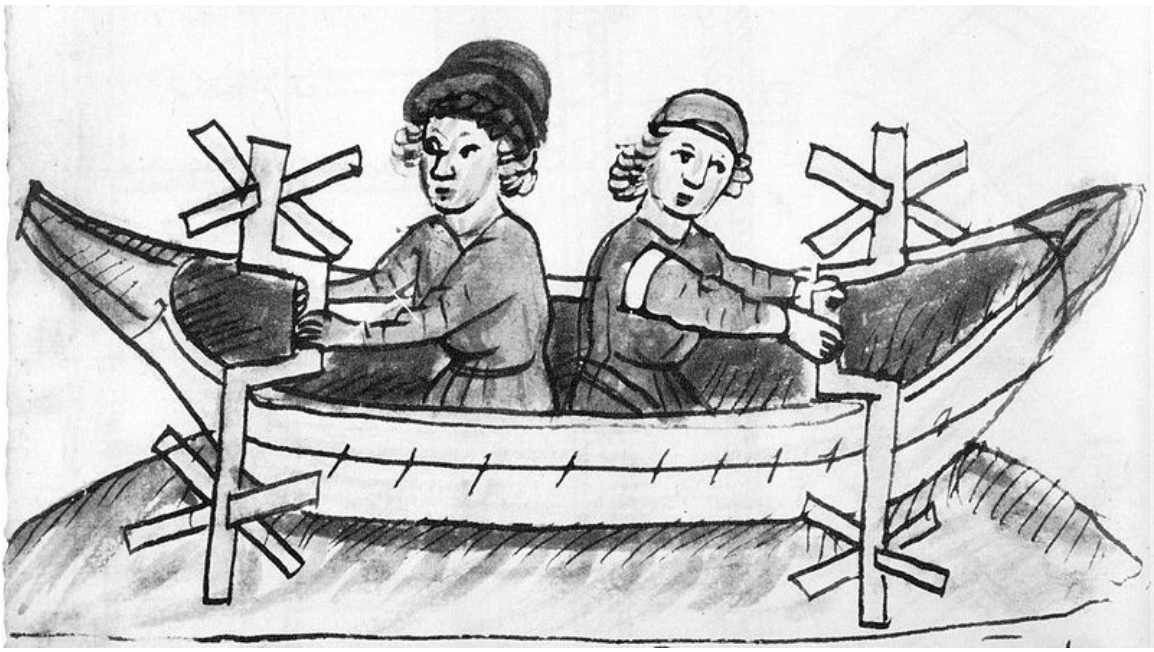
A rotary grindstone − the earliest representation thereof − which is operated by a crank handle is shown in the Carolingian manuscript *Utrecht Psalter*; the pen drawing of around 830 goes back to a late antique original. A musical tract ascribed to the abbot Odo of Cluny (ca. 878−942) describes a fretted stringed instrument which was sounded by a resined wheel turned with a crank; the device later appears in two 12th century illuminated manuscripts. There are also two pictures of Fortuna cranking her wheel of destiny from this and the following century.

The use of crank handles in trepanation drills was depicted in the 1887 edition of the *Dictionnaire des Antiquités Grecques et Romaines* to the credit of the Spanish Muslim surgeon Abu al-Qasim al-Zahrawi; however, the existence of such a device cannot be confirmed by the original illuminations and thus has to be discounted. The Benedictine monk Theophilus Presbyter (c. 1070−1125) described crank handles "used in the turning of casting cores".

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;

Medieval cranes were occasionally powered by cranks, although more often by windlasses.

Renaissance



15th century paddle-wheel boat whose paddles are turned by single-throw crankshafts (Anonymous of the Hussite Wars)

The crank became common in Europe by the early 15th century, often seen in the works of those such as the German military engineer Konrad Kyeser. Devices depicted in Kyeser's *Bellifortis* include cranked windlasses (instead of spoke-wheels) for spanning siege crossbows, cranked chain of buckets for water-lifting and cranks fitted to a wheel of bells. Kyeser also equipped the Archimedes screws for water-raising with a crank handle, an innovation which subsequently replaced the ancient practice of working the pipe by

treading. The earliest evidence for the fitting of a well-hoist with cranks is found in a miniature of c. 1425 in the German *Hausbuch of the Mendel Foundation*.

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'.

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.

Quelle: Deutsche Fotothek

Water-raising pump powered by crank and connecting rod mechanism (Georg Andreas Böckler, 1661)

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.

The 15th century also saw the introduction of cranked rack-and-pinion devices, called cranequins, which were fitted to the crossbow's stock as a means of exerting even more force while spanning the missile weapon. In the textile industry, cranked reels for winding skeins of yarn were introduced.

Around 1480, the early medieval rotary grindstone was improved with a treadle and crank mechanism. Cranks mounted on push-carts first appear in a German engraving of 1589.

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.

Far East

Tibetan operating a quern (1938). The perpendicular handle of such rotary handmills works as a crank.

The earliest true crank handle in Han China occurs, as Han era glazed-earthenware tomb models portray, in a agricultural winnowing fan, dated no later than 200 AD. The crank was used thereafter in China for silk-reeling and hemp-spinning, in the water-powered flour-sifter, for hydraulic-powered metallurgic bellows, and in the well windlass. However, the potential of the crank of converting circular motion into reciprocal one never seems to have been fully realized in China, and the crank was typically absent from such machines until the turn of the 20th century.

Middle East

While the US-American historian of technology Lynn White could not find "firm evidence of even the simplest application of the crank until al-Jazari's book of A.D. 1206", the crank appears according to Beeston in the mid-9th century in several of the hydraulic devices described by the Banū Mūsā brothers in their *Book of Ingenious Devices*. These devices, however, made only partial rotations and could not transmit much power, although only a small modification would have been required to convert it to a crankshaft.

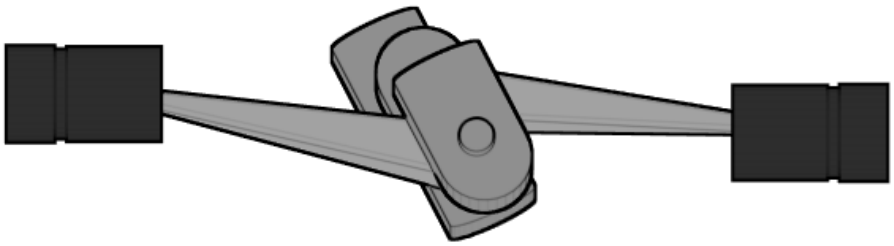
Al-Jazari (1136–1206) described a crank and connecting rod system in a rotating machine in two of his water-raising machines. His twin-cylinder pump incorporated a crankshaft, but the device was unnecessarily complex indicating that he still did not fully understand the concept of power conversion. Another other machine of al-Jazari incorporated the first known crank-slider mechanism.

After al-Jazari, according to White, cranks in Islamic technology are not traceable until an early 15th century copy of the *Mechanics* of the ancient Greek engineer Hero of Alexandria.

Cranks were formerly common on some machines in the early 20th century; for example almost all phonographs before the 1930s were powered by clockwork motors wound with cranks, and internal combustion engines of automobiles were usually started with cranks (known as *starting handles* in the UK), before electric starters came into general use.

Chapter 5

Flat Engine



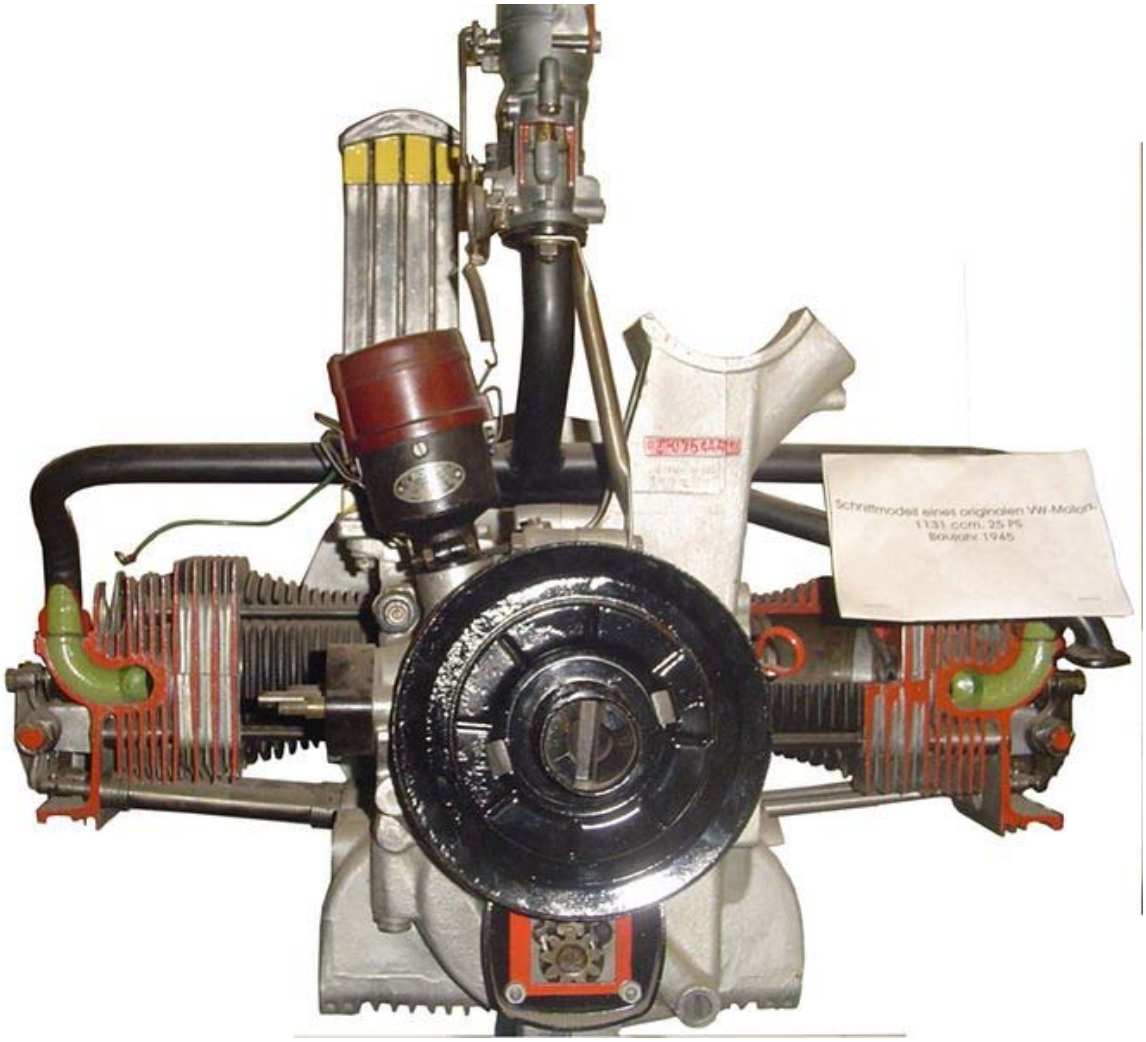
The boxer engine was first patented by German engineer Karl Benz.

A **flat engine** is an internal combustion engine with multiple pistons that move in a horizontal plane. Typically, the layout has cylinders arranged in two banks on either side of a single crankshaft and is generally known as the **boxer**, or horizontally-opposed engine—not to be confused with opposed-piston engines, which are mechanically different. This is the concept patented in 1896 by engineer Karl Benz, eight years after he started producing the world's first successful automobiles.

Another widely used form of flat engine consists of a straight engine with two, three, four or more cylinders canted 90 degrees into the horizontal plane, however this is not generally considered significantly different from other straight engines.

Configuration

1954 BMW "Boxer" motorcycle engine. The two cylinders cannot be directly opposite each other.



The Flat-4 Volkswagen air cooled engine

UL260i Flat-4 aircraft engine

Flat engines offer a low centre of gravity and thereby may offer a drive configuration with better stability and control. They are also wider than other engines configurations, presenting complications with the fitment of the engine within the engine bay of a front-engined car. With motorcycles, the flat engine's width may restrict cornering. Flat engines lend themselves well to aircraft engines.

Front-mounted air-cooled flat-twin engines were used in Tatra 11 and Tatra 30, by Citroën in their model 2CV and its derivatives, while the GS and GSA. Oltcit used a flat-four and a flat-six was proposed for the Citroën DS but rejected. BMW Motorrad used an air-cooled flat-twin in almost all of its motorcycles from 1921 until 1980 and still depends heavily on this layout, using it in many models to the present day. Cars such as the Porsche 911 use a flat-engine (in that particular case a six-cylinder) at the rear of the car, where its extra width does not interfere with the steering of the front wheels and there is a weight-saving since no prop-shaft is required.

All versions of the Subaru Impreza, Forester, Tribeca, Legacy, Outback and SVX use either a flat-4 or flat-6 engine.

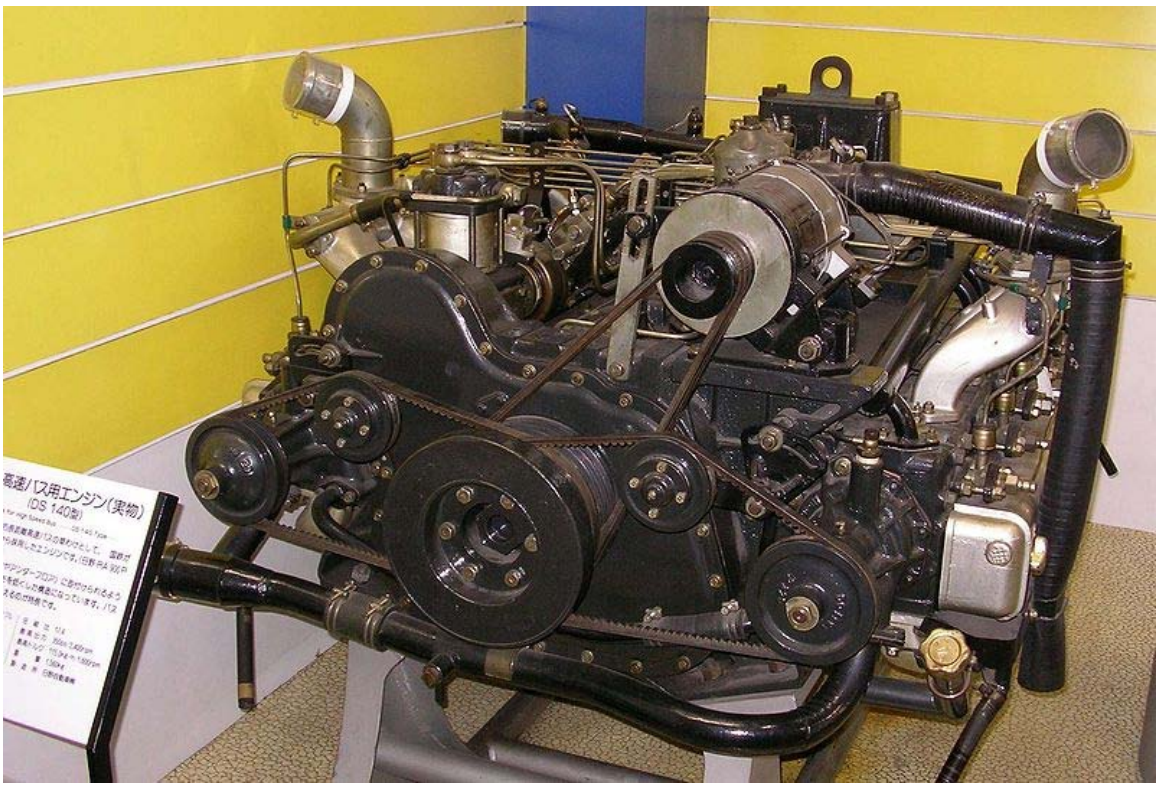
True boxers have each crankpin controlling only one piston/cylinder while 180° engines, which superficially appear very similar, share crankpins.

- The boxer engine (the true horizontally opposed engine) has corresponding pistons reaching top dead centre (TDC) simultaneously.

- The 180° V engine has corresponding pistons sharing a crankpin on the crankshaft and reaching TDC half a crankshaft revolution apart. They may use regular connecting rods side by side, or use a master/slave system, or a fork-and-blade system. Flat engines with more than eight cylinders are most commonly V engines.

Boxer engines must not be confused with opposed-piston engines, which are essentially the inverse, with two pistons compressing a single combustion space. These can be used in vehicles such as tanks.

Boxer engines



1969 Hino Motors DS140 12 cylinder boxer diesel engine

Boxer engines got their name because each pair of pistons moves simultaneously in and out rather than alternately, like boxers showing they are ready by clashing their gloved fists against each other before a fight. Boxer engines of up to eight cylinders have proved highly successful in automobiles and up to six cylinders in motorcycles and continue to be popular for light aircraft engines.

Boxers are one of only three cylinder layouts that have a natural dynamic balance; the others being the straight-6 and the V12. These engines can run very smoothly and free of

unbalanced forces with a four-stroke cycle and do not require a balance shaft or counterweights on the crankshaft to balance the weight of the reciprocating parts, which are required in other engine configurations. Note that this is generally true of boxer engines regardless of the number of cylinders (assumed to be even), but not true for all V or inline engines. However, in the case of boxer engines with fewer than six cylinders, unbalanced moments (a reciprocating torque also known as a "rocking couple") are unavoidable due to the "opposite" cylinders being slightly out of line with each other.

Boxer engines (and flat engines in general) tend to be noisier than other common engines for both intrinsic and other reasons, e.g., in cars, valve clatter from under the hood is not damped by large air filters and other components. Boxers need no balance weights on the crankshaft, which should be lighter and fast-accelerating - but, in practice (e.g. in cars), they need a flywheel to run smoothly at low speeds and this negates the advantage. They have a characteristic smoothness throughout the rev range and offer a low centre of gravity. When combined with a mounting position immediately ahead of the rear axle (e.g. Porsche Boxster and Cayman but not Porsche 911 nor Volkswagen Beetle), they have largely neutral handling.

Notable flat engines

Subaru Boxer Turbodiesel engine cutaway display

- In 1896, Karl Benz invented the first internal combustion engine with horizontally opposed pistons.
- In 1923 Max Friz designed the first BMW motorcycles, choosing a 500 cc boxer engine and unit transmission with shaft drive. This engine type is still in production today. The BMW 247 engine, known as an airhead due to its air cooling, was produced until 1995. BMW replaced it with the oilhead engine with partial oil cooling and four valves per cylinder, but still retaining the same boxer twin configuration.

- In 1948 Preston Tucker modified a helicopter flat-6 to be rear mounted in his Tucker Torpedo
- The Volkswagen air-cooled flat-4 engine used in the Volkswagen Beetle, SP2 and Karmann Ghia, and later developed further for the Volkswagen Type 2 (Bus) transporters and Volkswagen Type 3 cars. VW was rumoured to have worked on a Diesel version of the aircooled boxer but abandoned this engine due to noise and heat issues. The latest version of the VW boxer was watercooled and thus dubbed the 'Wasserboxer' or waterboxer by enthusiasts. This engine included many developments of the earlier engines. It was offered in capacities of 1.9 and 2.1 litres was used to power T3 buses and transporters.
- The Citroën 2CV and Panhard air-cooled flat-2 engines, both influenced by the flat-2s of BMW
- The air-cooled Chevrolet Corvair OHV flat-6
- In 1960 Lancia's flat-4 water-cooled engine debuted for the Lancia Flavia model, first Italian front-wheel drive car, like 1500 cc 90 PS (66 kW) coupé version and during the years become a 2000 cc with 142 bhp (106 kW) when was mounted the first electronic Injection by Bosch in 1970 in a flat four engine, Lancia also rebuild a new big flat-4 engine in 1976, 2484 cc, for his upper size model Lancia Gamma. It was produced until 1984 and was Lancia's last flat-4 engine.
- The flat-4 engines in Alfa Romeo's Alfasud, Sprint, 33 and early versions of the 145. The last of the line was a 1712 cc flat-4, 16 valves, producing up to 137 PS (101 kW).
- The water-cooled front-mounted flat-4 and flat-6 engines used by Subaru in all of its mid-sized cars. Subaru refers to these as boxer engines in publicity commentary, and include a variety of naturally aspirated and turbo driven engines from 1966, when the Subaru 1000 was introduced to current; both closed and semi-closed short blocks have been used. A print add for the 1973 Subaru GL coupe referred to the engine as "quadrozontal" The EJ series of 4 cylinder engines released first in 1990 has been the focus for the development of the Boxer engine in the late 20th century. Ranging from 1.6-2.5 litres, this engine in its 2 litre turbo arrangement has been the power behind World Rally Championship winning cars. Subaru also offers a boxer turbodiesel, called the Subaru EE series, the world's first to be fitted into a passenger car.
- Since its introduction in 1975, the Honda Goldwing has utilized a boxer engine, a 4-cylinder until 1987, and 6-cylinders since. The water-cooled SOHC 1832 cc flat-6 is fitted to the Honda Goldwing from 2001 on.
- The air-cooled flat-4, flat-6 and flat-8 engines were used for many years in early Porsches. The flat-12 in the 917 model is a 180° V-engine and not a boxer.
- The water-cooled flat-6 engines in the Porsche Boxster, Cayman and later 911 models
- General aviation aircraft often use air-cooled flat-4 and flat-6 engines made by companies such as Lycoming, Continental. Ultralight and microlight aircraft often use engines such as the Rotax 912 or Jabiru 2200.
- Ferrari made use of a flat-12 design in several models, including the Berlinetta Boxer, the Testarossa and its derivatives, such as the 512TR and the F512 M,

although this engine design is technically a V12 that has been flattened down to a 180° configuration, and therefore cannot be regarded as a true boxer engine.

Flat engine designs

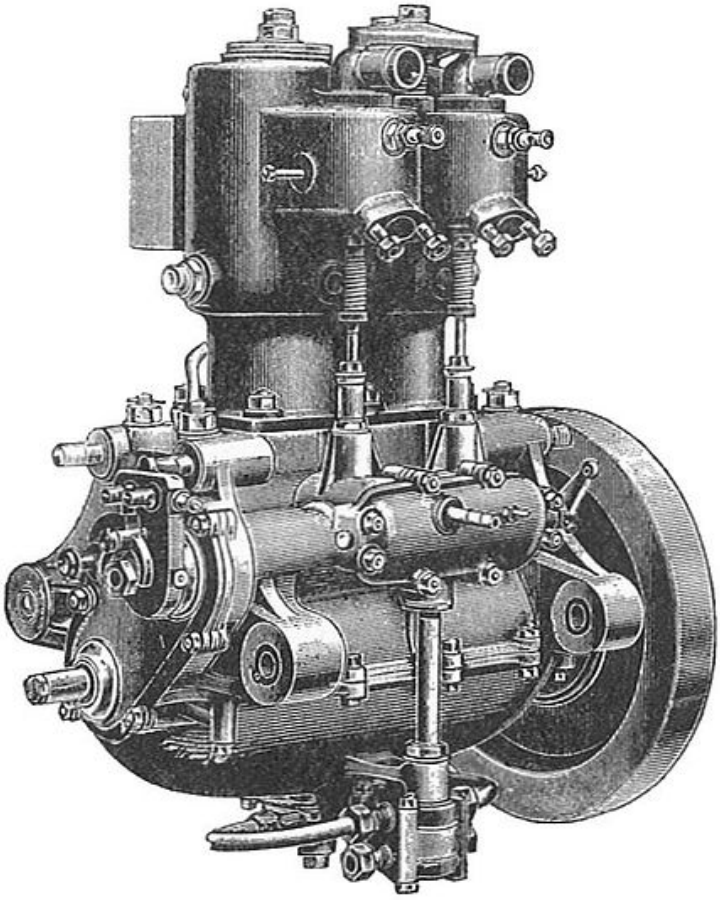
- Flat-twin
- Flat-4
- Flat-6
- Flat-8
- Flat-10
- Flat-12
- Flat-16
- H engine
- Controlled Combustion Engine

Other engine designs

- X engine
- V engine
- W engine
- Straight engine
- Rotary engine

Chapter 6

Monobloc Engine



De Dion-Bouton engine with monobloc cylinder heads, c. 1905

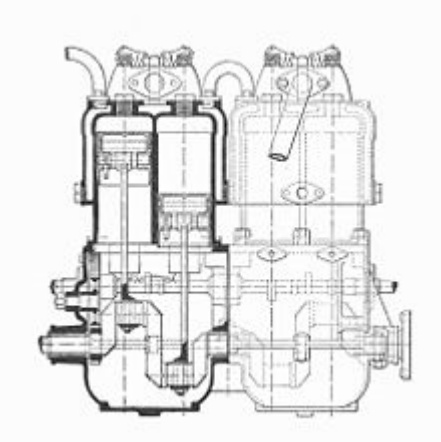
A ***monobloc*** or ***en bloc*** **engine** is an internal-combustion piston engine where some of the major components: cylinder head, cylinder block, or crankcase are formed, usually by casting, as a single integral unit, rather than being assembled later. This has the advantages of improving mechanical stiffness, and also improving the reliability of the sealing between them.

