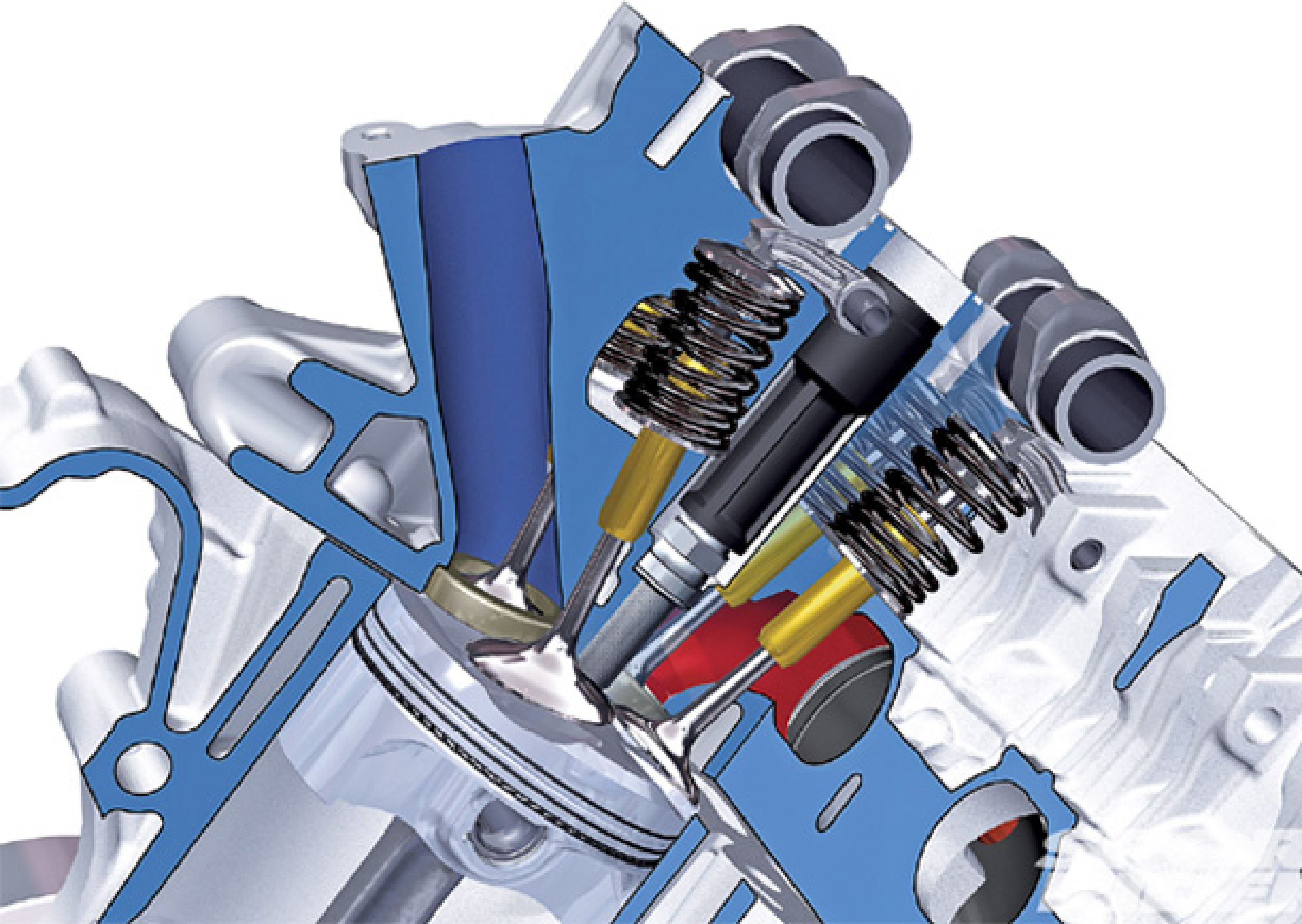
Engine Technology

Heike Settles



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Chapter 1

Engine Control Unit

An **engine control unit (ECU)**, also known as **power-train control module (PCM)**, or **engine control module (ECM)** is a type of electronic control unit that determines the amount of fuel, ignition timing and other parameters an internal combustion engine needs to keep running. It does this by reading values from multidimensional performance maps (so called LUTs), using input values (e.g. engine speed) calculated from signals coming from sensor devices monitoring the engine. Before ECU's, air/fuel mixture, ignition timing, and idle speed were directly controlled by mechanical and pneumatic sensors and actuators. One of the very first attempts to use such a unitized and automated "ECU" device to manage multiple engine control functions simultaneously was created by BMW in 1939, for their BMW 801 14-cylinder aviation engine, and known as the *Kommandogerät*, operated only by a single throttle lever.