Monobloc techniques date back to the beginnings of the internal combustion engine. Use of the term has changed over time, usually to address the most pressing mechanical problem affecting the engines of its day. There have thus been three distinct uses of the technique:

- Cylinder head and cylinder
- Cylinder block
- Cylinder block and crankcase

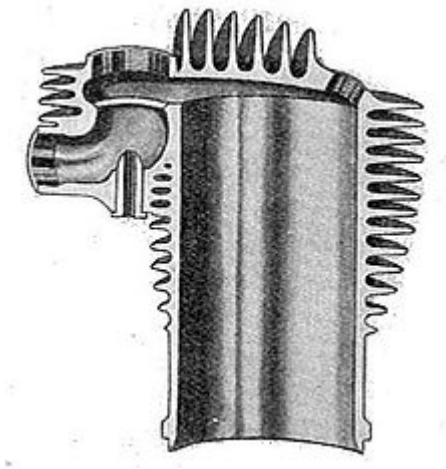
In most cases, any use of the term describes a deliberate single-unit construction, opposed to the more common contemporary practice. Where the monobloc technique has later become the norm, the specific term falls from favour. It is now usual and un-noteworthy practice to use monobloc cylinders and crankcases, but a monobloc head (for a water-cooled inline engine at least) would be regarded as peculiar and obsolescent.

Cylinder head



Napier engine, with monobloc head

DB 605 inverted aircraft engine of WW2, with monobloc cylinder blocks and heads



Sectioned view of an air-cooled single cylinder, with monobloc head and access plug above the side valve

The head gasket is the most highly-stressed static seal in an engine and was a source of considerable trouble in early years. The monobloc cylinder head forms both cylinder and head in one unit, thus avoiding the need for a seal.

Along with head gasket failure, one of the least reliable parts of the early petrol engine was the exhaust valve, which tended to fail by overheating and burning. A monobloc head could provide good water cooling, thus reduced valve wear, as it could extend the water jacket uninterrupted around both head and cylinder. Engines with gaskets required a metal-to-metal contact face here, disrupting water flow.

The drawback to the monobloc head is that access to the inside of the combustion chamber (the upper volume of the cylinder) becomes difficult. Access through the cylinder bore is restricted for machining the valve seats, or simply for inserting angled valves. An even more serious restriction is that for the maintenance task of de-coking and re-grinding the valve seats, a regular task on older engines. Rather than removing the cylinder head from above, the mechanic must now remove pistons, connecting rods and the entire crankshaft from beneath.

One solution to this for side-valve engines was to place a screwed plug directly above each valve, and to access the valves through this (illustrated). The tapered threads of the screwed plug provided a reliable seal. For low-powered engines this was a popular solution for some years. It was difficult to cool this plug, as the water jacket didn't extend into the plug. As performance increased, it also became important to have better combustion chamber designs with less "dead space". One solution was to place the spark plug in the centre of this plug, which at least made use of the space. However this also placed the spark plug further away from the main combustion chamber, leading to long flame paths and slower ignition.

During World War 1, development of the internal combustion engine progressed enormously. After the war, as civilian car production recommenced, the monobloc

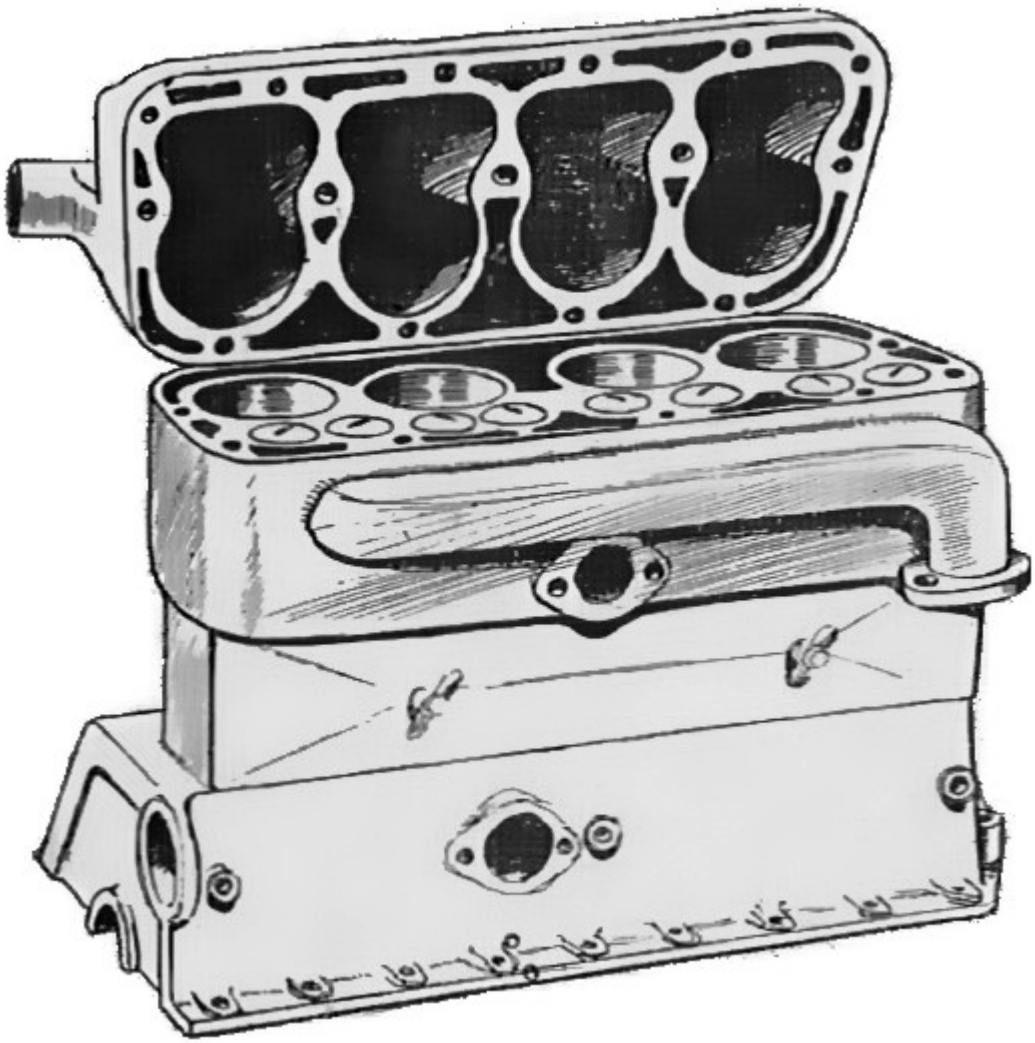
cylinder head was required less frequently. Only high-performance cars such as the Leyland Eight of 1920 persisted with it. Bentley and Bugatti were other racing marques who notably adhered to them, through the 1920s and into the 1930s.

Aircraft engines at this time were beginning to use high supercharging pressures, increasing the stress on their head gaskets. Engines such as the Rolls-Royce Buzzard used monobloc heads for reliability.

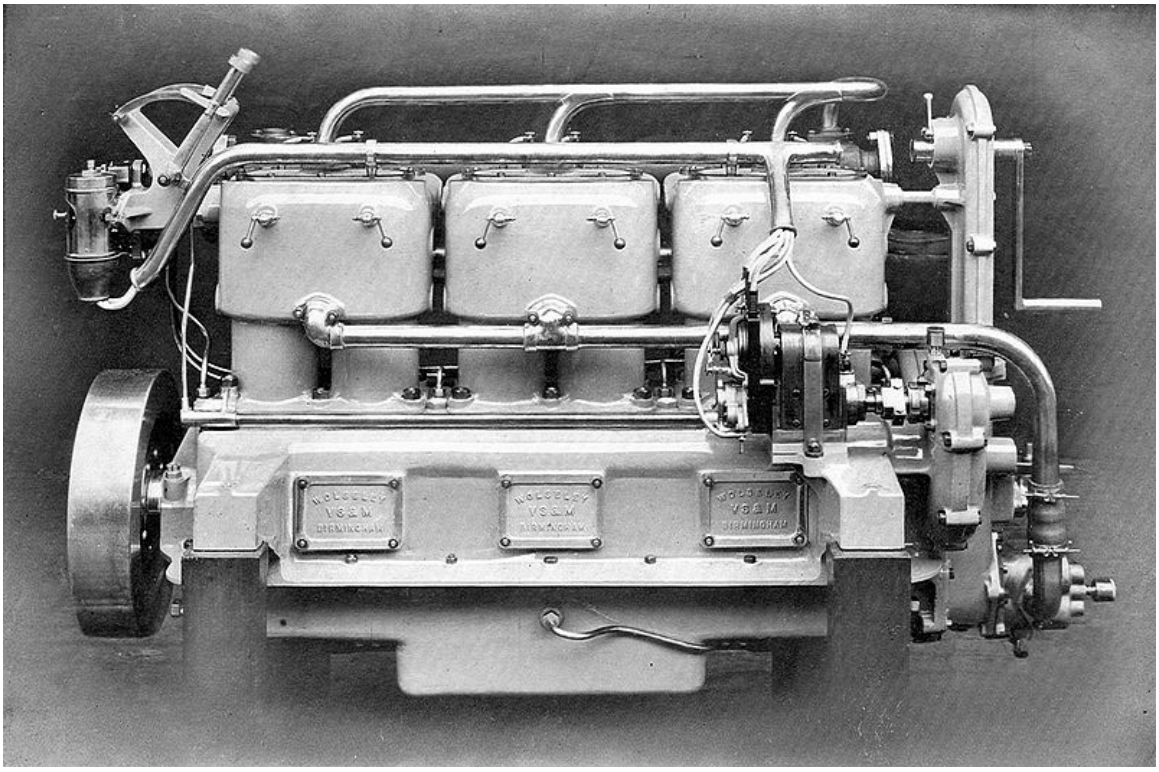
The last engines to make widespread use of monobloc cylinder heads were large air-cooled aircraft radial engines, such as the Wasp Major. These have individual cylinder barrels, so access as a monobloc is less restricted than on inline engine. As they are also of high specific power and require the utmost reliability, the advantages of the monobloc remained attractive.

The difficulties of machining, and maintaining, a monobloc cylinder head were always a severe drawback to it. As head gaskets became able to handle the heat and pressure necessary, the technique went out of use. It is almost unknown today.

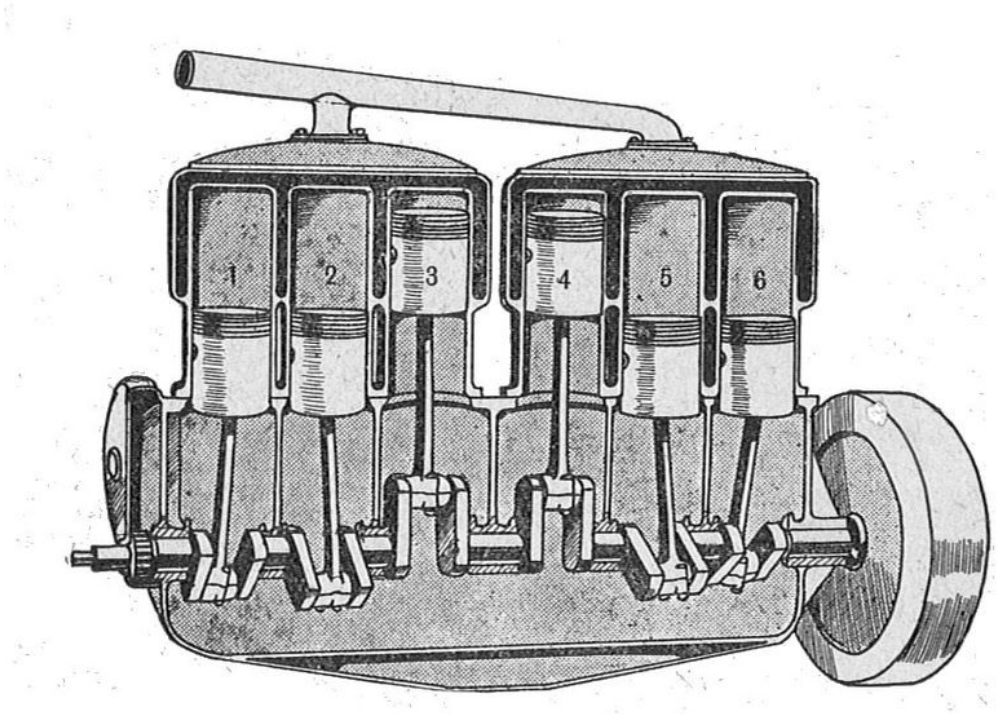
Cylinder block



Early monobloc engine: All cylinders are cast together with the crankcase



Non-monobloc engine: cylinders are cast in three pairs



Non-monobloc engine: cylinders are cast in two blocks of three

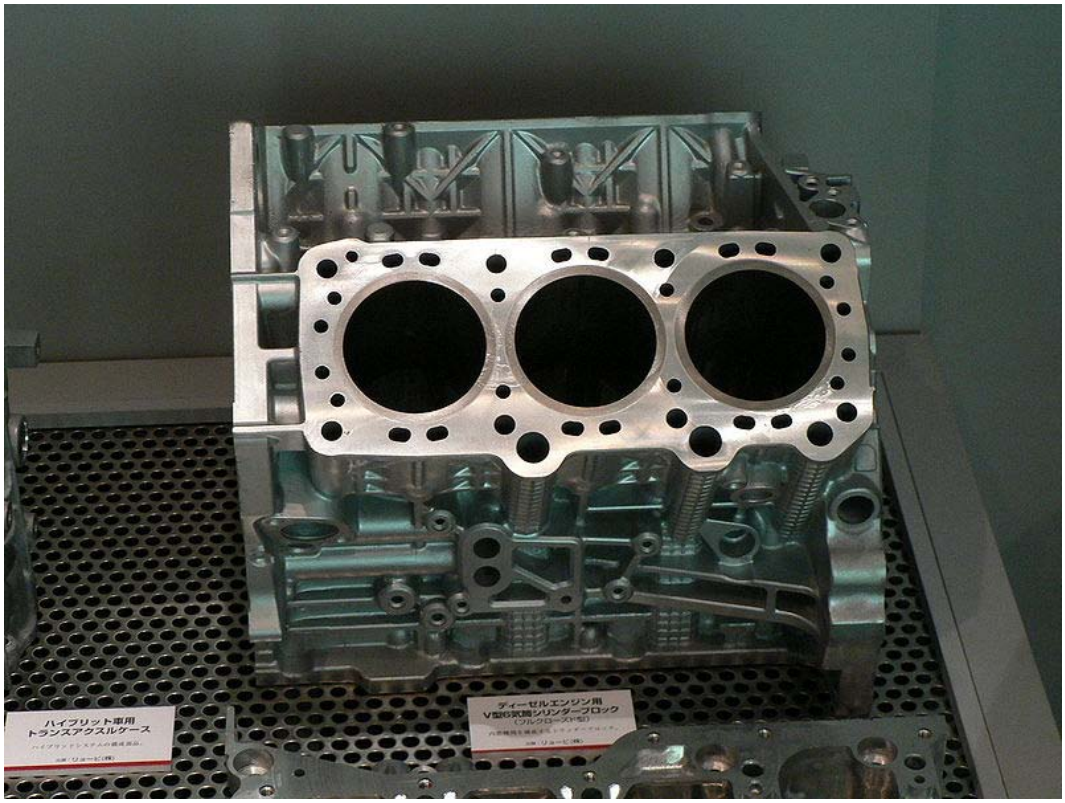
Casting technology at the dawn of the internal combustion engine could reliably cast either large castings, or castings with complex internal cores to allow for water jackets, but not both simultaneously. Most early engines, particularly those with more than four cylinders, had their cylinders cast as pairs or triplets of cylinders, then bolted to a single crankcase.

As casting techniques improved, the entire cylinder block of four, six or even eight cylinders could be cast as one. This was a simpler construction, thus cheaper to make, and the communal water jacket permitted closer spacing between cylinders. This also improved the mechanical stiffness of the engine, against bending and the increasingly important torsional twist, as cylinder numbers and engine lengths increased.

V engines remained with a separate block casting for each bank. For economy, some engines were designed to use identical castings for each bank, left and right. The complex ducting required for inlet manifolds between the banks were too complicated to cast otherwise. Some rare engines, such as the Lancia 22½° narrow-angle V12 of 1919, did use a single block casting for both banks.

Modern cylinders, except for air-cooled engines and V engines, are now universally cast as a single cylinder block.

Crankcase



A V6 diesel engine, with both blocks and crankcase formed *en bloc*

As casting improved and cylinder blocks became a monobloc, it also became possible to cast both cylinders and crankcase as one unit. The main reason for this was to improve stiffness of the engine construction, reducing vibration and permitting higher speeds.

Most engines, except some V engines, are now a monobloc of crankcase and cylinder block.

Modern engines - Combined block, head and crankcase

Light-duty consumer-grade Honda GC-family small engines use a monobloc design where the cylinder head, block, and half the crankcase share the same casting, termed 'uniblock' by Honda. One reason for this, apart from cost, is to produce an overall lower engine height. Being an air-cooled OHC design, this is possible thanks to current aluminum casting techniques and lack of complex hollow spaces for liquid cooling. The valves are vertical, so as to permit assembly in this confined space. On the other hand, performing basic repairs becomes so time-consuming that the engine can be considered disposable. Commercial-duty Honda GX-family engines (and their many popular knock-offs) have a more conventional design of a single crankcase and cylinder casting, with a separate cylinder head.

Honda produces many other head-block-crankcase monoblocs under a variety of different names, such as the GXV-series. They may all be externally identified by a gasket which would bisect the crankshaft on an approximately 45° angle.

Exhaust valve failure is common and, owing to the monobloc design, so labour-intensive to repair that the engine is normally discarded.

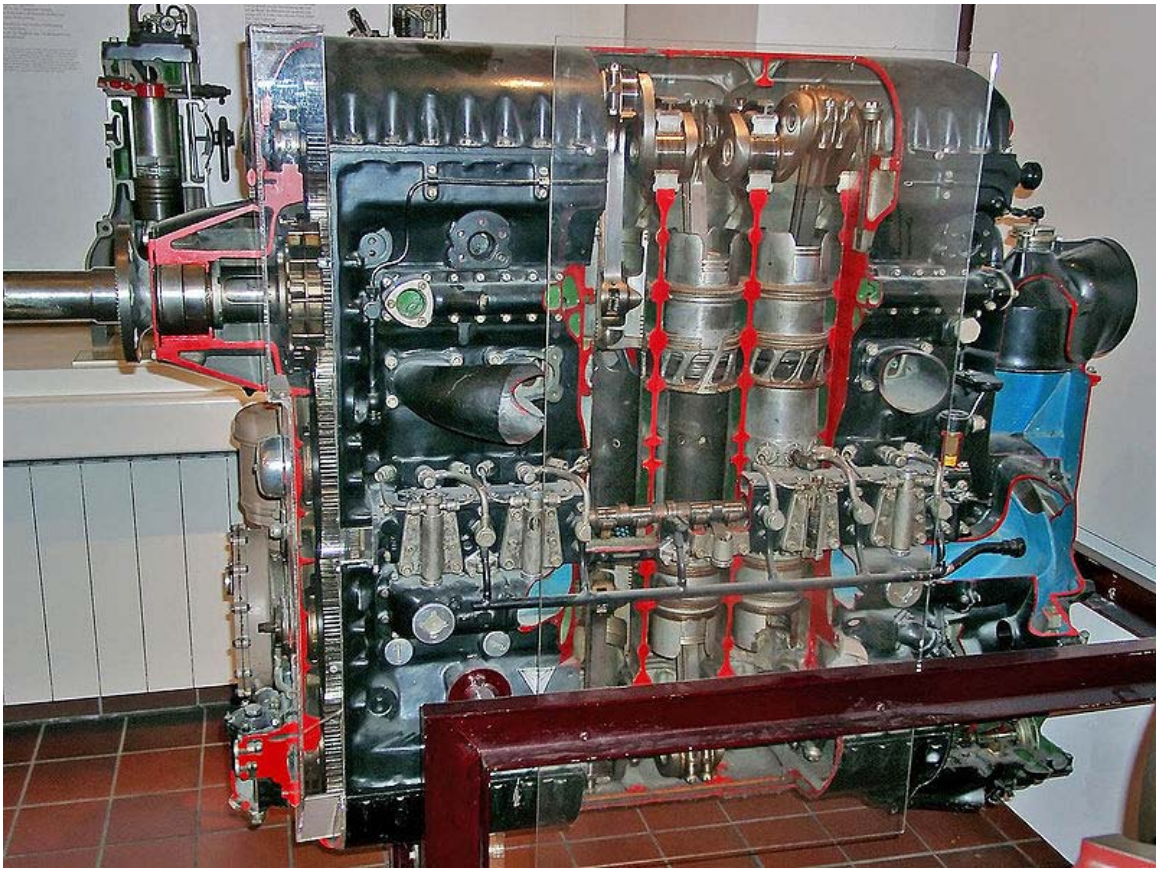
Chapter 7

Opposed-Piston Engine

Fairbanks-Morse opposed-piston diesel engines on the submarine *USS Pampanito*.

An **opposed-piston engine** is one in which the cylinders are double-ended, with a piston at each end and no cylinder head.

Configurations



Junkers Jumo 205 aircraft engine

Some variations of the Opposed Piston or OP designs use a single crankshaft like the Doxford ship engines and the Commer OP truck engines. They should not be confused with flat engines. Though flat engines are sometimes referred to as horizontally opposed, they are very different mechanically.

A more common layout uses two crankshafts, with the crankshafts geared together, or even three geared crankshafts in the Napier Deltic diesel engines. The Deltic uses three crankshafts serving three banks of double-ended cylinders arranged in an equilateral triangle, with the crankshafts at the corners. These were used in railway locomotives and to power fast patrol boats. Both types are now largely obsolete, although the Royal Navy still maintains some Deltic-powered Hunt class mine countermeasure vessels.

The first opposed-piston diesel engines were developed in the beginning of 20th century. In 1907, Raymond Koreyvo, the engineer of Kolomna Works, built an opposed-piston two-stroke diesel with two crankshafts connected by gearing. Although Koreyvo patented his engine in France in November, 1907, the management would not go on to manufacture opposed-piston engines.

An April, 1950 print advertisement for Fairbanks-Morse opposed-piston engines, touting their greater thermodynamic efficiency and lower maintenance cost than standard configurations

The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently a resurgence of this design in a boxer configuration as a small diesel aircraft engine, and for other application, called the 'OPOC' engine by Advanced Propulsion Technologies, Inc. of California. Later Junkers engines like the Junkers Jumo 205 diesel aircraft engine, use two crankshafts, one at either end of a single bank of cylinders. There are efforts to reintroduce the opposed-

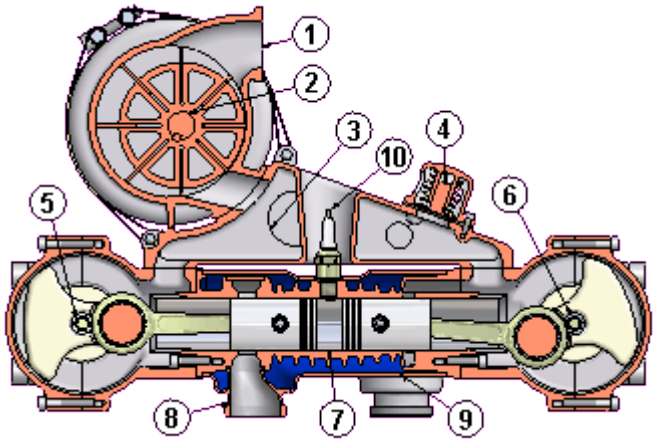
piston diesel aircraft engine with twin geared crankshafts for General aviation applications, by both Dair and PowerPlant Developments in the UK.

This configuration has also been used for marine auxiliary generators and for larger marine propulsion engines, notably Fairbanks-Morse diesel engines used in both conventional and nuclear US submarines. Fairbanks-Morse also used it in diesel locomotives starting in 1944. With the addition of a supercharger or turbocharger, opposed-piston designs can make very efficient two-stroke cycle Diesel engines. Attempts were made to build non-diesel 4-stroke engines, but as there is no cylinder head, the bad location of the valves and the spark plug makes them inefficient.

Koreyvo, Jumo and Deltic engines used one piston per cylinder to expose an intake port, and the other to expose an exhaust port. Each piston is referred to as either an *intake piston* or an *exhaust piston* depending on its function in this regard. This layout gives superior scavenging, as gas flow through the cylinder is axial rather than radial, and simplifies design of the piston crowns. In the Jumo 205 and its variants, the upper crankshaft serves the exhaust pistons, and the lower crankshaft the intake pistons. In designs using multiple cylinder banks, such as the Junkers Jumo 223 and the Deltic, each big end bearing serves one inlet and one exhaust piston, using a forked connecting rod for the exhaust piston.

The Doxford Engine Works of the UK designed and built very large opposed-piston engines for marine use. These engines differ in design from Jumo and Fairbanks-Morse engines by having external connecting rods outside the cylinder linking the upper and lower pistons, thus requiring only a single crankshaft. The first engine of this type was developed by Karl Otto Keller in 1912. Doxford obtained a sole UK license from Oechelhauser and Junkers to build this design of engine. After World War I, these engines were produced in a number of models, such as the P and J series, with outputs as high as 20,000 horsepower (15,000 kW). Certain models were license-built in the US. Production of Doxford engines in the UK ceased in 1980.

Assembly and function



An example of an opposed-piston engine.
1 intake for the fuel-air mixture
2 supercharger (here: rotary vane pump; original: Centrix)
3 airbox to buffer and distribute the mixture
4 waste valve to limit the pressure level
5 outlet crank mechanism (runs app. 20° past the outlet to achieve an asymmetric control diagram)
6 inlet crank mechanism
7 cylinder with inlet and outlet slots
8 exhaust
9 water cooling jacket
10 sparkplug
.

Shown (at right) is the layout of a two-stroke engine similar to the one developed by engineer Kurt Bang at the Prüssing Office on the basis of the prewar DKW race engine. There existed two versions: one with a displacement of 250 cm^3 (15 cu in), and one with 350 cm^3 (21 cu in) displacement. The engine had two cylinders with four pistons, two crankshafts and a supercharger. The crankshafts were connected by gears.

The supercharger takes in the fuel-air mixture, compressing it and pushing it into the airbox. From here it reaches the crank housings. On the outlet side it cools the thermically high loaded piston. After ignition the pistons move outwards, performing the power stroke. At first, the outlet piston opens its slots in the cylinder. The remaining pressure accelerates the gas column towards the exhaust. Then the other piston opens the inlet slots. The pressurized fresh mixture pushes the remaining waste gas out. While the inlet is still opened, the outlet is closed. The supercharger forces additional gas into the cylinder until the inlet slots are closed by the piston. Then the compression stroke starts and the cycle repeats. This type of two cycle system is similar to the famous Grey Marine Diesel, later to be known as the GM Diesel (Detroit Diesel). Production ceased in 1998 but the U.S. and British Militaries still purchase remanufactured engines on occasion.

Free-piston engine

An interesting variation on the opposed-piston engine is the free-piston engine which was patented in 1934 by Raúl Pateras de Pescara. It has no crankshaft and the pistons are returned after each firing stroke by compression and expansion of air in a separate cylinder. Early applications were for use as an air compressor or as a gas generator for a gas turbine, such as the Pratt & Whitney PT1 design. There is now renewed interest in it for powering vehicles by using it to drive a linear alternator.

Other notable opposed-piston engines

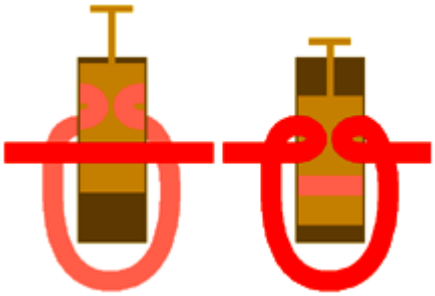
- Junkers Jumo 205.
- Commer TS3 "The Commer Knocker" commercial vehicle engine.
- Leyland L60 tank engine, used in the Chieftain tank.Similar in layout to the Junkers Jumo 205 and Napier Culverin.
- Rolls-Royce K60 engine, smaller and improved version of the L60 used in the FV430 series armoured fighting vehicles and Swedish tank Strv 103.

- Napier Deltic.
- Soviet engine 5TDF used on tank T-64.
- Soviet engine 6TD used on tanks T-80UD, T-84 and Al-Khalid.

Chapter 8

Piston Valve & H Engine

Piston Valve



Piston valve in a brass instrument

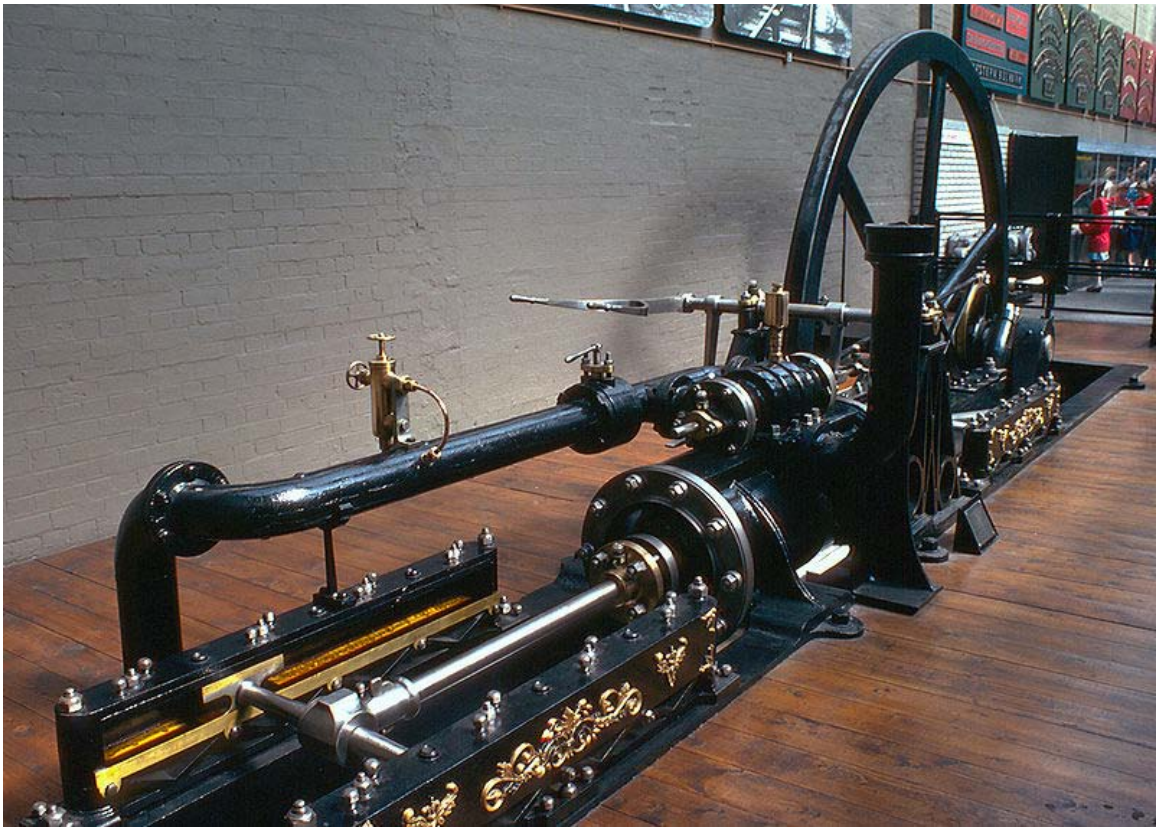
Piston check valve

A '**piston valve'** is a device used to control the motion of a fluid along a tube or pipe by means of the linear motion of a piston within a chamber or cylinder.

Examples of piston valves are:

- The valves used in the valve gear of many stationary steam engines and most steam locomotives.
- The valves used in many brass instruments.
- The valves used in pneumatic cannons.

Steam engines



The Swannington incline winding engine of 1833 incorporated a piston valve

The Swannington incline winding engine on the Leicester and Swannington Railway, manufactured by The Horsely Coal & Iron Company in 1833, shows a very early use of the piston valve. Piston valves had been used a year or two previously in the horizontal engines manufactured by Taylor and Martineau of London, but did not become general for stationary or locomotive engines until the end of the 19th century.

In the 19th century, most steam locomotives used slide valves to control the flow of steam into and out of the cylinders. In the 20th century, slide valves were gradually superseded by piston valves, particularly in engines using superheated steam. There were two reasons for this:

- With piston valves, the steam passages can be made shorter. This reduces resistance to the flow of steam and improves efficiency
- It is difficult to lubricate slide valves adequately in the presence of superheated steam

The usual locomotive valve gears, *e.g.*, the Stephenson valve gear, Walschaerts valve gear, and Baker valve gear, can be used with either slide valves or piston valves. Where poppet valves are used, a different gear, such as Caprotti valve gear is needed.

Brass instruments

First piston valve of a B ♭ trumpet

Cylindrical piston valves called Perinet valves (after their inventor, François Perinet), are used to change the length of tube in the playing of most brass instruments, particularly the trumpet-like members of the family (cornet, flugelhorn, saxhorn, etc.).

Other brass instruments use rotary valves. notably the orchestral horns and many tuba models, but also a number of rotary-valved variants of those brass instruments which more commonly employ piston valves.

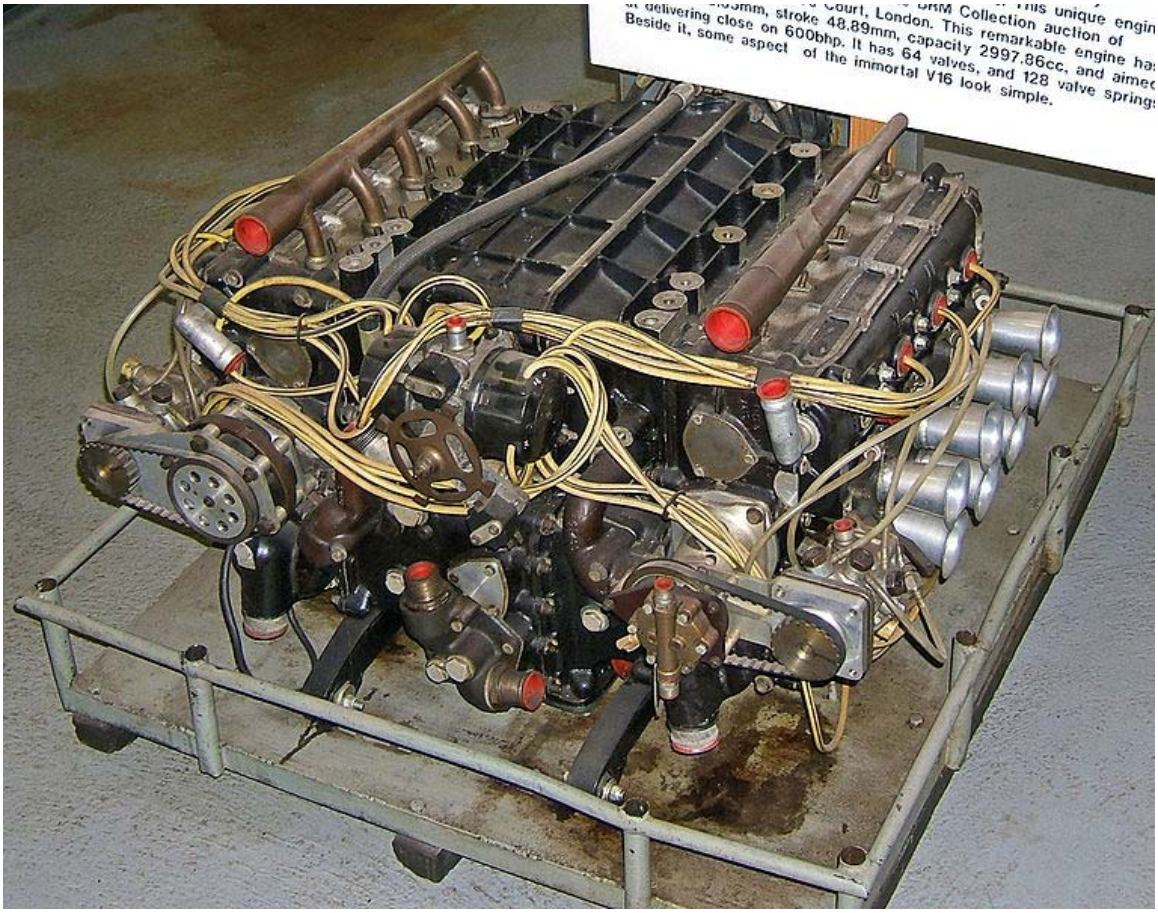
The first piston-valved musical instruments were developed just after the start of the 19th century. The Stölzel valve (invented by Heinrich Stölzel in 1814) was an early variety. In the mid 19th century the Vienna valve was an improved design. However most professional musicians preferred rotary valves for quicker, more reliable action, until better designs of piston valves were mass manufactured in towards the end of the 19th century.

Pneumatic cannons

A Piston valve can also refer to a 2-way 2-position, pilot operated valve. The term is extremely popular among spud gun enthusiasts who often build homemade piston valves for use in pneumatic cannons. Valves are typically constructed primarily from pipe fittings and machined plastics or metals. The inside of a piston valve contains a piston that blocks the output when the valve is pressurized, and a volume of air behind the piston. When the pressure behind the piston is released the piston is pushed back by the force of the pressure from the input. This allows the valve to be opened by a much smaller pilot valve, with speeds faster than possible with just a manually operated valve. Functionally these types of valves are comparable to quick exhaust valves.

This type of piston valve is also sometimes referred to as a back-pressure valve.

H Engine



The BRM H16 Formula One engine in its final, 64-valve incarnation.

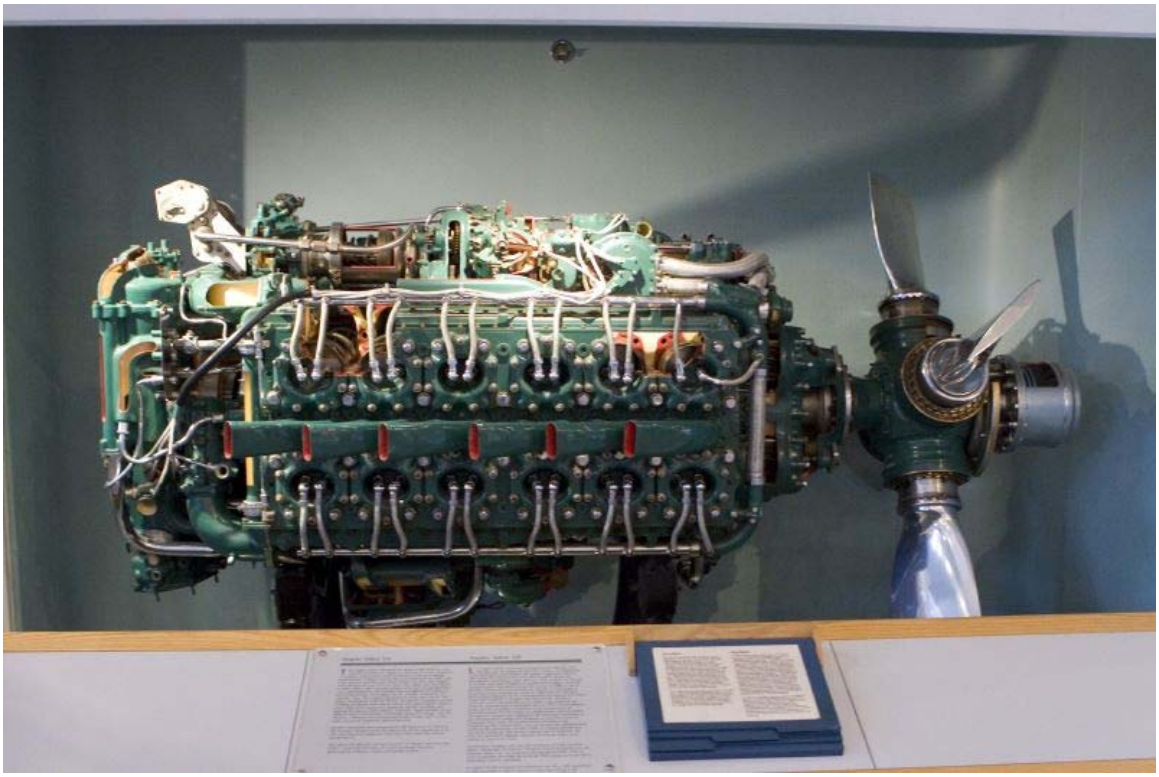
An **H engine** (or H-block) is an engine configuration in which the cylinders are aligned so that if viewed from the front, they appear to be in a vertical or horizontal letter H.

An H engine can be viewed as two flat engines, one atop or beside the other. The "two engines" each have their own crankshaft, which are then geared together at one end for power-take-off. The H configuration allows the building of multi-cylinder engines that are shorter than the alternatives, sometimes delivering advantages on aircraft. For race-car applications there is the disadvantage of a higher center of gravity, not only because one crankshaft is located atop the other, but also because the engine must be high enough off the ground to allow clearance underneath for a row of exhaust pipes. The power-to-weight ratio is not as good as simpler configurations employing one crankshaft. There is excellent mechanical balance, especially desirable and otherwise difficult to achieve in a four cylinder engine.

Two straight engines can be similarly joined to provide a U engine.

H engines

Aircraft engines



Napier Sabre H-24 engine. The two starboard 6-cylinder banks can be seen in this view

- Lycoming H 2470 "hyper engine".
- Fairey Aviation
  - Fairey Prince (H-16) (1939) - 1,500 hp
  - Fairey Monarch (1939) - H-24 2,240 hp
- Napier & Son, UK.
  - Rapier (1929) - H-16 air-cooled vertical, 8.83 litres 340 hp
  - Dagger (1934) - H-24, air-cooled vertical, 16.85 litres 890 hp, a development of the Rapier
  - Sabre (1938) - H-24, water cooled horizontal sleeve valves, 36.7 litres 3,500 hp. By 1944 in the Hawker Typhoon, the most powerful inline configuration piston engine ever.
- Rolls-Royce Eagle (1944) - H-24, 46.2 litres, 3,200 hp.

Other engines

Brough Superior H-4 motorcycle engine

A BRM H16 engine, mounted in the back of a BRM P83 Formula One car.

- The British Racing Motors (BRM) H-16 Formula One engine won the 1966 US Grand Prix with Jim Clark in a Lotus 43. As a racing-car engine it was hampered by a high center of gravity, and it was heavy and complex, with gear-driven twin overhead cams for each of four cylinder heads, two gear-coupled crankshafts, and mechanical fuel injection.
- The Brough Superior Golden Dream motorcycle, first shown in 1938. A 1,000 cc H-4 design and a few units were produced in early 1939. Any development planned was interrupted by WWII and subsequent years of austerity.
- Wooler built a motorcycle prototype with a similar configuration to the Brough Superior Golden Dream and exhibited it at the British International Motor Show at Earls Court in 1948 and again in 1951. This was replaced by a flat-4-engined prototype at the 1953 show.

Other uses of H term

Subaru produces water-cooled flat-4 and flat-6 "Horizontal" engines that are marketed as H-4 and H-6 (also thought to represent the configuration of the cylinders from a 'top down' POV as opposed to the traditional 'head-on' POV).

Chapter 9

Controlled Combustion Engine

REVETEC X4v2 Prototype Engine

Controlled Combustion Engine (CCE) is a term used by Revetec, an engine design company, to identify a type of experimental internal combustion engine (ICE) designed by Brad Howell-Smith. It uses two counter-rotating cams instead of a crankshaft. Pairs of cylinders oppose each other in a boxer flat engine or "X" arrangement.

History

The idea came to Howell-Smith, an automotive engineer residing in Australia, during REM sleep in 1995. He designed five different engine layouts with variations on each and established Revolution Engine Technologies Pty Ltd in 1996 with a budget of A$2000. The first working prototype was built by father-in-law Peter Koch in Howell-Smith's garage. Howell-Smith founded a company named Revetec Limited and set up a research and development site in Sydney. The prototype was displayed at the 1996 Sydney International Motor Show which brought public awareness to the design. Work began on a second prototype intended for use in generators and pumps, however interest expressed by the Middle East automotive market shifted focus towards automotive applications.

Engine description

The REVETEC Engine design consists of two counter-rotating "trilobate" (three lobed) cams geared together, so both cams contribute to forward motion. Two bearings run along the profile of both cams (four bearings in all) and stay in contact with the cams at all times. The bearings are mounted on the underside of the two inter-connected pistons, which maintain the desired clearance throughout the stroke.