Working of ECU

Control of fuel mixture

For an engine with fuel injection, an engine control unit (ECU) will determine the quantity of fuel to inject based on a number of parameters. If the throttle pedal is pressed further down, this will open the throttle body and allow more air to be pulled into the engine. The ECU will inject more fuel according to how much air is passing into the engine. If the engine has not warmed up yet, more fuel will be injected (causing the engine to run slightly 'rich' until the engine warms up). Mixture control on computer controlled carburetors works similarly but with a mixture control solenoid or stepper motor incorporated in the float bowl of the carburetor.

Control of ignition timing

A spark ignition engine requires a spark to initiate combustion in the combustion chamber. An ECU can adjust the exact timing of the spark (called ignition timing) to provide better power and economy. If the ECU detects knock, a condition which is potentially destructive to engines, and "judges" it to be the result of the ignition timing being too early in the compression stroke, it will delay (retard) the timing of the spark to prevent this. A second, more common source, cause, of knock/ping is operating the engine in too low of an RPM range for the "work" requirement of the moment. In this case the knock/ping results from the piston not being able to move downward as fast as the flame front is expanding, but this latter mostly applies only to manual transmission equipped vehicles. The ECU controlling an automatic transmission would simply downshift the transmission if this were the cause of knock/ping.

Control of idle speed

Most engine systems have idle speed control built into the ECU. The engine RPM is monitored by the crankshaft position sensor which plays a primary role in the engine timing functions for fuel injection, spark events, and valve timing. Idle speed is controlled by a programmable throttle stop or an idle air bypass control stepper motor. Early carburetor-based systems used a programmable throttle stop using a bidirectional DC motor. Early TBI systems used an idle air control stepper motor. Effective idle speed control must anticipate the engine load at idle. Changes in this idle load may come from HVAC systems, power steering systems, power brake systems, and electrical charging and supply systems. Engine temperature and transmission status, and lift and duration of camshaft also may change the engine load and/or the idle speed value desired.

A full authority throttle control system may be used to control idle speed, provide cruise control functions and top speed limitation.

Control of variable valve timing

Some engines have Variable Valve Timing. In such an engine, the ECU controls the time in the engine cycle at which the valves open. The valves are usually opened sooner at higher speed than at lower speed. This can optimize the flow of air into the cylinder, increasing power and economy.

Electronic valve control

Experimental engines have been made and tested that have no camshaft, but has full electronic control of the intake and exhaust valve opening, valve closing and area of the valve opening. Such engines can be started and run without a starter motor for certain multi-cylinder engines equipped with precision timed electronic ignition and fuel injection. Such a *static-start* engine would provide the efficiency and pollution-reduction improvements of a mild hybrid-electric drive, but without the expense and complexity of an oversized starter motor.

Programmable ECUs

A special category of ECUs are those which are programmable. These units do not have a fixed behavior, but can be reprogrammed by the user.

Programmable ECUs are required where significant aftermarket modifications have been made to a vehicle's engine. Examples include adding or changing of a turbocharger, adding or changing of an intercooler, changing of the exhaust system, and conversion to run on alternative fuel. As a consequence of these changes, the old ECU may not provide appropriate control for the new configuration. In these situations, a programmable ECU can be wired in. These can be programmed/mapped with a laptop connected using a serial or USB cable, while the engine is running.

The programmable ECU may control the amount of fuel to be injected into each cylinder. This varies depending on the engine's RPM and the position of the accelerator pedal (or the manifold air pressure). The engine tuner can adjust this by bringing up a spreadsheet-like page on the laptop where each cell represents an intersection between a specific RPM value and an accelerator pedal position (or the throttle position, as it is called). In this cell a number corresponding to the amount of fuel to be injected is entered. This spreadsheet is often referred to as a fuel table or fuel map.

By modifying these values while monitoring the exhausts using a wide band lambda probe to see if the engine runs rich or lean, the tuner can find the optimal amount of fuel to inject to the engine at every different combination of RPM and throttle position. This process is often carried out at a dynamometer, giving the tuner a controlled environment to work in. An engine dynamometer gives a more precise calibration for racing applications. Tuners often utilize a chassis dynamometer for street and other high performance applications.

Other parameters that are often mappable are:

- **Ignition:** Defines when the spark plug should fire for a cylinder.
- **Rev. limit:** Defines the maximum RPM that the engine is allowed to reach. After this fuel and/or ignition is cut. Some vehicles have a "soft" cut-off before the "hard" cut-off.
- **Water temperature correction:** Allows for additional fuel to be added when the engine is cold (choke) or dangerously hot.
- **Transient fueling:** Tells the ECU to add a specific amount of fuel when throttle is applied. The term is "acceleration enrichment"
- **Low fuel pressure modifier:** Tells the ECU to increase the injector fire time to compensate for a loss of fuel pressure.
- **Closed loop lambda:** Lets the ECU monitor a permanently installed lambda probe and modify the fueling to achieve stoichiometric (ideal) combustion. On traditional petrol powered vehicles this air:fuel ratio is 14.7:1.

Some of the more advanced race ECUs include functionality such as launch control, limiting the power of the engine in first gear to avoid burnouts. Other examples of advanced functions are:

- **Wastegate control:** Sets up the behavior of a turbocharger's wastegate, controlling boost.

- **Banked injection:** Sets up the behavior of double injectors per cylinder, used to get a finer fuel injection control and atomization over a wide RPM range.
- **Variable cam timing:** Tells the ECU how to control variable intake and exhaust cams.
- **Gear control:** Tells the ECU to cut ignition during (sequential gearbox) upshifts or blip the throttle during downshifts.

A race ECU is often equipped with a data logger recording all sensors for later analysis using special software in a PC. This can be useful to track down engine stalls, misfires or other undesired behaviors during a race by downloading the log data and looking for anomalies after the event. The data logger usually has a capacity between 0.5 and 16 megabytes.

In order to communicate with the driver, a race ECU can often be connected to a "data stack", which is a simple dash board presenting the driver with the current RPM, speed and other basic engine data. These race stacks, which are almost always digital, talk to the ECU using one of several proprietary protocols running over RS232 or CANbus, connecting to the DLC connector (Data Link Connector) usually located on the underside of the dash, inline with the steering wheel

History

Hybrid digital designs

Hybrid digital/analog designs were popular in the mid 1980s. This used analog techniques to measure and process input parameters from the engine, then used a look-up table stored in a digital ROM chip to yield precomputed output values. Later systems compute these outputs dynamically. The ROM type of system is amenable to tuning if one knows the system well. The disadvantage of such systems is that the precomputed values are only optimal for an idealised, new engine. As the engine wears, the system is less able to compensate than a CPU based system.

Modern ECUs

Modern ECUs use a microprocessor which can process the inputs from the engine sensors in real time. An electronic control unit contains the hardware and software (firmware). The hardware consists of electronic components on a printed circuit board (PCB), ceramic substrate or a thin laminate substrate. The main component on this circuit board is a microcontroller chip (CPU). The software is stored in the microcontroller or other chips on the PCB, typically in EPROMs or flash memory so the CPU can be re-programmed by uploading updated code or replacing chips. This is also referred to as an (electronic) Engine Management System (EMS).

Sophisticated engine management systems receive inputs from other sources, and control other parts of the engine; for instance, some variable valve timing systems are electronically controlled, and turbocharger wastegates can also be managed. They also may communicate with transmission control units or directly interface electronically-controlled automatic transmissions, traction control systems, and the like. The Controller Area Network or CAN bus automotive network is often used to achieve communication between these devices.

Modern ECUs sometimes include features such as cruise control, transmission control, anti-skid brake control, and anti-theft control, etc.

General Motors' first ECUs had a small application of hybrid digital ECUs as a pilot program in 1979, but by 1980, all active programs were using microprocessor based systems. Due to the large ramp up of volume of ECUs that were produced to meet the US Clean Air Act requirements for 1981, only one ECU model could be built for the 1981 model year. The high volume ECU that was installed in GM vehicles from the first high volume year, 1981, onward was a modern microprocessor based system. GM moved rapidly to replace carburetor based systems to fuel injection type systems starting in 1980/1981 Cadillac engines, following in 1982 with the Pontiac 2.5L "GM Iron Duke engine" and the Corvette Chevrolet L83 "Cross-Fire" engine. In just a few years all GM carburetor based engines had been replaced by throttle body injection (TBI) or intake manifold injection systems of various types. In 1988 Delco Electronics, Subsidiary of GM Hughes Electronics, produced more than 28,000 ECUs per day, the world's largest producer of on-board digital control computers at the time.