The two cams rotate and raise the piston with a scissor-like action to the bearings. Once at the top of the stroke the air/fuel mixture is fired. This is the power stroke during which the maximum mechanical advantage is reached after the piston has moved approximately 5% of its travel from top dead centre (approx. 10° ATDC), which makes better use of the high cylinder pressures at this point in the cycle. In comparison a conventional engine reaches its maximum mechanical advantage after the piston has moved approximately 40% of its travel from top dead centre (approx. 60° ATDC). A side effect of this is a CCE can idle at a much lower RPM.

Because the piston assembly only moves in one dimension (unlike the case in an engine with connecting rods), contact with the cylinder wall is minimised, which reduces wear and lubrication requirements. The cams create less piston shock, which allows ceramic components to be used. The engine can run in either direction if symmetrical lobes are used.

The effective cranking distance is determined by the length from the point of bearing contact to the centre of the output shaft (not the stroke).

The dual bearings contact the two cams in the opposite side which cancels the side forces out. The piston assembly does not experience any side force which will reduce wear and lubrication requirements at the cylinder contact. One module which consists of a minimum of five moving components, produces six power strokes per revolution. Increasing the number of lobes on each cam to five produces ten power strokes without increasing the number of components.

Claimed Advantages

The following advantages are claimed for the CCE engine at.

- Predicted production power to dressed weight ratio is 0.40 bhp/lb. For comparison a Continental 100 hp (75 kW) engine is 0.465 hp/lb, dressed
- Efficiency - Recent tests gave good results, for a gasoline engine, when running lean.
- fewer moving and total components. As a result of fewer components, more easily manufactured than conventional engines.
- identical cylinder head assembly (“top end") to conventional engines. Most existing head technology can be either adapted or utilised.
- Flexible design - can be four-stroke, two-stroke, petrol, diesel or gas, natural or forced aspiration.
- Eliminated irregularly reciprocating components such as connecting rods. No second order balancing required.
- Output shaft can be run in either direction if multilobed cams with symmetrical lobes are employed.
- The CCE can be designed to operate at greatly reduced operating speeds while delivering high torque output.
- Substantial reduction in stroke reduces heat loss through cylinder wall.
- Extended piston dwell is possible because engine design allows a lower than normal compression ratio to be used reducing power loss from compression cycle.
- Able to fire on a leaner mixture than conventional engines.
- Maximum mechanical advantage can be applied to output shaft at only 20 degrees ATDC utilising high cylinder pressure early in the stroke, compared to around 60 degrees ATDC for conventional engines.
- Lower emissions can be achieved due to increased control over combustion.
- Low idle speed due to increase in mechanical efficiency at the top of the stroke.
- Little or no bore contact/piston side thrust, which reduces wear on cylinder bore.
- Can have different port timing on compression stroke than power stroke allowing better control.
- Lower centre of gravity on the boxer design.
- Due to controlled piston acceleration rates the CCE reduces engine vibration.
- A hollow output shaft can be utilised for specialty applications, such as peristaltic pumps.

Disadvantages

The following have yet to be verified independently.

- Vibration
- Reliability, especially when running lean as is required for good economy.
- Emissions

Patents

U.S. Patent 5,992,356 "Opposed piston combustion engine "; November 30, 1999; Howell-Smith; Bradely David (Worongary, AU).

Revetec has a PCT patent application pending for the "X" design lodged late 2006.

Performance

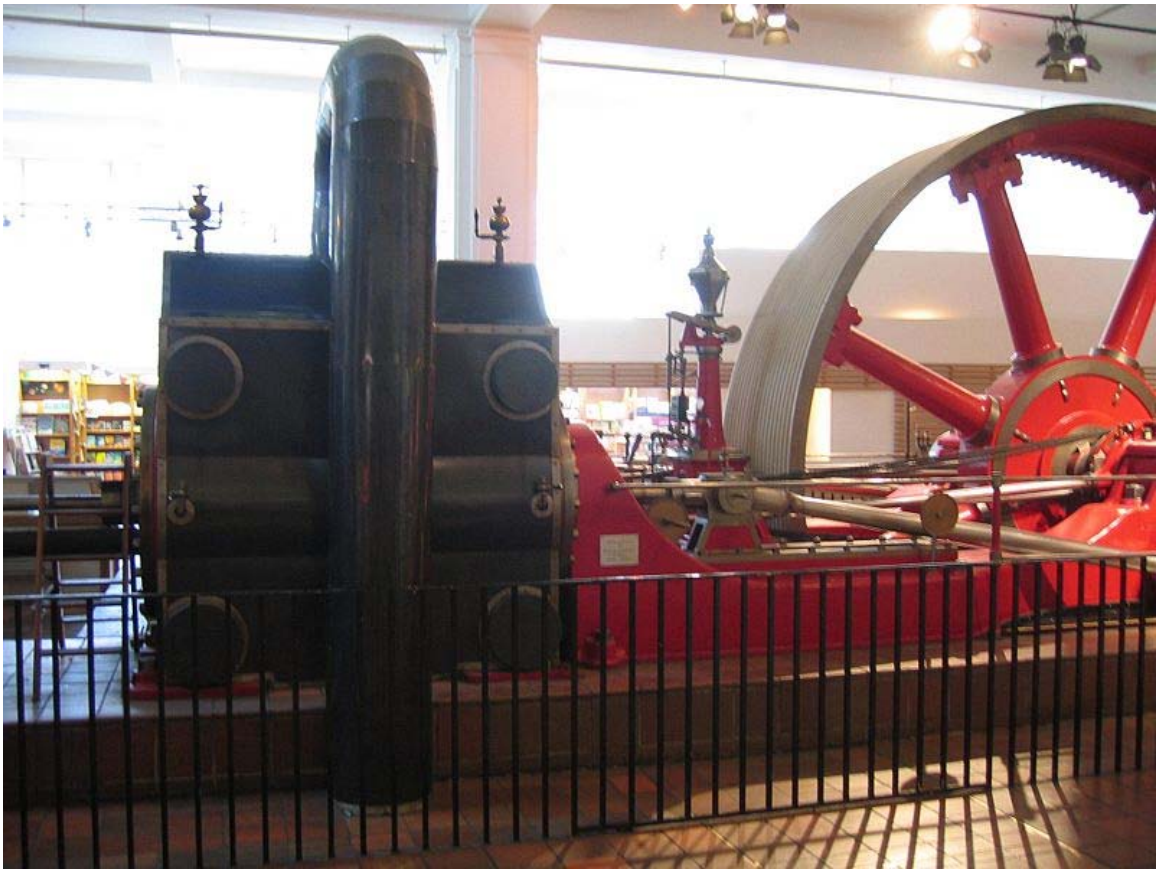
A dyno graph of the Revetec 1.38litr engine is shown on their development page, shows a flat torque curve.

Test results (11 November 2007) on the X4v2 engine showing torque and power curves and the fuel injection map.

In April 2008, Revetec completed their first Independently Certified Test Report carried out by Orbital Australia, achieving a repeatable BSFC figure of 212g/kW-h (38.6% efficiency) with a best tested figure of 207g/kW-h (39.5% efficiency).

Chapter 10

Corliss Steam Engine



Horizontal mill engine, and valve covers

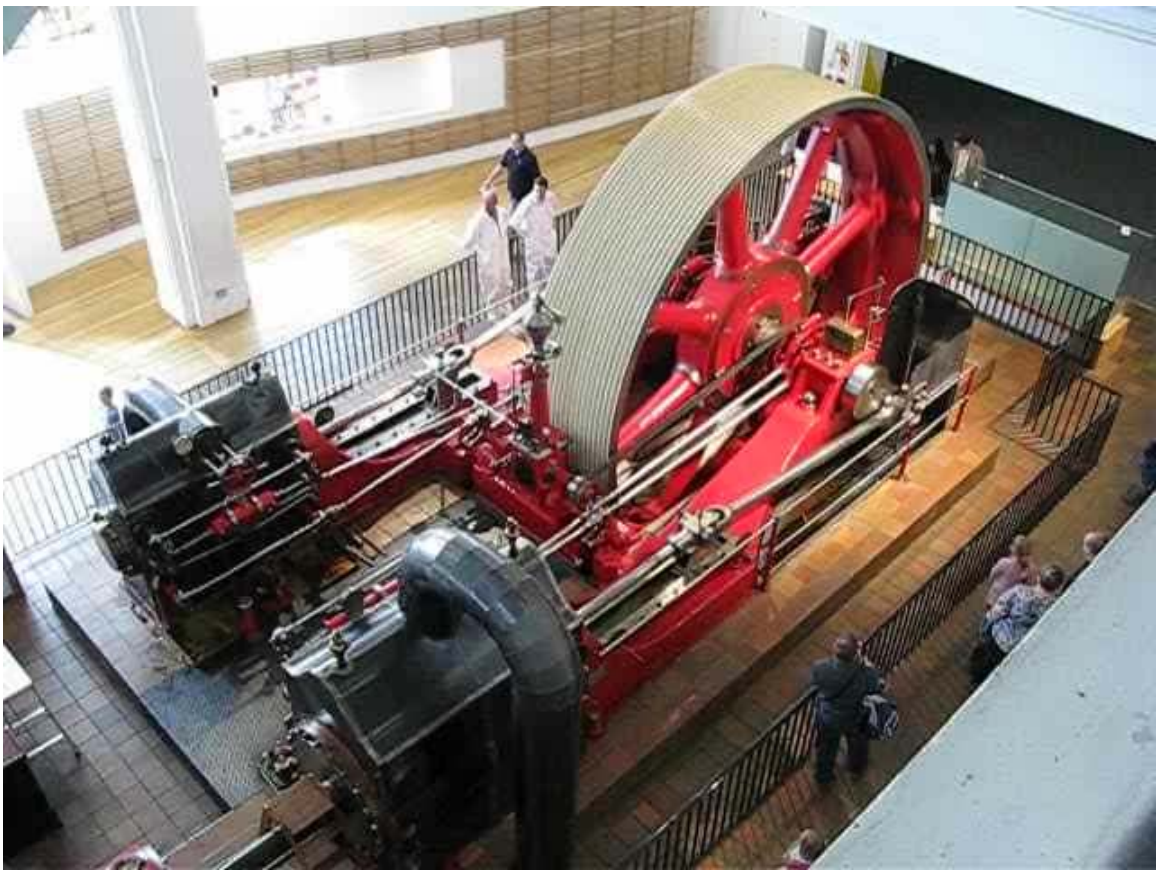
A **Corliss steam engine** (or **Corliss engine**) is a steam engine, fitted with rotary valves and with variable valve timing patented in 1849, invented by and named after the American engineer George Henry Corliss.

Engines fitted with Corliss valve gear offered the best thermal efficiency of any type of stationary steam engine until the refinement of the uniflow steam engine and steam

turbine in the 20th century. Corliss engines were generally about 30 percent more fuel efficient than conventional steam engines with fixed cutoff. This increased efficiency made steam power more economical than water power, allowing industrial development away from millponds.

Corliss engines were typically used as stationary engines to provide mechanical power to line shafting in factories and mills and to drive dynamos to generate electricity. Many were quite large, standing several stories tall, and developing several hundred horsepower, albeit at low speed, turning massive flywheels weighing several tons at about 100 revolutions per minute. Some of these engines had unique roles as mechanical legacy systems and because of their relatively high efficiency and low maintenance requirements, some remain in service in early 21st century (see, for example, the engines at the Hook Norton Brewery and the *Distillerie Dillon* in the list of operational engines).

Corliss engine mechanisms



Corliss steam engine in motion

Corliss engines have four valves for each cylinder, with steam and exhaust valves located at each end. Corliss engines incorporate distinct refinements in both the valves themselves and in the valve gear, that is, the system of linkages that operate the valves.

The use of separate valves for admission and exhaust means that neither the valves nor the steam passages between cylinders and valves need to change temperature during the power and exhaust cycle, and it means that the timing of the admission and exhaust valves can be independently controlled. In contrast, conventional steam engines have a slide or piston valve that alternately feeds and exhausts through passages to each end of the cylinder. These passages are exposed to wide temperature swings during engine operation, and there are high temperature gradients within the valve mechanism itself.

Corliss valve gear

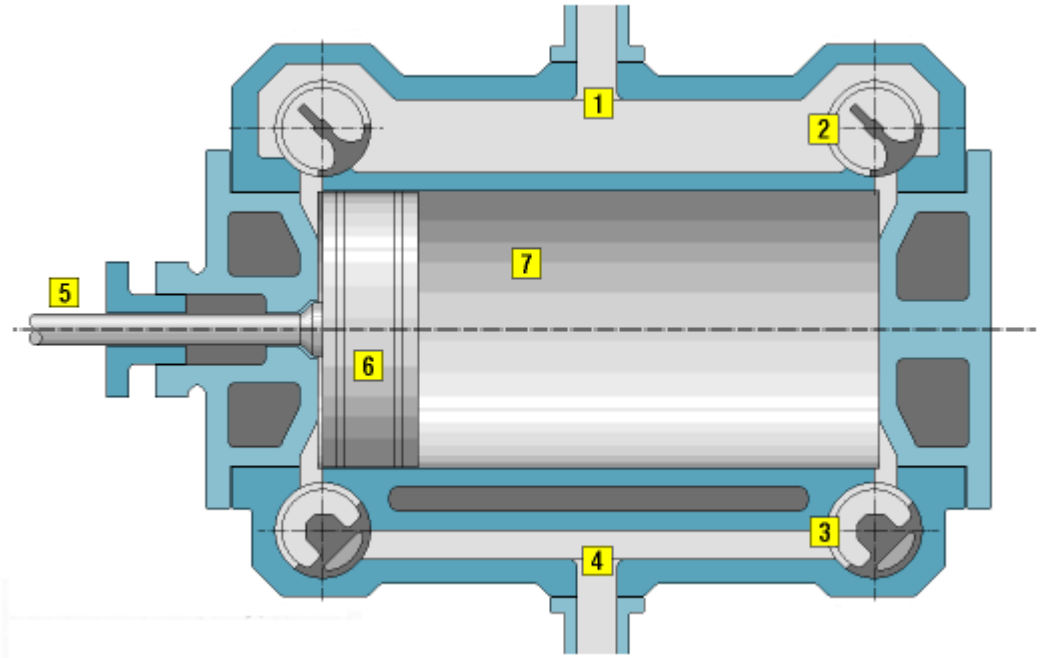
George Corliss received US Patent 6162 for his valve gear on March 10, 1849. This patent covered the use of a *wrist-plate* to convey the valve motion from a single eccentric to the four valves of the engine, and it covered the use of trip valves with variable cutoff under governor control that characterize Corliss Engines. Unlike later engines, most of which were horizontal, this patent describes a vertical cylinder beam engine, and it used individual slide valves for admission and exhaust at each end of the cylinder.

The inlet valves are pulled open with an eccentric-driven pawl; when the pawl trips, the rapid closure is damped using a dashpot. In many engines, the same dashpot acts as a vacuum spring to pull the valves closed, but Corliss's early engines were slow enough that it was the weight of the dashpot piston and rod that closed the valve.

The speed of a Corliss engine is controlled by varying the cutoff of steam during each power stroke, while leaving the throttle wide open at all times. To accomplish this, the centrifugal governor is linked to a pair of cams, one for each admission valve. These cams determine the point during the piston stroke that the pawl will release, allowing that valve to close.

As with all steam engines where the cutoff can be regulated, the virtue of doing so lies in the fact that most of the power stroke is powered by the expansion of steam in the cylinder after the admission valve has closed. This comes far closer to the ideal Carnot cycle than is possible with an engine where the admission valve is open for the length of the power stroke and speed is regulated by a throttle valve.

Corliss valves



Sectioned cylinder, showing rotating valves

Corliss valves open directly into the cylinder. The valves connect the cylinder to separate steam and exhaust plenums. Initially, Corliss used slide valves with linear actuators, but by 1851, Corliss had shifted to rotary valve actuators, as documented in U.S. Patent 8253. In this engine, the wrist plate was moved to the center of the cylinder side, as on later Corliss engines. This was still a beam engine, however, and the rotary valve actuators operated linear slide valves inside the four valve chests of the engine.

Corliss valves are in the form of a minor circular segment, rotating inside a cylindrical valve-face. Their actuating mechanism is off along the axis of the valve, thus they have little "dead space" such as the stem of a poppet valve and the entire port area can be used efficiently for gas flow.

As the area of a Corliss valve is small compared to the port area, the effects of gas flow generate relatively little torque on the valve axle compared to some other sorts of valve. These advantages have led to the Corliss form of valve being used in other roles, apart from steam engines with Corliss gear.

The Rolls-Royce Merlin aero-engine used a rectangular butterfly valve as a throttle. Gas-flow forces acting asymmetrically on this butterfly could lead to poor control of the power in some circumstances. Late models, from the 134, used a Corliss throttle valve instead to avoid this problem.

Barring and barring engines

A common feature of large Corliss engines is one or two sets of narrow gear teeth in the rim of the flywheel. These teeth allow the flywheel to be *barred*, that is, turned with the aid of a crowbar. This may be needed during engine maintenance, for example, to set the cutoff and admission valve timing, and it may be needed during engine starting.

The need for barring the engine during starting is most obvious on single cylinder engines, where a careless engine operator might stop the engine with piston in dead center. Once stopped in dead center, the engine cannot be started under its own power, so it must be barred to a more favorable position for starting.

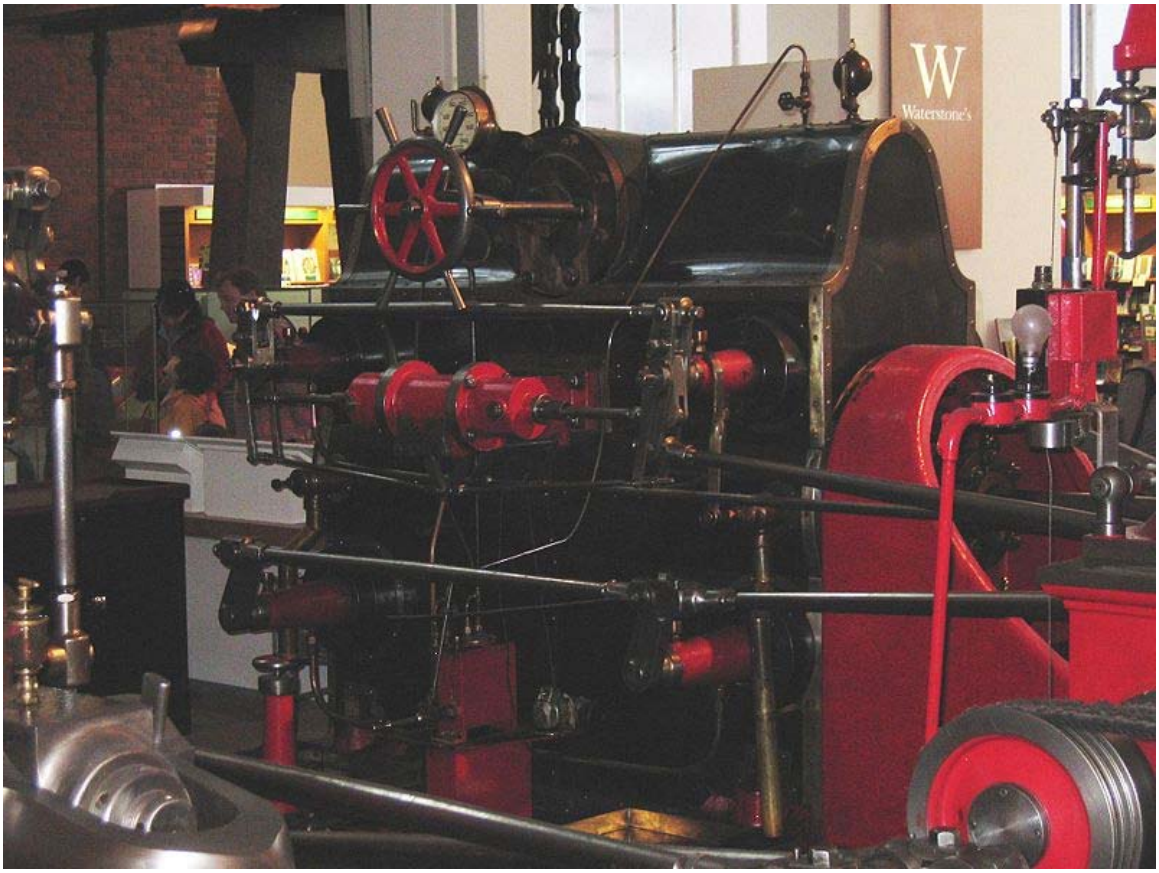
Large Corliss engines cannot be safely started cold, so it is common to admit low-pressure steam to both sides of the cylinder to warm up the metalwork. Turning the engine slowly during this process ensures that the entire engine is uniformly warmed, and it ensures that oil is uniformly distributed through the mechanism before applying power. Again, barring may be used to do this, although operators sometimes do this by careful manual manipulation of the valves.

For large engines, muscle powered barring is sufficiently difficult that *barring engines* are frequently installed. These are small engines with gear teeth cut to mate with the teeth on the flywheel. Generally, the drive gears of the barring engine are designed to automatically disengage if the engine begins running under its own power while the barring gears are engaged.

Company history

The Corliss Steam Engine Company was originally known as Fairbanks, Clark & Co. in the 1830s. In 1843 it was renamed Fairbanks, Bancroft & Co. when Edward Bancroft joined the company. In 1846 it was renamed Bancroft, Nightingale & Co. when George H. Corliss joined the company, and in 1847 it was renamed Corliss, Nightingale and Co. In 1848 the company moved to the Charles Street Railroad Crossing in Providence, Rhode Island.

In 1857 the company was renamed for the last time to Corliss Steam Engine Company. By 1864 Corliss bought out his partners and was the sole owner of the company. In 1900 the Corliss Steam Engine Company was purchased by the International Power Company. In 1905 it was purchased by the American and British Manufacturing Company. In 1925 the company merged into Franklin Machine Company. By then Franklin Machine Company was already owned by the William A. Harris Steam Engine Company.

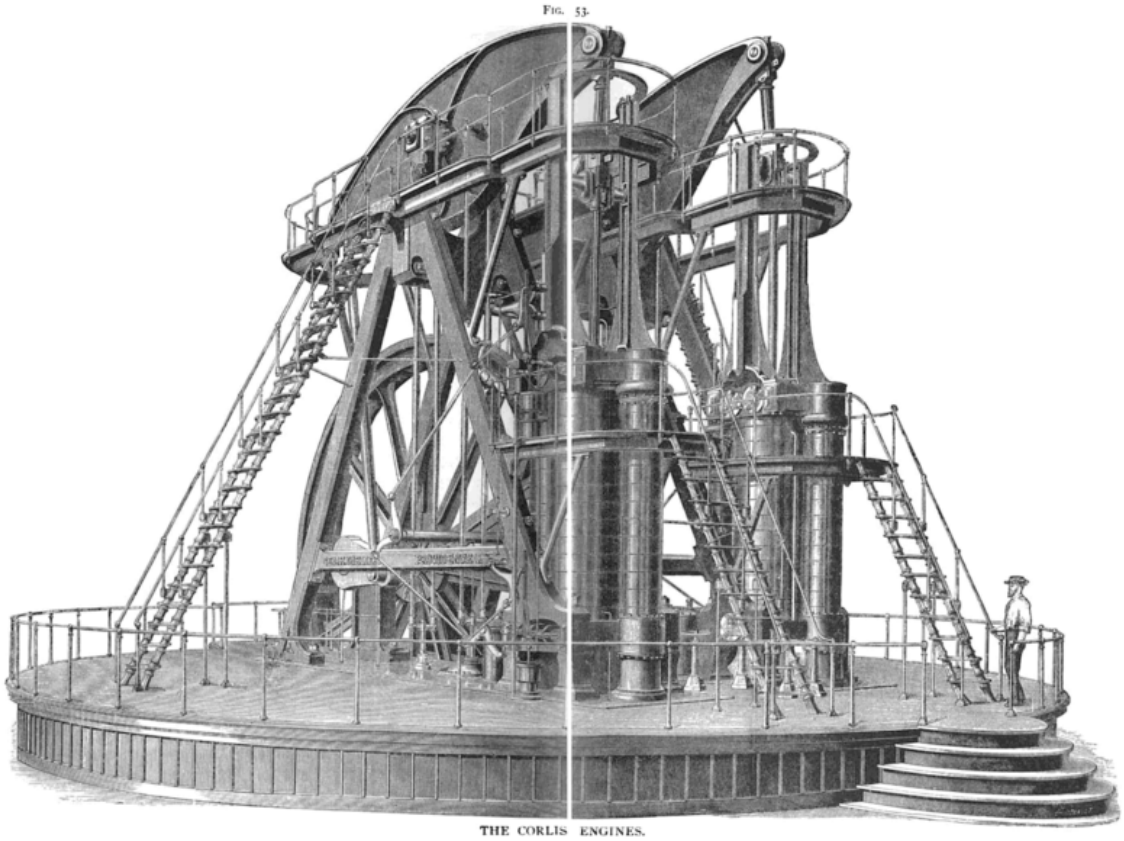


Valve gear typical of engines developed by Corliss competitors. The horizontal arrangement of the dashpots and the lack of a wrist plate avoided key claims in the Corliss patents.

By 1859, all of the key features of what we now know as the Corliss engine were in place. Patents granted to Corliss and others incorporated rotary valves and crank shafts in-line with the cylinders. See, for example, Corliss' U.S. Patent 24,618, granted July 5, 1859. Competing inventors worked hard to invent alternatives to Corliss' mechanisms; they generally avoided Corlis's use of a wrist plate and adopted alternative releasing mechanisms for the steam valves, as in Jamieson's U.S. Patent 19,640, granted March 16, 1858.

Corliss' 1849 patent expired in 1870; the term of this patent had been extended by U.S. Patent reissue 200 on May 13, 1851 and U.S. Patent reissues 758 and 763 on July 12, 1859. After 1870, numerous other companies began to manufacture Corliss engines. Among them, the William A. Harris Steam Engine Company , the Worthington Pump and Machinery Company , and Allis-Chalmers . In general, these machines were referred to as Corliss engines regardless of who made them.

Centennial Engine



The Centennial Engine

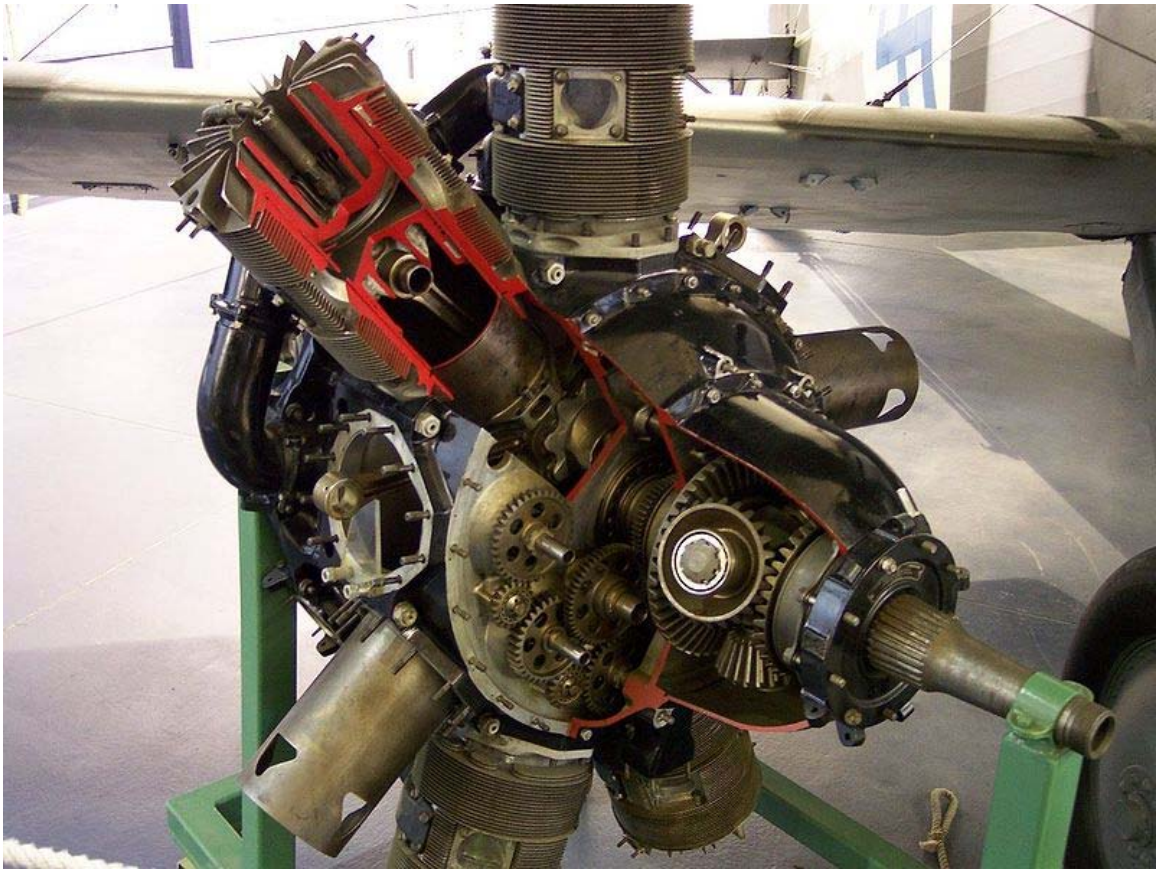
The Corliss Centennial Engine was an all-inclusive, specially-built rotative beam engine that powered virtually all of the exhibits at the Centennial Exposition in Philadelphia in 1876 through shafts totaling over a mile in length. Switched on by President Ulysses Grant and Emperor Dom Pedro of Brazil, the engine was in public view for the duration of the fair.

The engine was configured as two cylinders side-by-side. Each cylinder was bored to 44 inches (1.1 m) with a stroke of 10 feet (3.0 m), making it the largest engine of the nineteenth century. The Centennial Engine was 45 feet (14 m) tall, had a flywheel 30 feet (9.1 m) in diameter, and produced 1,400 hp. After the fair it was disassembled and shipped back to Corliss's plant in Providence. Seven years later it was sold and powered a Chicago factory owned by George Pullman until 1910, when it was sold as scrap.

This engine became a cultural icon, so much so that to many modern historians the term **Corliss Engine** (or **Corliss Steam Engine**) refers to this specific engine and not to the broad class of engines fitted with Corliss valve gear.

Chapter 11

Sleeve Valve



Bristol Perseus

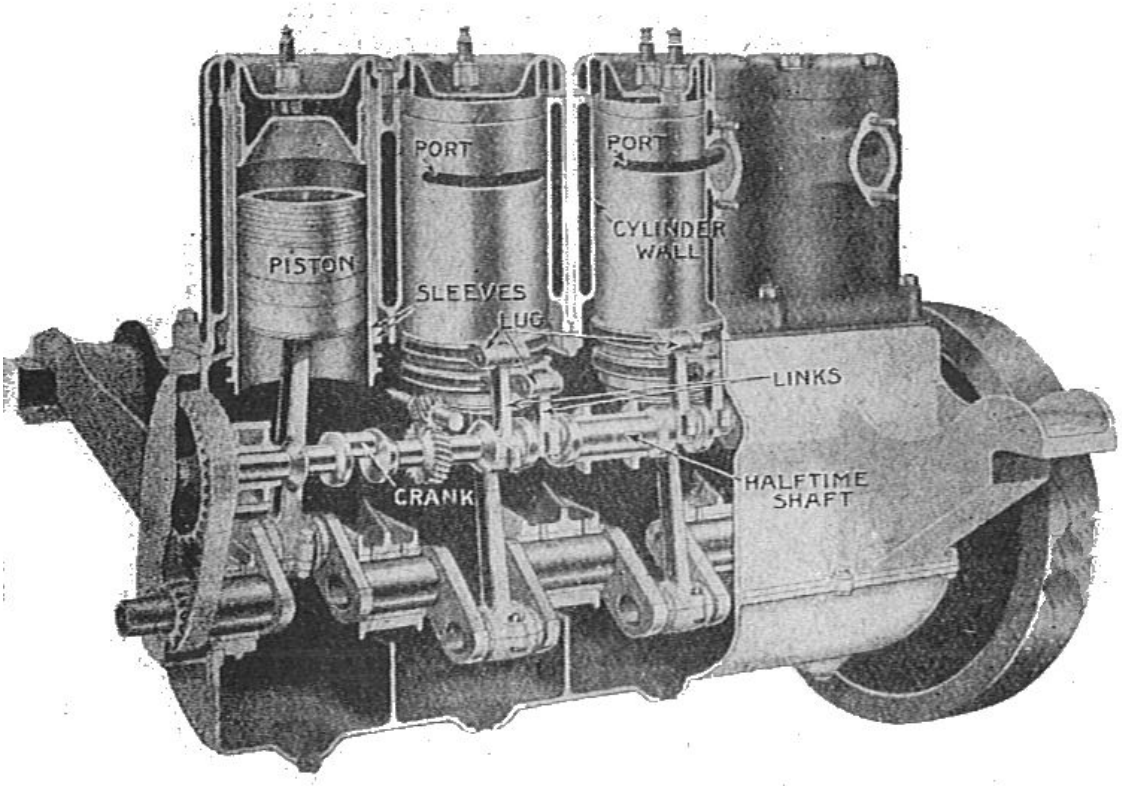
The **sleeve valve** is a type of valve mechanism for piston engines, distinct from the more common poppet valve. Sleeve-valve engines saw use in a number of pre-World War II luxury cars, sports cars, the Willys-Knight car and light truck, the British Daimler and French Avions Voisin luxury cars, also used the same Willys-Knight double-sleeve system. They subsequently fell from use due to advances in poppet-valve technology (sodium cooling) and to their tendency to burn a lot of lubricating oil or to seize due to

lack of it. The Scottish Argyll company used its own, much simpler and efficient, single-sleeve system in its cars, a system which, after extensive development, saw substantial use in aircraft engines of the 1940s, such as the Napier Sabre and Bristol Hercules and Centaurus, only to be supplanted by the jet engine.

Description

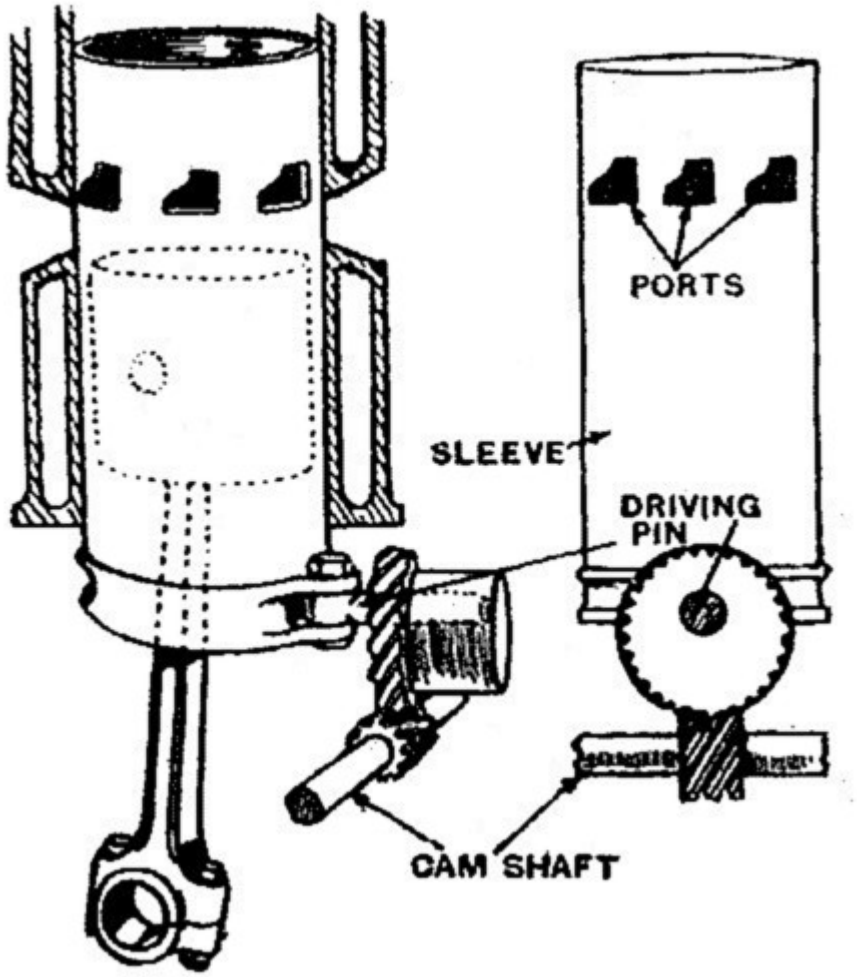
A sleeve valve takes the form of one or more machined sleeves. It fits between the piston and the cylinder wall in the cylinder of an internal combustion engine where it rotates and/or slides, ports (holes) in the side of the valve(s) aligning with the cylinder's inlet and exhaust ports at the appropriate stages in the engine's cycle.

Types of sleeve valve



Knight sleeve valve engine

The first successful sleeve valve was patented by Charles Yale Knight, and used twin alternating sliding sleeves. It was used in some luxury automobiles, notably Daimler, but was noted for its high oil consumption.



Argyll single sleeve valve

The Burt-McCollum sleeve valve, as used by the Scottish company Argyll for its cars, and later adopted by Bristol for its radial aircraft engines, used a single sleeve which rotated around a timing axle set at 90 degrees to the cylinder axle. Mechanically simpler and more rugged, the Burt-McCollum valve had the additional advantage of reducing oil consumption (compared to other sleeve valve designs), while retaining the rational combustion chambers and big, uncluttered, porting area possible in the Knight system.

A small number of designs used a "cuff" sleeve in the cylinder head instead of the cylinder proper, providing a more "classic" layout compared to traditional poppet valve engines. This design also had the advantage of not having the piston within the sleeve, although in practice this appears to have had little practical value. On the downside, this arrangement limited the size of the ports to that of the cylinder head, whereas in-cylinder sleeves could have much larger ports.

Advantages/disadvantages

Advantages

The main advantages of the sleeve valve engine are:

- Increased volumetric efficiency due to very large port openings. Sir Harry Ricardo also demonstrated better mechanical efficiency. An additional advantage of the system is that the size of the ports can be readily controlled. This is important when an engine operates over a wide RPM range, since the speed at which air can enter and exit the cylinder is defined by the size of the duct leading to the cylinder, and varies according to the cube of the RPM. In other words, at higher RPM the engine typically requires larger ports that remain open for a greater proportion of the cycle, which is fairly easy to achieve with sleeve valves, but difficult in a poppet valve system.

- Good exhaust scavenging and controllable swirl of the inlet air/fuel mixture in single-sleeve designs. When the intake ports open, the fuel air mixture can be made to enter tangentially to the cylinder. This helps scavenging when exhaust/inlet timing overlap is used and a wide speed range required, whereas poor poppet valve exhaust scavenging can dilute the fresh air/fuel mixture intake to a greater degree, being more speed dependent (relying principally on exhaust/inlet system resonant tuning to separate the two streams). Greater freedom of combustion chamber design (few constraints other than the spark plug positioning) means that fuel/air mixture swirl at TDC can also be more controlled allowing improved ignition and flame travel which as demonstrated by Ricardo, at least one extra unit of compression ratio before detonation c.f. the poppet valve engine.

- The combustion chamber formed with the sleeve at the top of its stroke is ideal for complete, detonation-free combustion of the charge, as it does not have to contend with compromised chamber shape and hot exhaust (poppet) valve(s).

- No springs are involved in the sleeve valve system, therefore the power needed to operate the valve remains largely constant with the engine's RPM, meaning that the system can be used at very high speeds with no penalty for doing so. A problem with high-speed engines which use poppet valves is that as engine speed increases, the speed at which the valve moves also has to increase. This in turn increases the loads involved due to the inertia of the valve, which has to be opened quickly, brought to a stop, then reversed in direction and closed and brought to a stop again. Large valves that allow good air-flow have considerable mass and require a strong spring to overcome the opening inertia. At some point, the valve spring reaches its resonance frequency, causing a compression wave to oscillate within the spring, which in turn causes it to become effectively weaker and unable to properly close the valve. This valve float can result in the valve not closing quickly, and it may strike the top of the rising piston. In addition,

camshaft, pushrods, and valve rockers can be eliminated in a sleeve valve design, as the sleeve valves are generally driven by a single gear powered from the crankshaft. In an aircraft engine this provided reductions in weight and complexity.

- Longevity, as demonstrated in early automotive applications of the Knight engine. Prior to the advent of leaded gasolines, poppet-valve engines typically required grinding of the valves and valve seats after 20,000 to 30,000 miles (32,000 to 48,000 km) of service. Sleeve valves did not suffer from the wear and recession caused by the repetitive impact of the poppet valve against its seat. Sleeve valves were also subjected to less intense heat buildup than poppet valves, owing to their greater area of contact with other metal surfaces. In the Knight engine, carbon build-up actually helped to improve the sealing of the sleeves, the engines being said to "improve with use", in contrast to poppet valve engines, which lose compression and power as valves and valve stems/guides wear. Due to the continued motion of the sleeve (Burt-McCollum type), the high wear points linked to poor lubrication in the TDC/BDC of piston course are suppressed, therefore rings and cylinders lasted much longer.

- Cylinder head is not required to house valves, allowing the spark plug to be placed in the best possible location for efficient ignition of the combustion mixture. For very big engines, where flame propagation speed limits both size and speed, the swirl induced by ports as described by Ricardo can be an additional advantage.

Most of these advantages were evaluated and established during the 1920s by Sir Harry Ricardo, possibly the sleeve-valve engine's greatest advocate. He conceded that some of these advantages were significantly eroded as fuels improved up to and during World War II and as sodium-cooled exhaust valves were introduced in high output aircraft engines.

Disadvantages

The sleeve valve's one major disadvantage is that perfect sealing is difficult to achieve. In a poppet valve engine, the piston possesses piston rings (often at least three and sometimes as many as eight) which form a seal with the cylinder bore. During the "breaking in" period (known as "running-in" in the UK) any imperfections in one are scraped into the other, resulting in a good fit. This type of "breaking in" is not possible on a sleeve valve engine, however, because the piston and sleeve move in different directions and in some systems even rotate in relation to one another. Unlike a traditional design, the imperfections in the piston do not always line up with the same point on the sleeve. In the 1940s this was not a major concern because the poppet valves of the time typically leaked appreciably more than they do today, so that oil consumption was significant in either case.

The high oil consumption problem associated with the Knight double sleeve valve was fixed with the Burt-McCollum single sleeve valve, as perfected by Bristol. At top dead center (TDC), the single sleeve valve rotates in relation to the piston. This prevents boundary lubrication problems, as piston ring ridge wear at TDC and bottom dead center (BDC) does not occur. The Hercules overhaul time was rated at 3,000 hr at wide open throttle. An inherent disadvantage may be that the piston in its course partially obscures the ports, thus making it difficult for gases to flow during the crucial overlap between the intake and exhaust valve timing usual in modern engines. The German engineer Max Bentele, after studying a British sleeve valve aero engine (probably a Hercules), complained that the arrangement required more than 100 gearwheels for the engine, too many for his taste.

History

Charles Yale Knight

In 1901 Knight bought an air-cooled, single cylinder three-wheeler whose noisy valves annoyed him. He believed that he could design a better engine and did so, inventing his double sleeve principle in 1904. Backed by Chicago entrepreneur L.B. Kilbourne, a number of engines were constructed followed by the "Silent Knight" touring car which was shown at the 1906 Chicago Auto Show.

Knight's design had two cast-iron sleeves per cylinder, one sliding inside the other with the piston inside the inner sleeve. The sleeves were operated by small connected rods actuated by an eccentric shaft. They had ports cut out at their upper ends. The design was remarkably quiet, and the sleeve valves needed little attention. It was, however, more expensive to manufacture due to the precision grinding required on the sleeves' surfaces. It also used more oil at high speeds and was harder to start in cold weather.

Although he was initially unable to sell his Knight Engine in the United States, a trip to Europe secured several luxury car firms as customers willing to pay his expensive premiums. He first patented the design in Britain in 1908. As part of the licensing agreement, "Knight" was to be included in the car's name.

Among the companies using Knight's technology were Gabriel Voisin (in his Avions Voisin cars), Daimler (in their V-12 "Double Six", from 1909–1930), Panhard (1911–39), Mercedes (1909–24), Willys (as the Willys-Knight, plus the associated Falcon-Knight), Stearns, Mors, Peugeot, and Belgium's Minerva company, some thirty companies in all. Itala also experimented with sleeve valves.

Upon Knight's return to America he was able to get some firms to use his design; here his brand name was "Silent Knight" (1905–1907) — the selling point was that his engines were quieter than those with standard poppet valves. The best known of these were the F.B. Stearns Company of Cleveland, which sold a car named the Stearns-Knight, and the Willys firm which offered a car called the Willys-Knight, which was produced in far greater numbers than any other sleeve-valve car.

Burt-McCollum

The Burt-McCollum sleeve valve consisted of a single sleeve, which was given a combination of up-and-down and partial rotary motion. It was developed in about 1909 and was first used in the 1911 Argyll car. Argyll went out of business after high expenses of a litigation with the Knight patent holders. Its greatest success was in Bristol's large aircraft engines, and was also used in the Napier Sabre and Rolls-Royce Eagle aircraft engines. The single valve system also cured the high oil consumption associated with the Knight double sleeve valve.

A number of sleeve valve aircraft engines were developed following a seminal 1927 research paper from the RAE by Harry Ricardo. This paper outlined the advantages of the sleeve valve, and suggested that poppet valve engines would not be able to offer power outputs much beyond 1500 hp (1,100 kW). Napier and Bristol began the development of sleeve valve engines that would eventually result in two of the most powerful piston engines in the world: the Napier Sabre and Bristol Centaurus.

Potentially the most powerful of all sleeve-valve engines (though it never reached production) was the Rolls-Royce Crecy V-12 (oddly, using a 90 degree V-angle), two-stroke, direct-injected, force-scavenged (turbocharged) aero-engine of 26.1 litres capacity. It achieved a very high specific output, and surprisingly good specific fuel consumption (SFC). In 1945 the single cylinder test-engine (E65) produced the equivalent of 5,000 HP (192 BHP/Litre) when water injected, although the full V12 would probably have been initially type rated at circa 2,500 hp (1,900 kW). Sir Harry Ricardo, who specified the layout and design goals, felt that a reliable 4,000 HP military rating would be possible. Ricardo was constantly frustrated during the war with Rolls-Royce's (RR) efforts. Hives & RR were very much focused on their Merlin, Griffon, then Eagle and finally Whittle's jets, which had a clearly defined production purpose. Ricardo and Tizard eventually realized that the Crecy would never get the development attention it deserved unless it was specified for installation in a particular aircraft, but by 1945, their "Spitfire on steroids" concept of a rapidly-climbing interceptor powered by the lightweight Crecy engine had become an aircraft without a purpose.