Other applications

Such systems are used for many internal combustion engines in other applications. In aeronautical applications, the systems are known as "FADECs" (Full Authority Digital Engine Controls). This kind of electronic control is less common in piston-engined aeroplanes than in automobiles, because of the large costs of certifying parts for aviation use, relatively small demand, and the consequent stagnation of technological innovation in this market. Also, a carbureted engine with magneto ignition and a gravity feed fuel system does not require electrical power generated by an alternator to run, which is considered a safety advantage.

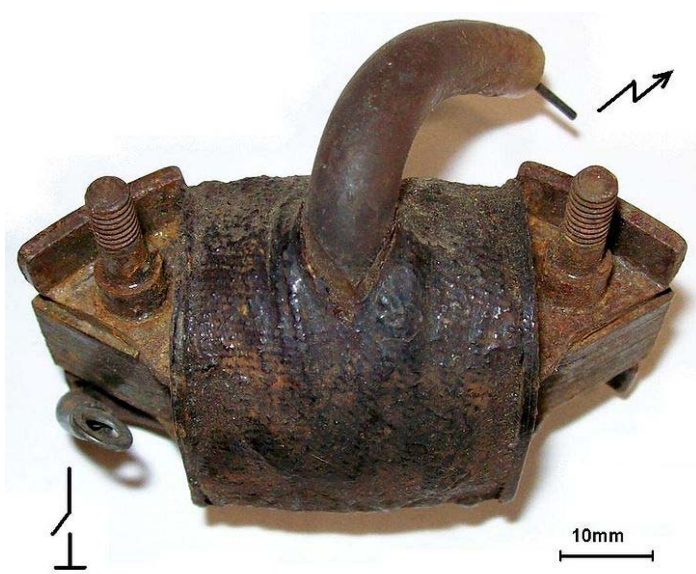
Chapter 2

Ignition System

An **ignition system** is a system for igniting a fuel-air mixture. It is best known in the field of internal combustion engines but also has other applications, e.g. in oil-fired and gas-fired boilers. The earliest internal combustion engines used a flame, or a heated tube, for ignition but these were quickly replaced by systems using an electric spark.

History

Magneto systems



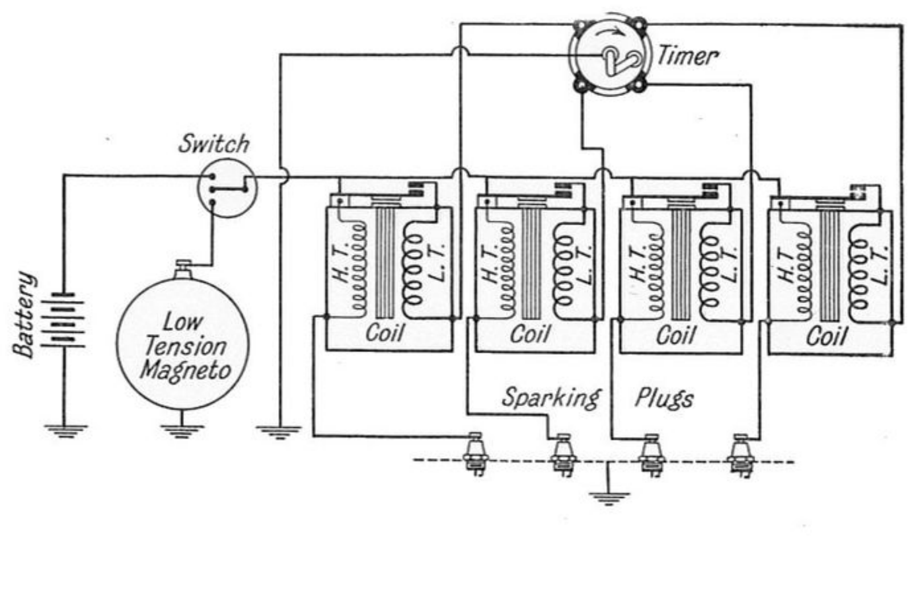
Magneto ignition coil

The simplest form of spark ignition is that using a magnet. The engine spins a magnet inside a coil, or, in the earlier designs, a coil inside a fixed magnet, and also operates a contact breaker, interrupting the current and causing the voltage to be increased sufficiently to jump a small gap. The spark plugs are connected directly from the magneto output. Early magnetos had one coil, with the contact breaker (sparking plug) inside the combustion chamber. In about 1902, Bosch introduced a double-coil magneto, with a fixed sparking plug, and the contact breaker outside the cylinder. Magnetos are not used in modern cars, but because they generate their own electricity they are often found on piston-engined aircraft engines and small engines such as those found in mopeds, lawnmowers, snowblowers, chainsaws, etc. where a battery-based electrical system is not present for any combination of necessity, weight, cost, and reliability reasons.