Following World War II the sleeve valve disappeared from use, as the previous problems with sealing and wear on poppet valves had been remedied by the use of better materials, and the inertia problems with the use of large valves were reduced by using several smaller valves instead, giving increased flow area and reduced mass. Up to that point, the single sleeve valve had won every contest against the poppet valve hands down in comparison of power to displacement. The difficulty of nitride hardening, then finish grinding the sleeve valve for truing the circularity, may have been a factor in its lack of commercial application.

Modern usage

The sleeve valve has begun to make something of a comeback, due to modern materials, dramatically better engineering tolerances and modern construction techniques, which

produce a sleeve valve that leaks very little oil. However, most advanced engine research is concentrated on improving other internal combustion engine designs, such as the Wankel.

Mike Hewland and Keith Duckworth experimented with a single-cylinder sleeve-valve test engine when looking at Cosworth DFV replacements. Hewland claimed to have obtained 72 hp (54 kW) from a 500 cc single cylinder engine, with a specific fuel consumption of 170 gr/HP/hr -.45 to .39 lb/hp/hr-, the engine being able to work on creosote, with no specific lubrication supply for the sleeve. Hewland reported also that the highest temperature measured in the cylinder head didn't exceed 150°C, sleeve temperatures were around 140°C,T was 270°C in the center of cylinder and 240°C in the edge.

A recent SAE paper deals with a high speed, small displacement sleeve valve engine, calculated, but not experimentally shown, to have a higher SFC than the poppet valve alternative, a non-surprising result, considering the difficulty in obtaining the high intake and exhaust overlap that very fast-running engines require, additional work compares two different side opening intake strategies for sleeve valve engines.

An unusual form of four stroke model engine to use what is essentially a sleeve-valve format, is the British RCV series of "SP" model engines, which use a rotating cylinder liner driven through a bevel gear at the cylinder liner's "bottom", and even more unusually have the propeller shaft emerging from what would normally be the cylinder's "top", at the extreme front of the engine, achieving a 2:1 gear reduction ratio compared to the vertically oriented crankshaft's rotational speed. The same firm's "CD" series of model engines use a conventional upright single cylinder instead, with the crankshaft used to directly spin the propeller, and also use the rotating cylinder valve. As a parallel with the earlier Charles Knight-designed sleeve-valved automotive powerplants, any RCV sleeve-valved model engine that is run on model glow engine fuel using castor oil as a small percentage (about 2% to 4% content) of the lubricant in the fuel allows the "varnish" created through engine operation to provide a better pneumatic seal between the rotating cylinder valve and the unitized engine cylinder/head castings, initially formed while the engine is being broken-in.

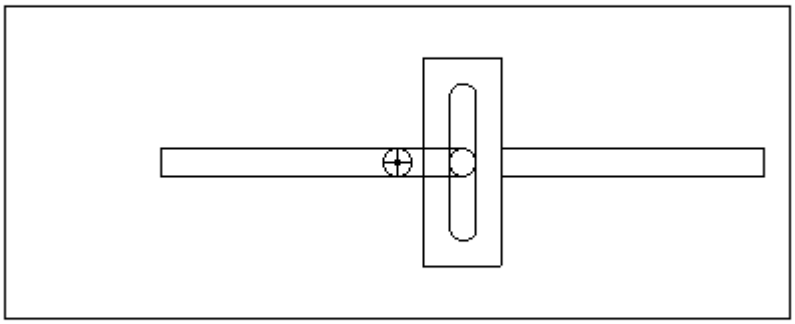
Steam engine

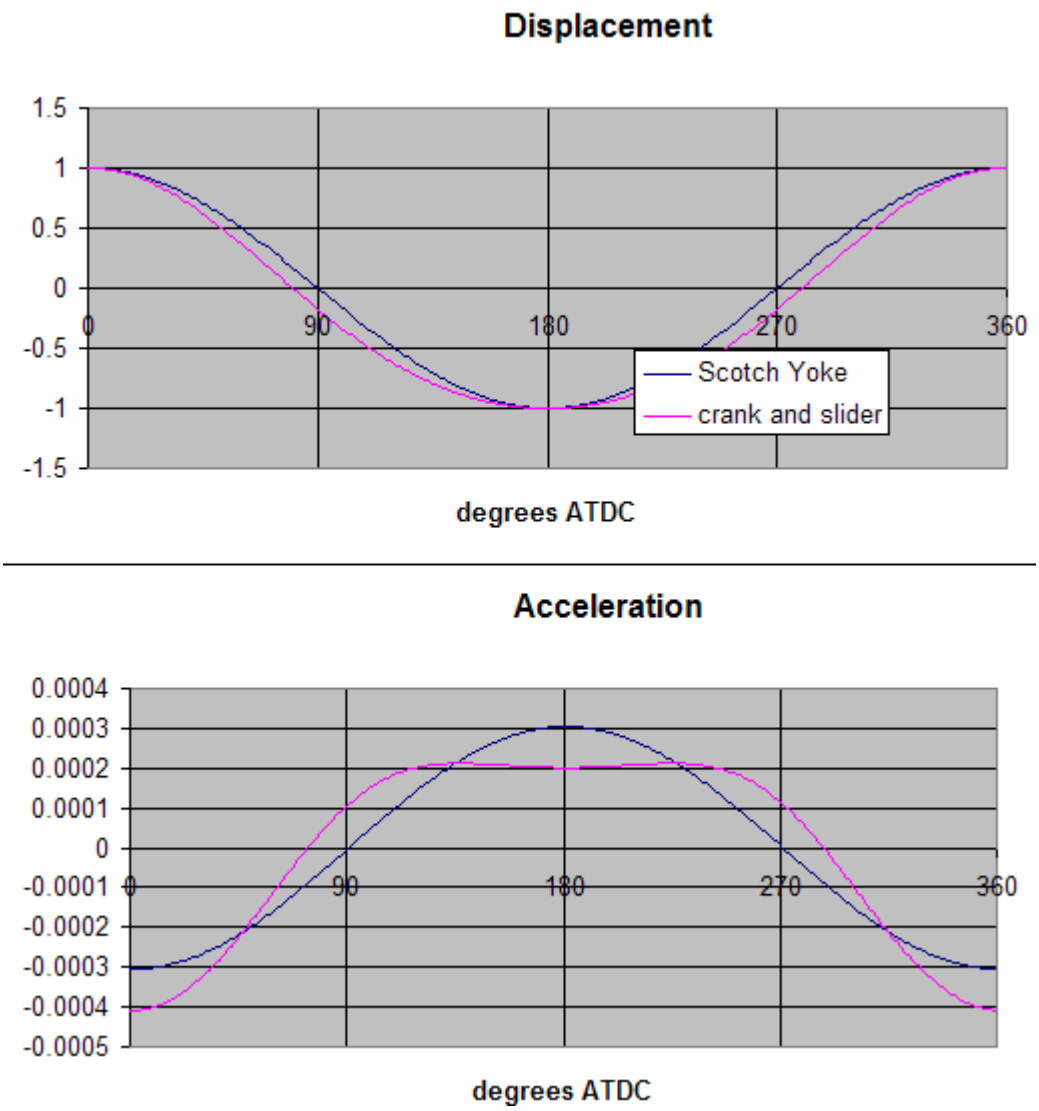
Sleeve valves have occasionally been used on steam engines, for example the SR Leader class.

Chapter 12

Scotch Yoke & Slide Valve

Scotch Yoke





Comparison of displacement and acceleration for a Scotch Yoke compared with a crank and slider

The **Scotch yoke** is a mechanism for converting the linear motion of a slider into rotational motion or vice-versa. The piston or other reciprocating part is directly coupled to a sliding yoke with a slot that engages a pin on the rotating part. The shape of the motion of the piston is a pure sine wave over time given a constant rotational speed.

Advantages

The advantages compared to a standard crankshaft and connecting rod setup are:

- Fewer moving parts.
- Smoother operation.

- Higher percentage of the time spent at top dead center (dwell) improving theoretical engine efficiency of constant volume combustion cycles, though actual gains have not been demonstrated.
- In an engine application, elimination of joint typically served by a wrist pin, and near elimination of piston skirt and cylinder scuffing, as side loading of piston due to sine of connecting rod angle is eliminated.

Disadvantages

The disadvantages are:

- Rapid wear of the slot in the yoke caused by sliding friction and high contact pressures.
- Increased heat loss during combustion due to extended dwell at top dead center offsets any constant volume combustion improvements in real engines.
- Lesser percentage of the time spent at bottom dead center reducing blowdown time for two stroke engines, when compared with a conventional piston and crankshaft mechanism.

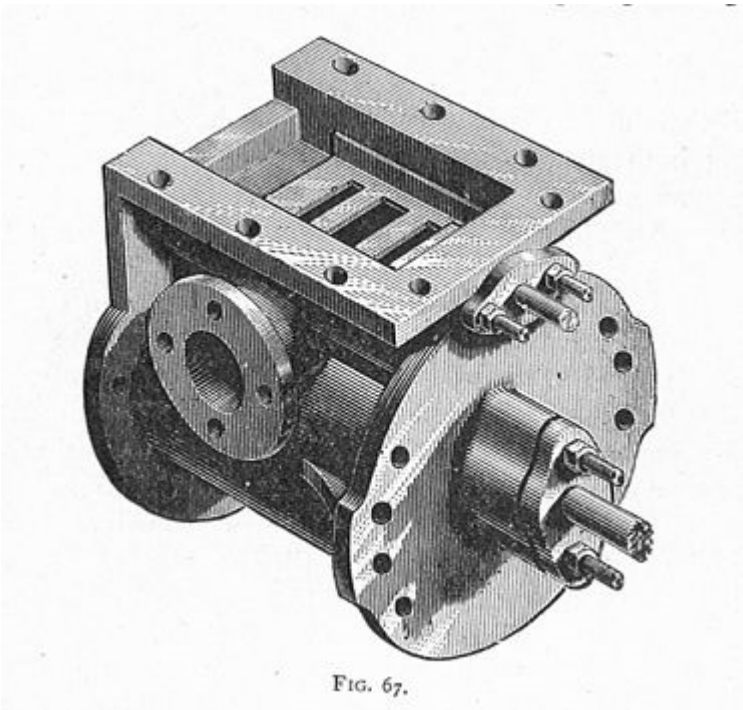
Applications

This setup is most commonly used in control valve actuators in high pressure oil and gas pipelines.

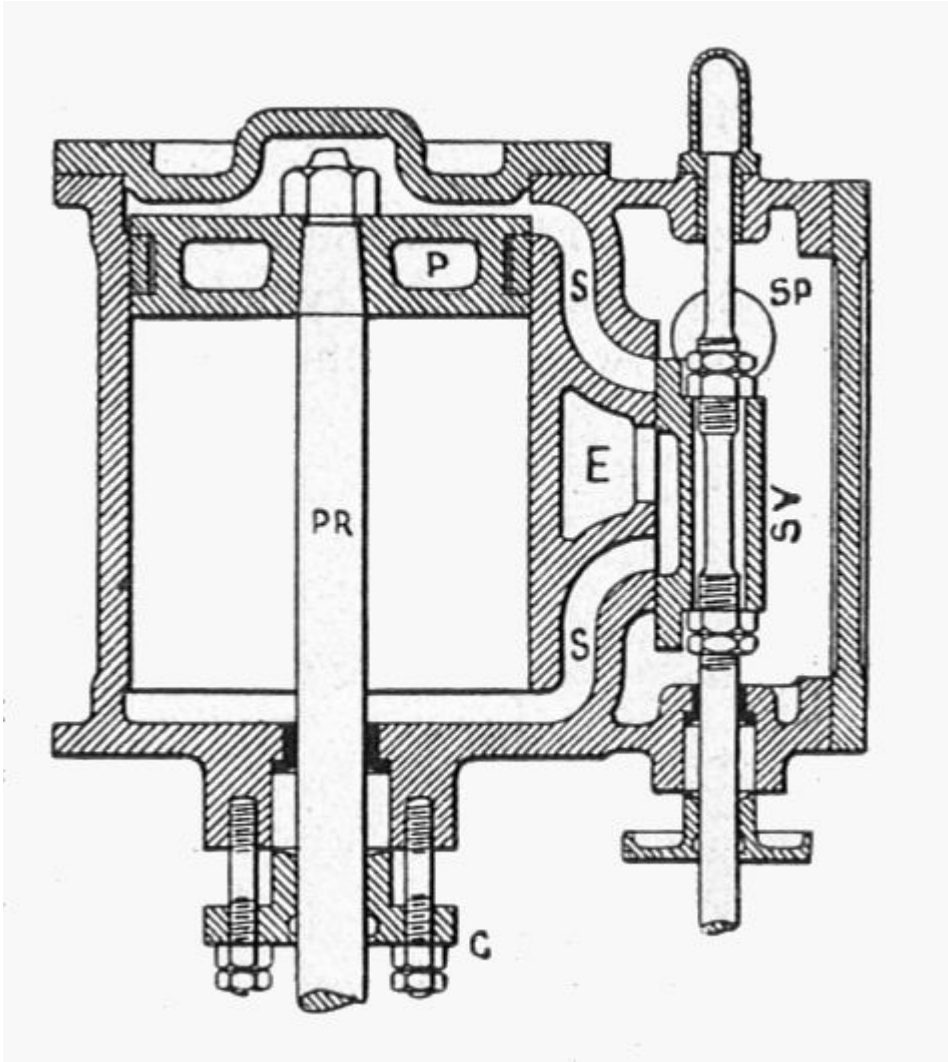
It has been used in various internal combustion engines, such as the Bourke engine, SyTech engine, and many hot air engines and steam engines.

Experiments have shown that extended dwell time will not work well with constant volume combustion (Otto, Bourke or similar) cycles. Gains might be more apparent using a stratified direct injection (diesel or similar) cycle to reduce heat losses.

Slide Valve

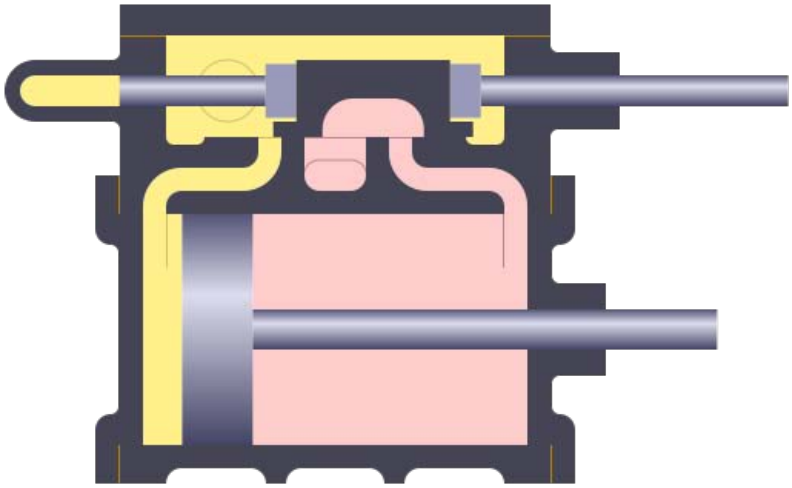


Cylinder, with slide valve removed to show ports



A double-acting slide valve cylinder.
Steam enters via the steam port *SP*, and is admitted by the slide valve *SV* through the upper passage *S* to push down the piston *P*. At the same time, exhaust steam from below the piston passes back up the lower passage *S*, via the valve cavity, to exhaust *E*. As the piston descends, the valve moves upwards to admit steam below the piston and release exhaust from above.

The **slide valve** is a rectilinear valve used to control the admission of steam into, and emission of exhaust from, the cylinder of a steam engine.



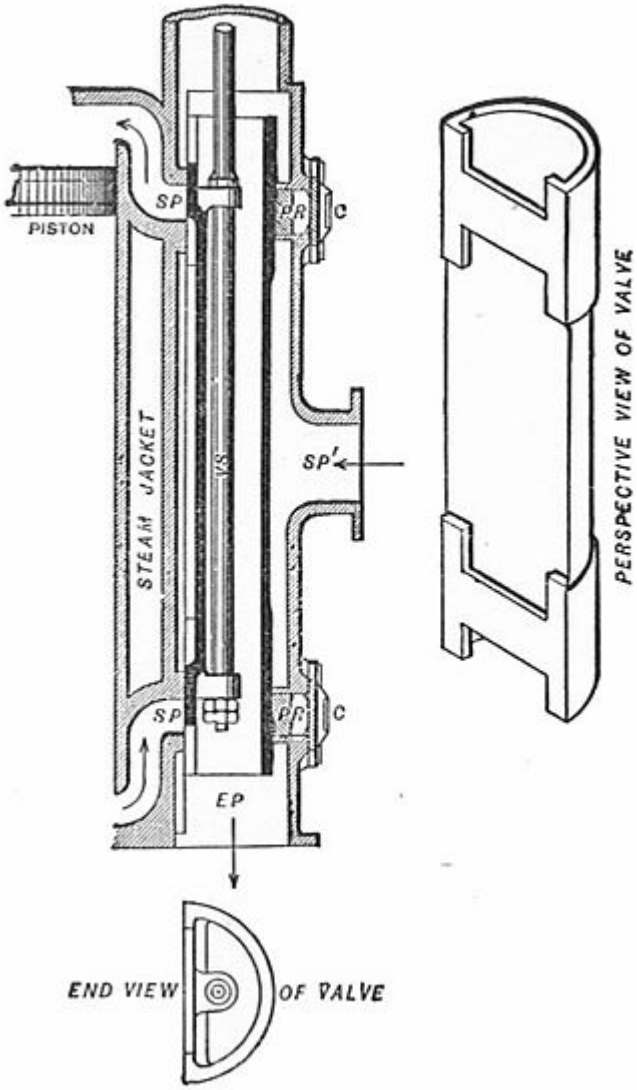
The image description page explains how this SVG animation can be viewed

Use

In the 19th century, most steam locomotives used slide valves to control the flow of steam into and out of the cylinders. In the 20th century, slide valves were gradually superseded by piston valves, particularly in engines using superheated steam. There were two reasons for this:

- With piston valves, the steam passages can be made shorter. This reduces resistance to the flow of steam and improves efficiency.
- It is difficult to lubricate slide valves adequately in the presence of superheated steam.

Murdoch's D slide valve



Murdoch's long D slide valve

The **D slide valve**, or more specifically **Long D slide valve**, is a form of slide valve, invented by William Murdoch and patented in 1799. It is named after the hollow central D-sectioned piston.

This valve worked by "connecting the upper and lower valves so as to be worked by one rod or spindle, and in making the stem or tube which connects them hollow, so as to serve for an induction pipe to the upper end of the cylinder." This allowed two valves to do the work of four.

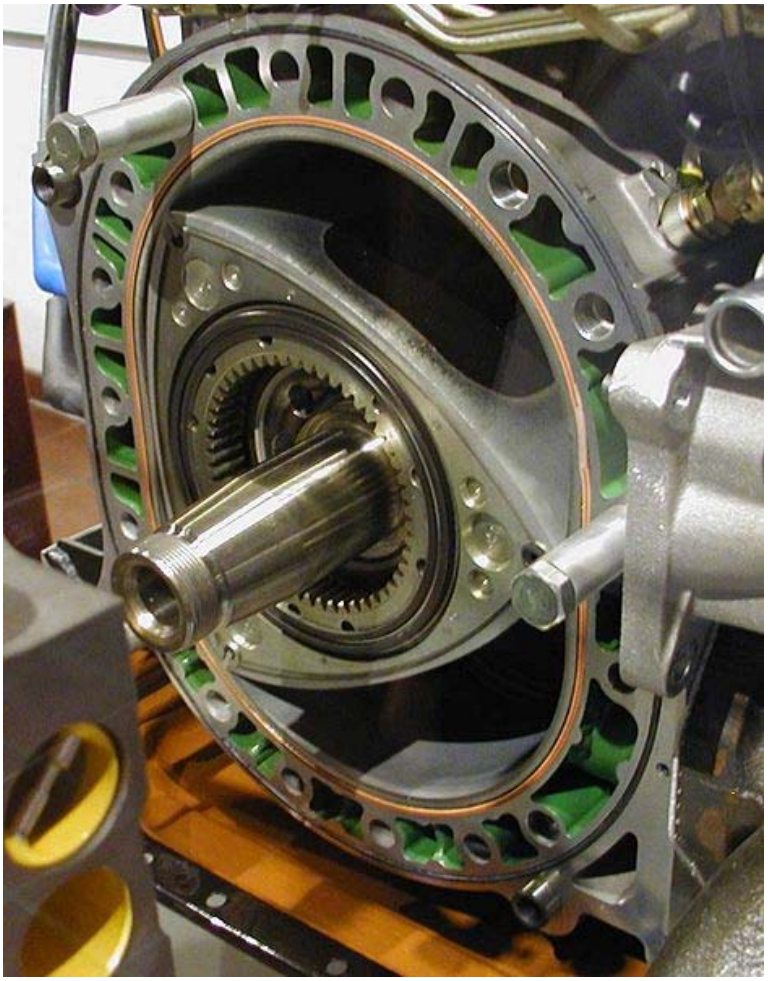
The above description (referring to upper and lower valves) clearly relates to an engine with a vertical cylinder, such as a beam engine. Where the cylinders are horizontal, as in a steam locomotive, the valves would be side-by-side.

Balanced slide valve

The balanced slide valve was invented by the Scottish engineer Alexander Allan. It was not much used in the UK but, at one time, had great popularity in the USA. It gave some of the advantages of a piston valve to a slide valve by relieving the pressure on the back of the valve, thus reducing friction and wear.

Chapter 13

Wankel Engine



A Wankel engine in Deutsches Museum in Munich, Germany

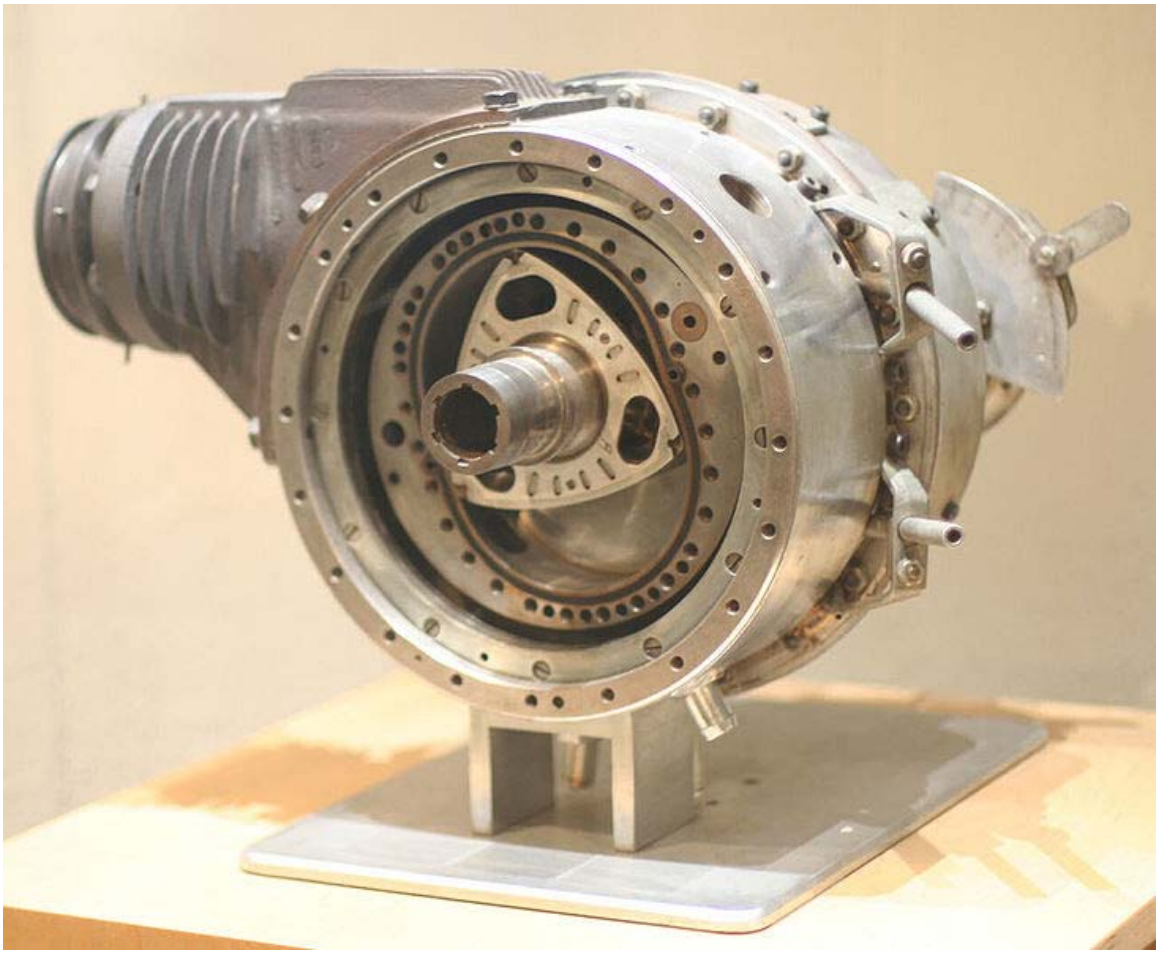
The Mazda RX-8, a sports car powered by a Wankel engine

The **Wankel engine** is a type of internal combustion engine that uses a rotary design to convert pressure into a rotating motion instead of using reciprocating pistons. Its four-stroke cycle takes place in a space between the inside of an oval-like epitrochoid-shaped housing and a rotor that is similar in shape to a Reuleaux triangle but with sides that are somewhat flatter. This design delivers smooth high-rpm power from a compact size. It is the only internal combustion engine invented in the twentieth century to go into production. Since its introduction the engine has been commonly referred to as the **rotary engine**, though this name is also applied to several completely different designs.

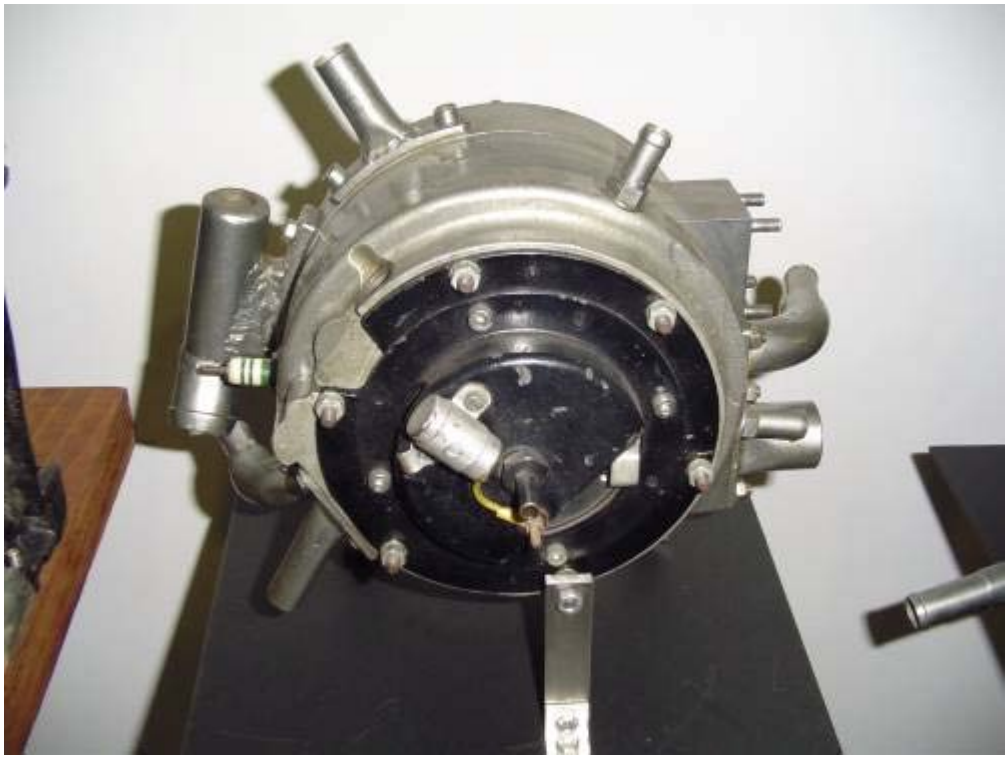
The engine was invented by German engineer Felix Wankel. He received his first patent for the engine in 1929, began development in the early 1950s at NSU Motorenwerke AG (NSU), and completed a working prototype in 1957. NSU then licensed the concept to companies around the world, which have continued to improve the design.

Because of their compact design, Wankel rotary engines have been installed in a variety of vehicles and devices such as automobiles (including racing cars), along with aircraft, go-karts, personal water craft, chain saws, and auxiliary power units. The most extensive automotive use of the Wankel engine has been by the Japanese company Mazda.

History



First DKM Wankel Engine DKM 54 (*Drehkolbenmotor*), at the Deutsches Museum in Bonn, Germany



First KKM Wankel Engine NSU KKM 57P (*Kreiskolbenmotor*), at Autovision und Forum, Germany

In 1951, the German engineer Felix Wankel began development of the engine at NSU Motorenwerke AG, where he first conceived his rotary engine in 1954 (DKM 54, *Drehkolbenmotor*). The so-called KKM 57 (the Wankel rotary engine, *Kreiskolbenmotor*) was constructed by NSU engineer Hanns Dieter Paschke in 1957 without the knowledge of Felix Wankel, who remarked "*you've turned my race horse into a plow mare*". The first working prototype DKM 54 was running on February 1, 1957 at the NSU research and development department *Versuchsabteilung TX*. It produced 21 horsepower; unlike modern Wankel engines, both the rotor and the housing rotated.

Considerable effort went into designing rotary engines in the 1950s and 1960s. They were of particular interest because they were smooth and quiet running, and because of the reliability resulting from their simplicity. An early problem of buildup of cracks in the epitrochoid surface was solved by installing the spark plugs in a separate metal piece instead of screwing them directly into the block.

Among the manufacturers signing licensing agreements to develop Wankel engines were Alfa Romeo, American Motors, Citroen, Ford, General Motors, Mercedes-Benz, Nissan, Porsche, Rolls-Royce, Suzuki, and Toyota. In the United States, in 1959 under license from NSU, Curtiss-Wright pioneered minor improvements in the basic engine design. In Britain, in the 1960s, Rolls Royce Motor Car Division pioneered a two-stage diesel version of the Wankel engine.

Also in Britain, Norton Motorcycles developed a Wankel rotary engine for motorcycles, based on the Sachs air cooled Wankel that powered the DKW/Hercules W-2000 motorcycle, which was included in their Commander and F1; Suzuki also made a production motorcycle with a Wankel engine, the RE-5, where they used ferrotic alloy apex seals and an NSU rotor in a successful attempt to prolong the engine's life. In 1971 and 1972 Arctic Cat produced snowmobiles powered by 303 cc Wankel rotary engines manufactured by Sachs in Germany. Deere & Company designed a version that was capable of using a variety of fuels. The design was proposed as the power source for United States Marine Corps combat vehicles and other equipment in the late 1980s.

Mazda and NSU signed a study contract to develop the Wankel engine in 1961 and competed to bring the first Wankel powered automobile to market. Although Mazda produced an experimental Wankel that year, NSU was first with a Wankel automobile on sale, the sporty NSU Spider in 1964; Mazda countered with a display of two and four rotor Wankel engines at that year's Tokyo Motor Show. In 1967, NSU began production of a Wankel engined luxury car, the Ro 80. However, problems with apex seal wear led to frequent engine failure, which led to large warranty costs for NSU, and curtailed further Wankel engine development.

Mazda's first Wankel engine, at the Mazda Museum in Hiroshima, Japan

Mazda, however, claimed to have solved the apex seal problem, and was able to run test engines at high speed for 300 hours without failure. After years of development, Mazda's first Wankel engine car was the 1967 Cosmo 110S. The company followed with a number of Wankel ("rotary" in the company's terminology) vehicles, including a bus and a pickup truck. Customers often cited the cars' smoothness of operation. However, Mazda chose a method to comply with hydrocarbon emission standards that, while less expensive to produce, increased fuel consumption, just before a sharp rise in fuel prices. Mazda later abandoned the Wankel in most of their automotive designs, but continued using it in their RX-7 sports car until August 2002 (RX-7 importation for Canada ceased with only the 1993 year being sold. The USA ended with the 1994 model year with remaining unsold stock being carried over as the '1995' year.). The company normally used two-rotor designs, but the 1991 Eunos Cosmo used a twin-turbo three-rotor engine. In 2003, Mazda introduced the Renesis engine with the RX-8. The Renesis engine relocated the ports for exhaust and intake from the periphery of the rotary housing to the sides, allowing for larger overall ports, better airflow, and further power gains. Early Wankel engines had also side intake and exhaust ports, but the concept was abandoned because of carbon buildup in ports and side of rotor. The Renesis engine solved the problem by using a keystone scraper side seal. The Renesis is capable of delivering 238 hp (177 kW) with better fuel economy, reliability, and environmental friendliness than previous Mazda rotary engines, all from its 1.3 L displacement.

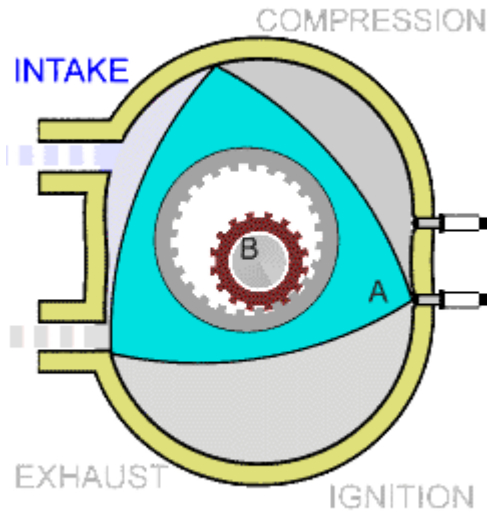
In 1961, the Soviet research organization of NATI, NAMI and VNIImotoprom started experimental development, and created experimental engines with different technologies.

Soviet automobile manufacturer AvtoVAZ also experimented with the use of Wankel engines in cars but without the benefit of a license. In 1974 they created a special engine design bureau, which in 1978 designed an engine designated as VAZ-311. In 1980, the company started delivering Wankel-powered VAZ-2106s (VAZ-411 engine with two-rotors) and Ladas, mostly to security services, of which about 200 were made. The next models were the VAZ-4132 and VAZ-415. Aviadvigatel, the Soviet aircraft engine design bureau, is known to have produced Wankel engines with electronic injection for aircraft and helicopters, though little specific information has surfaced.

Although many manufacturers licensed the design, including Citroën with their M35 and GS Birotor, using engines produced by Comotor, General Motors, which seems to have concluded that the Wankel engine was slightly more expensive to build than an equivalent reciprocating engine, and Mercedes-Benz which used it for their C111 concept car, only Mazda has produced Wankel engines in large numbers. American Motors (AMC) was so convinced "...that the rotary engine will play an important role as a powerplant for cars and trucks of the future...", according to Chairman Roy D. Chapin Jr., that the smallest U.S. automaker signed an agreement in February 1973, after a year's negotiations, to build Wankels for both passenger cars and Jeeps, as well as the right to sell any rotary engines it produces to other companies. It even designed the unique Pacer around the engine, even though by then, AMC had decided to buy the Wankel engines from GM instead of building them itself. However, GM's engines had not reached production when the Pacer was to hit the showrooms. Part of the demise of this feature

was the 1973 oil crisis with rising fuel prices, and also concerns about proposed US emission standards legislation. General Motors' Wankel did not comply with those emission standards, so in 1974 the company canceled its development, although GM claimed having solved the fuel consumption problem; unfortunately, they never published the results of their research. This meant the Pacer had to be reconfigured to house AMC's venerable AMC Straight-6 engine with rear-wheel drive

Design



The Wankel cycle. The "A" marks one of the three apexes of the rotor. The "B" marks the eccentric shaft and the white portion is the lobe of the eccentric shaft. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

In the Wankel engine, the four strokes of a typical Otto cycle occur in the space between a three-sided symmetric rotor and the inside of a housing. The expansion phase of the Wankel cycle is much longer than that of the Otto cycle. In the basic single-rotor Wankel engine, the oval-like epitrochoid-shaped housing surrounds a rotor which is triangular with bow-shaped flanks (often confused with a Reuleaux triangle, a three-pointed curve of constant width, but with the bulge in the middle of each side a bit more flattened). The theoretical shape of the rotor between the fixed corners is the result of a minimization of the volume of the geometric combustion chamber and a maximization of the compression ratio, respectively. The symmetric curve connecting two arbitrary apexes of the rotor is maximized in the direction of the inner housing shape with the constraint that it not touch the housing at any angle of rotation (an arc is not a solution of this optimization problem).

The central drive shaft, called the eccentric shaft or E-shaft, passes through the center of the rotor and is supported by fixed bearings. The rotors ride on eccentrics (analogous to

cranks) integral to the eccentric shaft (analogous to a crankshaft). The rotors both rotate around the eccentrics and make orbital revolutions around the eccentric shaft. Seals at the corners of the rotor seal against the periphery of the housing, dividing it into three moving combustion chambers. The rotation of each rotor on its own axis is caused and controlled by a pair of synchronizing gears A fixed gear mounted on one side of the rotor housing engages a ring gear attached to the rotor and ensures the rotor moves exactly 1/3 turn for each turn of the eccentric shaft. The power output of the engine is not transmitted through the synchronizing gears. The force of gas pressure on the rotor (to a first approximation) goes directly to the center of the eccentric, part of the output shaft.

The best way to visualize the action of the engine in the animation at left is to look not at the rotor itself, but the cavity created between it and the housing. The Wankel engine is actually a variable-volume progressing-cavity system. Thus there are 3 cavities per housing, all repeating the same cycle. Note as well that points A and B on the rotor and e-shaft turn at different speed, point B moves 3 times faster than point A, so that one full orbit of the rotor equates to 3 turns of the e-shaft.

As the rotor rotates and orbitally revolves, each side of the rotor is brought closer to and then away from the wall of the housing, compressing and expanding the combustion chamber like the strokes of a piston in a reciprocating engine. The power vector of the combustion stage goes through the center of the offset lobe.

While a four-stroke piston engine makes one combustion stroke per cylinder for every two rotations of the crankshaft (that is, one-half power stroke per crankshaft rotation per cylinder), each combustion chamber in the Wankel generates one combustion stroke per each driveshaft rotation, i.e. one power stroke per rotor orbital revolution and three power strokes per rotor rotation. Thus, power output of a Wankel engine is generally higher than that of a four-stroke piston engine of similar engine displacement in a similar state of tune; and higher than that of a four-stroke piston engine of similar physical dimensions and weight.

Wankel engines also generally have a much higher redline than a reciprocating engine of similar power output. This is in part because the smoothness inherent in circular motion, but especially because they do not have highly stressed parts such as a crankshaft or connecting rods. Eccentric shafts do not have the stress-raising internal corners of crankshafts. The redline of a rotary engine is limited by wear of the synchronizing gears. Hardened steel gears are used for extended operation above 7000 or 8000 rpm. Mazda Wankel engines in auto racing are operated above 10,000 rpm. In aircraft they are used conservatively, up to 6500 or 7500 rpm. However, as gas pressure participates in seal efficiency, running a Wankel engine at high rpm under no load conditions can destroy the engine.

National agencies that tax automobiles according to displacement and regulatory bodies in automobile racing variously consider the Wankel engine to be equivalent to a four-stroke engine of 1.5 to 2 times the displacement; some racing series ban it altogether.

Engineering

Apex seals, left NSU Ro80 Serie and Research and right Mazda 12A and 13B

Left Mazda old L10A Camber axial cooling, middle Audi NSU EA871 axial water cooling only hot bow, right Diamond Engines Wankel radial cooling only in the hot bow

Felix Wankel managed to overcome most of the problems that made previous rotary engines fail by developing a configuration with vane seals that could be made of more durable materials than piston ring metal that led to the failure of previous rotary designs.

Rotary engines have a thermodynamic problem not found in reciprocating four-stroke engines in that their "cylinder block" operates at steady state, with intake, compression, combustion, and exhaust occurring at fixed housing locations for all "cylinders". In contrast, reciprocating engines perform these four strokes in one chamber, so that extremes of "freezing" intake and "flaming" exhaust are averaged and shielded by a boundary layer from overheating working parts.

The boundary layer shields and the oil film act as thermal insulation, leading to a low temperature of the lubricating film (max. ~200 °C/400 °F) on a water-cooled Wankel engine. This gives a more constant surface temperature. The temperature around the spark plug is about the same as the temperature in the combustion chamber of a reciprocating engine. With circumferential or axial flow cooling, the temperature difference remains tolerable.

Four-stroke reciprocating engines are less suitable for hydrogen. The hydrogen can misfire on hot parts like the exhaust valve and spark plugs. Another problem concerns the hydrogenate attack on the lubricating film in reciprocating engines. In a Wankel engine, this problem is circumvented by using a ceramic apex seal against a ceramic surface: there is no oil film to suffer hydrogenate attack. Since ceramic piston rings are not

available as of 2009, the problem remains with the reciprocating engine. The piston shell must be lubricated and cooled with oil. This substantially increases the lubricating oil consumption in a four-stroke hydrogen engine.

Materials

Unlike a piston engine, where the cylinder is cooled by the incoming charge after being heated by combustion, Wankel rotor housings are constantly heated on one side and cooled on the other, leading to high local temperatures and unequal thermal expansion. While this places high demands on the materials used, the simplicity of the Wankel makes it easier to use alternative materials like exotic alloys and ceramics. With water cooling in a radial or axial flow direction, with the hot water from the hot bow heating the cold bow, the thermal expansion remains tolerable.

Sealing

Early engine designs had a high incidence of sealing loss, both between the rotor and the housing and also between the various pieces making up the housing. Also, in earlier model Wankel engines carbon particles could become trapped between the seal and the casing, jamming the engine and requiring a partial rebuild. It was common for very early Mazda engines to require rebuilding after 50,000 miles (80,000 km). Further sealing problems arise from the uneven thermal distribution within the housings causing distortion and loss of sealing and compression. This thermal distortion also causes uneven wear between the apex seal and the rotor housing, quite evident on higher mileage engines. The problem is exacerbated when the engine is stressed before reaching operating temperature. However, Mazda Wankel engines have solved these problems. Current engines have nearly 100 seal-related parts.

Fuel consumption and emissions

Just as the shape of the Wankel combustion chamber is resistant to preignition and will run on lower-octane rating gasoline than a comparable piston engine, it also leads to relatively incomplete combustion of the air-fuel charge, with a larger amount of unburned hydrocarbons released into the exhaust. The exhaust is, however, relatively low in NOx emissions; this allowed Mazda to meet the United States Clean Air Act of 1970 in 1973 with a simple and inexpensive 'thermal reactor' (an enlarged open chamber in the exhaust manifold) by paradoxically enriching the air-fuel ratio to the point where the unburned hydrocarbons (HC) in the exhaust would support complete combustion in the thermal reactor; while piston-engine cars required expensive catalytic converters to deal with both unburned hydrocarbons and NOx emissions. This raised fuel consumption, however, (already a weak point for the Wankel engine) at the same time that the oil crisis of 1973 raised the price of gasoline. Mazda was able to improve the fuel efficiency of the thermal reactor system by 40% by the time of introduction of the RX-7 in 1978, but eventually shifted to the catalytic converter system. According to the Curtiss-Wright research, the extreme that controls the amount of unburned HC in the exhaust is the rotor surface temperature, higher temperatures producing less HC. They showed also that the rotor can

be widened. Quenching is the dominant source of HC at high speeds, and leakage at low speeds. The shape and positioning of rotor recess-combustion chamber- influences emissions and fuel use, the MDR being chosen as a compromise.

In Mazda's RX-8 with the Renesis engine, fuel consumption is now within normal limits while passing California State emissions requirements, including California's Low Emissions Vehicle or LEV standards. The exhaust ports, which in earlier Mazda rotaries were located in the rotor housings, were moved to the sides of the combustion chamber. This approach allowed Mazda to eliminate overlap between intake and exhaust port openings, while simultaneously increasing exhaust port area. The side port trapped the unburned fuel in the chamber decreased the oil consumption and improved the combustion stability in the low-speed and light load range. The HC emissions from the side exhaust port Wankel engine is 35 to 50 percent less than those from the peripheral exhaust port Wankel engine.

Advantages

NSU Wankel Spider, the first line of cars sold with a rotor Wankel engine

Mazda Cosmo, the first series two rotor Wankel engine sports car

Wankel engines are considerably simpler, lighter, and contain far fewer moving parts than piston engines of equivalent power output. For instance, because valving is accomplished by simple ports cut into the walls of the rotor housing, they have no valves or complex valve trains; in addition, since the rotor rides directly on a large bearing on the output shaft, there are no connecting rods and there is no crankshaft. The elimination of reciprocating mass and the elimination of the most highly stressed and failure prone parts of piston engines gives the Wankel engine high reliability, a smoother flow of power, and a high power-to-weight ratio.

The surface/volume-ratio problem is so complex that one cannot make a direct comparison between a reciprocating piston engine and a Wankel engine in terms of the surface/volume-ratio. The flow velocity and the heat losses behave quite differently. Surface temperatures behave absolutely differently; the film of oil in the Wankel engine acts as insulation. Engines with a higher compression ratio have a worse surface/volume-ratio. The surface/volume-ratio of a Diesel engine is much worse than a gasoline engine, but Diesel engines are well known for a higher efficiency factor than gasoline engines. Thus, engines with equal power should be compared: a naturally aspirated 1.3-liter Wankel engine with a naturally aspirated 1.3-liter four-stroke reciprocating piston engine with equal power. But such a four-stroke engine is not possible and needs twice the displacement for the same power as a Wankel engine. The extra or "empty" stroke(s)

should not be ignored, as a 4-stroke cylinder produces a power stroke only every other rotation of the crankshaft. In actuality, this doubles the real surface/volume-ratio for the four-stroke reciprocating piston engine and the demand of displacement. The Wankel, therefore, has higher volumetric efficiency and a lower pumping loss through the absence of choking valves. Because of the quasi-overlap of the power strokes that cause the smoothness of the engine and the avoidance of the 4-stroke cycle in a reciprocating engine, the Wankel engine is very quick to react to throttle changes and is able to quickly deliver a surge of power when the demand arises, especially at higher rpm. This difference is more pronounced when compared to four-cylinder reciprocating engines and less pronounced when compared to higher cylinder counts.

In addition to the removal of internal reciprocating stresses by virtue of the complete removal of reciprocating internal parts typically found in a piston engine, the Wankel engine is constructed with an iron rotor within a housing made of aluminium, which has a greater coefficient of thermal expansion. This ensures that even a severely overheated Wankel engine cannot seize, as would be likely to occur in an overheated piston engine. This is a substantial safety benefit of use in aircraft. In addition, valves and valve trains that don't exist can't burn out, jam, break, or malfunction in any way, again increasing safety.

A further advantage of the Wankel engine for use in aircraft is the fact that a Wankel engine generally has a smaller frontal area than a piston engine of equivalent power, allowing a more aerodynamic nose to be designed around it. The simplicity of design and smaller size of the Wankel engine also allows for savings in construction costs, compared to piston engines of comparable power output.

Wankel engines that operate within their original design parameters are almost immune to catastrophic failure. A Wankel engine that loses compression, cooling or oil pressure will lose a large amount of power, and will die over a short period of time; however, it will usually continue to produce some power during that time. Piston engines under the same circumstances are prone to seizing or breaking parts that almost certainly results in major internal damage of the engine and an instant loss of power. For this reason, Wankel engines are very well suited to snowmobiles and aircraft, which often take users into remote places where a failure could result in frostbite or death.

Due to a 50% longer stroke duration compared to a four-cycle engine, there is more time to complete the combustion. This leads to greater suitability for direct injection. A Wankel rotary engine has stronger flows of air-fuel mixture and a longer operating cycle than a reciprocating engine, so it realizes concomitantly thorough mixing of hydrogen and air. The result is a homogeneous mixture, which is crucial for hydrogen combustion.

Disadvantages

Rolls Royce R6 two stage Wankel Diesel engine

Although in two dimensions the seal system of a Wankel looks to be even simpler than that of a corresponding multi-cylinder piston engine, in three dimensions the opposite is true. As well as the rotor apex seals evident in the conceptual diagram, the rotor must also seal against the chamber ends.

Piston rings are not perfect seals: each has a gap to allow for expansion. The sealing at the Wankel apexes is less critical, as leakage is between adjacent chambers on adjacent strokes of the cycle, rather than to the crankcase. However, the less effective sealing of the Wankel is one factor reducing its efficiency, limiting its use mainly to applications such as racing engines and sports vehicles where neither efficiency nor long engine life are major considerations. Comparison tests have shown that the Mazda rotary powered RX-8 uses more fuel than a heavier vehicle powered by larger displacement V-8 engine for similar performance results.

The time available for fuel to be port-injected into a Wankel engine is significantly shorter, compared to four-stroke piston engines, due to the way the three chambers rotate. The fuel-air mixture cannot be pre-stored as there is no intake valve. Also the Wankel engine, compared to a piston engine, has 50% longer stroke duration. The four Otto cycles last 1080° for a Wankel engine versus 720° for a four-stroke reciprocating piston engine.

There are various methods of calculating the engine displacement of a Wankel. The Japanese regulations for calculating displacements for engine ratings use the volume displacement of one rotor face only, and the auto industry commonly accepts this method as the standard for calculating the displacement of a rotary. However, when compared on the basis of specific output, the convention results in large imbalances in favor of the Wankel motor.

For comparison purposes between a Wankel Rotary engine and a piston engine, displacement and corresponding power output can more accurately be compared on the basis of displacement per revolution of the eccentric shaft. A calculation of this form dictates that a two rotor Wankel displacing 654 cc per face will have a displacement of 1.3 liters per every rotation of the eccentric shaft (only two total faces, one face per rotor going through a full power stroke) and 2.6 liters after two revolutions (four total faces, two faces per rotor going through a full power stroke). The results are directly comparable to a 2.6-liter piston engine with an even number of cylinders in a conventional firing order, which will likewise displace 1.3 liters through its power stroke after one revolution of the crankshaft, and 2.6 liters through its power strokes after two revolutions of the crankshaft. A Wankel Rotary engine is still a 4-stroke engine and pumping losses from non-power strokes still apply, but the absence of throttling valves and a 50% longer stroke duration result in a significantly lower pumping loss compared against a four-stroke reciprocating piston engine. Measuring a Wankel rotary engine in this way more accurately explains its specific output, as the volume of its air fuel mixture put through a complete power stroke per revolution is directly responsible for torque and thus power produced.

The trailing side of the rotary engine's combustion chamber develops a squeeze stream which pushes back the flamefront. With the conventional two-spark-plug or one-spark-plug system and homogenous mixture, this squeeze stream prevents the flame from propagating to the combustion chamber's trailing side in the mid and high engine speed ranges. This is why there can be more carbon monoxide and unburnt hydrocarbons in a Wankel's exhaust stream. A side-port exhaust, as is used in the Renesis, avoids this because the unburned mixture cannot escape. The Mazda 26B avoided this issue through a 3-spark plug ignition system. (As a result, at the Le Mans 24 hour endurance race in 1991, the 26B had significantly lower fuel consumption than the competing reciprocating piston engines. All competitors had only the same amount of fuel available, because of the Le Mans 24 h limited fuel quantity rule.) A peripheral intake port gives the highest MEP, however, side intake porting produces a more steady idle.

All Mazda-made Wankel rotaries, including the new Renesis found in the RX-8, burn a small quantity of oil by design; it is metered into the combustion chamber to preserve the apex seals. Owners must periodically add small amounts of oil, marginally increasing running costs — though it is still reasonable and comparable in some instances when compared to many reciprocating piston engines.

Applications

Automobile racing

Mazda 787B

In the racing world, Mazda has had substantial success with two-rotor, three-rotor, and four-rotor cars. Private racers have also had considerable success with stock and modified Mazda Wankel-engine cars.

The Sigma MC74 powered by a Mazda 12A engine was the first engine and only team from outside Western Europe or the United States to finish the entire 24 hours of the 24 Hours of Le Mans race, in 1974. Mazda is the only team from outside Western Europe or the United States to have won Le Mans outright and the only non-piston engine ever to win Le Mans, which the company accomplished in 1991 with their four-rotor 787B (2,622 cc/160 cu in—actual displacement, rated by FIA formula at 4,708 cc/287 cu in). The following year, a planned rule change at Le Mans made the Mazda 787B ineligible to race anymore due to weight advantages.

The Mazda RX-7 has won more IMSA races in its class than any other model of automobile, with its one hundredth victory on September 2, 1990. Following that, the RX-7 won its class in the IMSA 24 Hours of Daytona race ten years in a row, starting in 1982. The RX7 won the IMSA Grand Touring Under Two Liter (GTU) championship each year from 1980 through 1987, inclusive.

Formula Mazda Racing features open-wheel race cars with Mazda Wankel engines, adaptable to both oval tracks and road courses, on several levels of competition. Since 1991, the professionally organized Star Mazda Series has been the most popular format for sponsors, spectators, and upward bound drivers. The engines are all built by one engine builder, certified to produce the prescribed power, and sealed to discourage tampering. They are in a relatively mild state of racing tune, so that they are extremely reliable and can go years between motor rebuilds.

The Malibu Grand Prix chain, similar in concept to commercial recreational kart racing tracks, operates several venues in the United States where a customer can purchase several laps around a track in a vehicle very similar to open wheel racing vehicles, but powered by a small Curtiss-Wright rotary engine.

In engines having more than two rotors, or two rotor race engines intended for high-rpm use, a multi-piece eccentric shaft may be used, allowing additional bearings between rotors. While this approach does increase the complexity of the eccentric shaft design, it has been used successfully in the Mazda's production three-rotor 20B-REW engine, as well as many low volume production race engines. (The C-111-2 4 Rotor Mercedes-Benz eccentric shaft for the KE Serie 70, Typ DB M950 KE409 is made in one piece. Mercedes-Benz used split bearings.)

Motorcycle engines

Norton Interpol2 prototype

From 1974 to 1977 Hercules produced a limited number of motorcycles powered by Wankel engines. The motor tooling and blank apex seals were later used by Norton to produce the Norton Commander model in the early 1980s.

The Suzuki RE5 was a Wankel-powered motorcycle produced in 1975 and 1976. It was touted as the future of motorcycling, however, other problems and a lack of parts interchangeability meant low sales.

Dutch motorcycle importer and manufacturer van Veen produced small quantities of their dual rotor Wankel-engined OCR-1000 between 1978 and 1980, using surplus Comotor engines.

However, from the 1980s onwards, rotary engines have not been produced for sale to the general public for road use. Norton has used a Wankel engine in several models including the F1, F1 Sports, RC588, RCW588, NRS588, most notably Steve Hislop riding to various victories on Norton's F1 in the TT in 1992. Norton now makes a 588cc twin-rotor model called the NRV588 and is in the process of making a 700cc version called the NRV700.

Aircraft engines

Diamond DA20 with Diamond Engines Wankel

Sikorsky Cypher UAV powered with a UEL AR801 Wankel engine

The first Wankel rotary-engine aircraft was the experimental Lockheed Q-Star civilian version of the United States Army's reconnaissance QT-2, basically a powered Schweizer sailplane, in 1968 or 1969. It was powered by a 185 hp (138 kW) Curtiss-Wright RC2-60 Wankel rotary engine.

Aircraft Wankels have made something of a comeback in recent years. None of their advantages have been lost in comparison to other engines. They are increasingly being found in roles where their compact size and quiet operation is important, notably in drones, or UAVs. Many companies and hobbyists adapt Mazda rotary engines (taken from automobiles) to aircraft use; others, including Wankel GmbH itself, manufacture Wankel rotary engines dedicated for the purpose. One such use are the "Rotapower" engines in the Moller Skycar M400.

Wankel engines are also becoming increasingly popular in homebuilt experimental aircraft. Most are Mazda 12A and 13B automobile engines, converted to aviation use. This is a very cost-effective alternative to certified aircraft engines, providing engines ranging from 100 to 300 horsepower (220 kW) at a fraction of the cost of traditional engines. These conversions first took place in the early 1970s. With a number of these engines mounted on aircraft, as of 10 December 2006 the National Transportation Safety Board has only seven reports of incidents involving aircraft with Mazda engines, and none of these were a failure due to design or manufacturing flaws.

Peter Garrison, Contributing Editor for *Flying* magazine, has said that "the most promising engine for aviation use is the Mazda rotary." Mazdas have indeed worked well when converted for use in homebuilt aircraft. However, the real challenge in aviation is

producing FAA-certified alternatives to the standard reciprocating engines that power most small general aviation aircraft. Mistral Engines, based in Switzerland, developed purpose-built rotaries for factory and retro-fit installations on certified production aircraft. The G-190 and G-230-TS rotary engines were already flying in the experimental market, and Mistral Engines hoped for FAA and JAA certification by 2011. As of June 2010, G-300 rotary engine development ceased, with the company citing a need for cash flow to complete development.

Mistral claims to have overcome the challenges of fuel consumption inherent in the rotary, at least to the extent that the engines are demonstrating specific fuel consumption within a few points of reciprocating engines of similar displacement. While fuel burn is still marginally higher than traditional engines, it is outweighed by other beneficial factors.

Since Wankel engines operate at a relatively high rotational speed with relatively low torque, propeller aircraft must use a Propeller Speed Reduction Unit (PSRU) to keep conventional propellers within the proper speed range. There are many experimental aircraft flying with this arrangement.

Pratt & Whitney Rocketdyne have been commissioned by DARPA to develop a diesel wankel engine for use in a prototype VTOL flying car called the "Transformer". The engine, based on an earlier UAV diesel wankel concept called 'EnduroCORE', will utilize wankel rotors of varying sizes on a shared eccentric shaft to increase efficiency. The engine is claimed to be a 'full-compression, full-expansion, diesel-cycle engine', which sets it apart from the earlier Rolls-Royce prototype that required an external air compressor to achieve high enough compression for diesel-cycle combustion.

Other uses

UEL UAV-741 Wankel engine for a UAV

Small Wankel engines are being found increasingly in other roles, such as go-karts, personal water craft and auxiliary power units for aircraft. The Graupner/O.S. 49-PI is a 1.27 hp (947 W) 5 cc Wankel engine for model airplane use which has been in production essentially unchanged since 1970; even with a large muffler, the entire package weighs only 380 grams (13.4 ounces).

The simplicity of the Wankel makes it well-suited for mini, micro, and micro-mini engine designs. The Microelectromechanical systems (MEMS) Rotary Engine Lab at the University of California, Berkeley has been developing Wankel engines of down to 1 mm in diameter with displacements less than 0.1 cc. Materials include silicon and motive power includes compressed air. The goal is to eventually develop an internal combustion engine that will deliver 100 milliwatts of electrical power; the engine itself will serve as the rotor of the generator, with magnets built into the engine rotor itself.

The largest Wankel engine was built by Ingersoll-Rand; available in 550 hp (410 kW) one rotor and 1,100 hp (820 kW) two rotor versions, displacing 41 liters per rotor with a

rotor approximately one meter in diameter, it was available between 1975 and 1985. It was derived from a previous, unsuccessful Curtiss-Wright design, which failed because of a well-known problem with all internal combustion engines: the fixed speed at which the flame front travels limits the distance combustion can travel from the point of ignition in a given time, and thereby limiting the maximum size of the cylinder or rotor chamber which can be used. This problem was solved by limiting the engine speed to only 1200 rpm and the use of natural gas as fuel; this was particularly well chosen, since one of the major uses of the engine was to drive compressors on natural gas pipelines. Yanmar Diesel of Japan, produced some small, charge cooled rotor rotary engines for uses such as chainsaws and outboard engines, some of their contributions are that the LDR (rotor recess in the leading edge of combustion chamber) engines had better exhaust emissions profiles, and that reed-valve controlled intake ports improve part-load and low RPM performance.(Kojiro Yamaoka & Hiroshi Tado, SAE paper 720466, 1972)

In 2010 Audi revealed that in their electric car the A1 e-tron they would have a small 250 cc Wankel engine running at 5,000 rpm that would recharge the car's batteries as needed.

Non-internal combustion

In addition for use as an internal combustion engine, the basic Wankel design has also been utilized for gas compressors, and superchargers for internal combustion engines, but in these cases, although the design still offers advantages in reliability, the basic advantages of the Wankel in size and weight over the four-stroke internal combustion engine are irrelevant. In a design using a Wankel supercharger on a Wankel engine, the supercharger is twice the size of the engine.

The Wankel design is used in the seat belt pre-tensioner system of some Mercedes-Benz and Volkswagen cars. When the deceleration sensors sense a potential crash, small explosive cartridges are triggered electrically and the resulting pressurized gas feeds into tiny Wankel engines which rotate to take up the slack in the seat belt systems, anchoring the driver and passengers firmly in the seat before a collision.

Chapter 14

Poppet Valve

Poppet valve & components

A **poppet valve** (also called **mushroom valve**) is a valve consisting of a hole, usually round or oval, and a tapered plug, usually a disk shape on the end of a shaft also called a valve stem. The shaft guides the plug portion by sliding through a valve guide. In most applications a pressure differential helps to seal the valve and in some applications also open it.

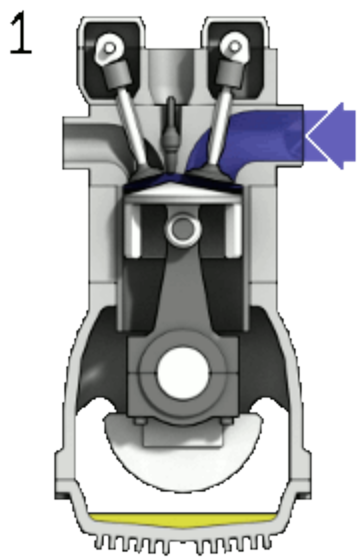
Presta and Schrader valves used on pneumatic tires are examples of poppet valves. The Presta valve has no spring and relies on a pressure differential for opening and closing while being inflated.

Etymology

The word poppet shares etymology with "puppet": it is from the Middle English *popet* ("youth" or "doll"), from Middle French *poupette*, which is a diminutive of *poupe*. The use of the word *poppet* to describe a valve comes from the same word applied to marionettes, which – like the poppet valve – move bodily in response to remote motion transmitted linearly. In the past, "puppet valve" was a synonym for *poppet valve*; however, this usage of "puppet" is now obsolete.

Operation

The operating principle of poppet valves is described in "How Poppet Valves Work". In most cases it is beneficial to have a "balanced poppet" in a direct acting valve. Less force is needed to move the poppet because all forces on the poppet are nullified by equal and opposite forces. The solenoid coil has to counteract only the spring force.



Poppet valves in action at the top of the cylinder

Applications

Poppet valves are used in many industrial process from controlling the flow of milk to isolating sterile air in the semiconductor industry. However, they are most well-known for their use in internal combustion and steam engines, as described below.

Internal combustion engine

Poppet valves are used in most piston engines to open and close the intake and exhaust ports in the cylinder head. The valve is usually a flat disk of metal with a long rod known as the *valve stem* attached to one side.

The stem is used to push down on the valve and open it, with a spring generally used to return it to the close position when the stem is not being depressed. At high RPM, spring forces are too slow to return the valve to its seat between cycles, leading to 'valve float' . In this situation Desmodromic valves are used which, being closed by a positive mechanical action instead of by a spring, are able to cycle at the high speeds required in, for instance, motorcycle and auto racing engines .

The engine normally operates the valves by pushing on the stems with cams and Cam followers. The shape and position of the cam determines the valve lift and when and how quickly (or slowly) the valve is opened. The cams are normally placed on a fixed camshaft which is then geared to the crankshaft, running at half crankshaft speed in a four-stroke engine. On high performance engines, the camshaft is movable and the cams have a varying height, so by axially moving the camshaft in relation with the engine RPM, also the valve lift varies.

For certain applications the valve stem and disk are made of different steel alloys, or the valve stems may be hollow and filled with sodium to improve heat transport and transfer. Although better heat conductors, aluminum cylinder heads require steel valve seat inserts while cast iron cylinder heads often used integral valve seats in the past. Because the valve stem extends into lubrication in the cam chamber it must be sealed against blow-by to prevent cylinder gases from escaping into the crankcase. A rubber lip-type seal ensures that excessive amounts of oil are not drawn in from the crankcase on the induction stroke and that exhaust gas does not enter the crankcase on the exhaust stroke. Worn valve seals are characterised by a puff of blue smoke from the exhaust when pressing back down on the accelerator pedal after allowing the engine to over-run, such as when changing gears.

Valve position

In very early engine designs the valves were 'upside down' in the block, parallel to the cylinders - the so called **L-head** engine because of the shape of the cylinder and combustion chamber, also called 'flathead engine' as the top of the cylinder head is flat. Although this design makes for simplified and cheap construction, it has two major drawbacks; the tortuous path followed by the intake charge limits air flow and effectively prevents speeds greater than 2,000-2,500 RPM, and the travels of the exhaust through the block can cause overheating under sustained heavy load. This design evolved into 'Intake Over Exhaust', **IOE** or **F-head**, where the intake valve was in the head and the exhaust valve was in the block; later both valves moved to the head.

In most such designs the camshaft remained relatively near the crankshaft and the valves were operated through pushrods and rocker arms. This led to significant energy losses in

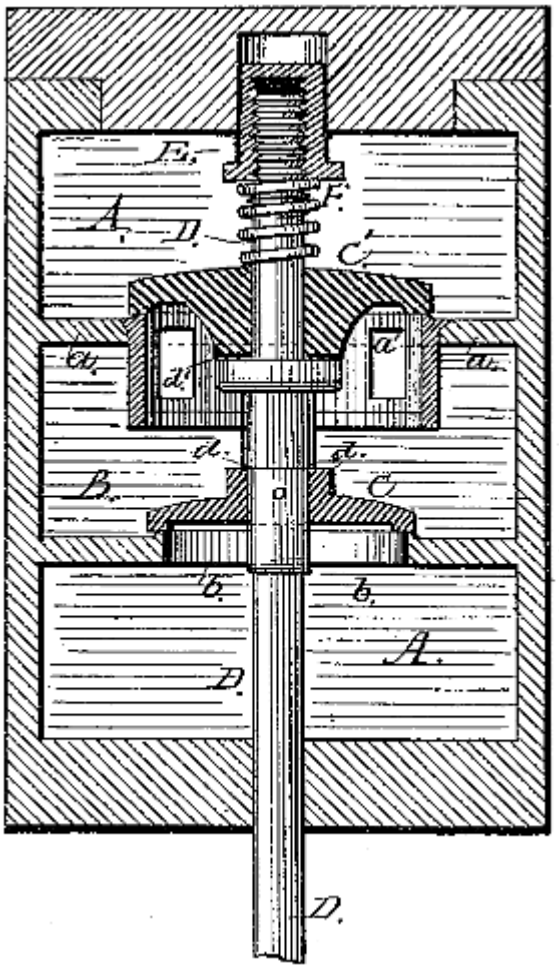
the engine, but was simpler, especially in a V engine where one camshaft can actuate the valves for both cylinder banks; for this reason, pushrod engine designs persisted longer in these configurations than others.

More modern designs have the camshaft on top of the cylinder head, pushing directly on the valve stem (again through cam followers, also known as tappets), a system known as *overhead camshaft*; if there is just one camshaft, this is a single overhead cam or *SOHC* engine. Often there are two camshafts, one for the intake and one for exhaust valves, creating the dual overhead cam, or *DOHC*. The camshaft is driven by the crankshaft - through gears, a chain or a timing belt.

Valve wear

In the early days of engine building, the poppet valve was a major problem. Metallurgy was not what it is today, and the rapid opening and closing of the valves against the cylinder heads led to rapid wear. They would need to be re-ground every two years or so, in an expensive and time consuming process known as a *valve job*. Adding tetra-ethyl lead to the petrol reduced this problem to some degree as the lead would coat the valve seats, in effect lubricating the metal. Valve seats made of improved alloys such as stellite have generally made this problem disappear completely and made leaded fuel unnecessary.

Steam engine



Balanced Poppet Valve from U.S. Patent 339,809. High pressure steam enters at A and exits at B. The valve stem D moves up to open the valve discs C

When used in high pressure applications, for example, as admission valves on steam engines, the same pressure that helps seal poppet valves also contributes significantly to the force required to open them. This has led to the development of the balanced poppet or double beat valve, in which two valve plugs ride on a common stem, with the pressure on one plug largely balancing the pressure on the other. In these valves, the force needed to open the valve is determined by the pressure and the difference between the areas of the two valve openings.

Poppet valves have been used on steam locomotives, often in conjunction with Lentz or Caprotti valve gear. British examples include:

- LNER Class B12
- LNER Class D49
- LNER Class P2

- LMS Stanier Class 5 4-6-0
- BR standard class 5
- BR standard class 8 71000 Duke of Gloucester.

Sentinel Waggon Works used poppet valves in their steam wagons and steam locomotives. Reversing was achieved by a simple sliding camshaft system.

The poppet valve was also used on the American Pennsylvania Railroad's T1 duplex locomotives, although the valves commonly failed due to the fact that that the locomotives were commonly operated in excess of 160 km/h (100 mph), and the valves were not meant for the stresses of such speeds.