Magnetos were used on the small engine's ancestor, the stationary "hit or miss" engine which was used in the early twentieth century, on older gasoline or distillate farm tractors before battery starting and lighting became common, and on aircraft piston engines. Magnetos were used in these engines because their simplicity and self-contained operation was more reliable, and because magnetos weighed less than having a battery and dynamo or alternator.

Aircraft engines usually have multiple magnetos to provide redundancy in the event of a failure. Some older automobiles had both a magneto system and a battery actuated system running simultaneously to ensure proper ignition under all conditions with the limited performance each system provided at the time.This gave the benefits of easy starting (from the battery system) with reliable sparking at speed (from the magneto).

Switchable systems



Ford Model T ignition circuit

The output of a magneto depends on the speed of the engine, and therefore starting can be problematic. Some magnetos include an impulse system, which spins the magnet quickly at the proper moment, making easier starting at slow cranking speeds. Some engines, such as aircraft but also the Ford Model T, used a system which relied on non rechargeable dry cells, (similar to a large flashlight battery, and which was not maintained by a charging system as on modern automobiles) to start the engine or for starting and running at low speed. The operator would manually switch the ignition over to magneto operation for high speed operation.

In order to provide high voltage for the spark from the low voltage batteries, a 'tickler' was used, which was essentially a larger version of the once widespread electric buzzer. With this apparatus, the direct current passes through an electromagnetic coil which pulls open a pair of contact points, interrupting the current; the magnetic field collapses, the spring-loaded points close again, the circuit is reestablished, and the cycle repeats rapidly. The rapidly collapsing magnetic field, however, induces a high voltage across the coil which can only relieve itself by arcing across the contact points; while in the case of the buzzer this is a problem as it causes the points to oxidize and/or weld together, in the case of the ignition system this becomes the source of the high voltage to operate the spark plugs.

In this mode of operation, the coil would "buzz" continuously, producing a constant train of sparks. The entire apparatus was known as the 'Model T spark coil' (in contrast to the modern ignition coil which is *only* the actual coil component of the system). Long after the demise of the Model T as transportation they remained a popular self-contained source of high voltage for electrical home experimenters, appearing in articles in magazines such as *Popular Mechanics* and projects for school science fairs as late as the early 1960s. In the UK these devices were commonly known as trembler coils and were popular in cars pre-1910, and also in commercial vehicles with large engines until around 1925 to ease starting.

The Model T (built into the flywheel) differed from modern implementations by not providing high voltage directly at the output; the maximum voltage produced was about 30 volts, and therefore also had to be run through the spark coil to provide high enough voltage for ignition, as described above, although the coil would not "buzz" continuously in this case, only going through one cycle per spark. In either case, the low voltage was switched to the appropriate spark plug by the *'timer'* mounted on the front of the engine. This performed the equivalent function to the modern distributor, although by directing the low voltage, not the high voltage as for the distributor. The timing of the spark was adjustable by rotating this mechanism through a lever mounted on the steering column. As the precise timing of the spark depends on *both* the 'timer' and the trembler contacts within the coil, this is less consistent than the breaker points of the later distributor. However for the low speed and the low compression of such early engines, this imprecise timing was acceptable.

Battery-operated ignition

With the universal adaptation of electrical starting for automobiles, and the concomitant availability of a large battery to provide a constant source of electricity, magneto systems were abandoned for systems which interrupted current at battery voltage, used an ignition coil (a type of autotransformer) to step the voltage up to the needs of the ignition, and a distributor to route the ensuing pulse to the correct spark plug at the correct time.

The first reliable battery operated ignition was developed by the Dayton Engineering Laboratories Co. (Delco) and introduced in the 1910 Cadillac. This ignition was developed by Charles Kettering and was a wonder in its day. It consisted of a single coil, points (the switch), a capacitor and a distributor set up to allocate the spark from the ignition coil timed to the correct cylinder. The coil was basically an autotransformer set up to step up the low (6 or 12 V) voltage supply to the high ignition voltage required to jump a spark plug gap.

The points allow the coil to charge magnetically and then, when they are opened by a cam arrangement, the magnetic field collapses and a large (20 kV or greater) voltage is produced. The capacitor is used to absorb the back EMF from the magnetic field in the coil to minimize point contact burning and maximize point life. The Kettering system became the primary ignition system for many years in the automotive industry due to its lower cost, higher reliability and relative simplicity.

Modern ignition systems

The ignition system is typically controlled by a key operated Ignition switch.

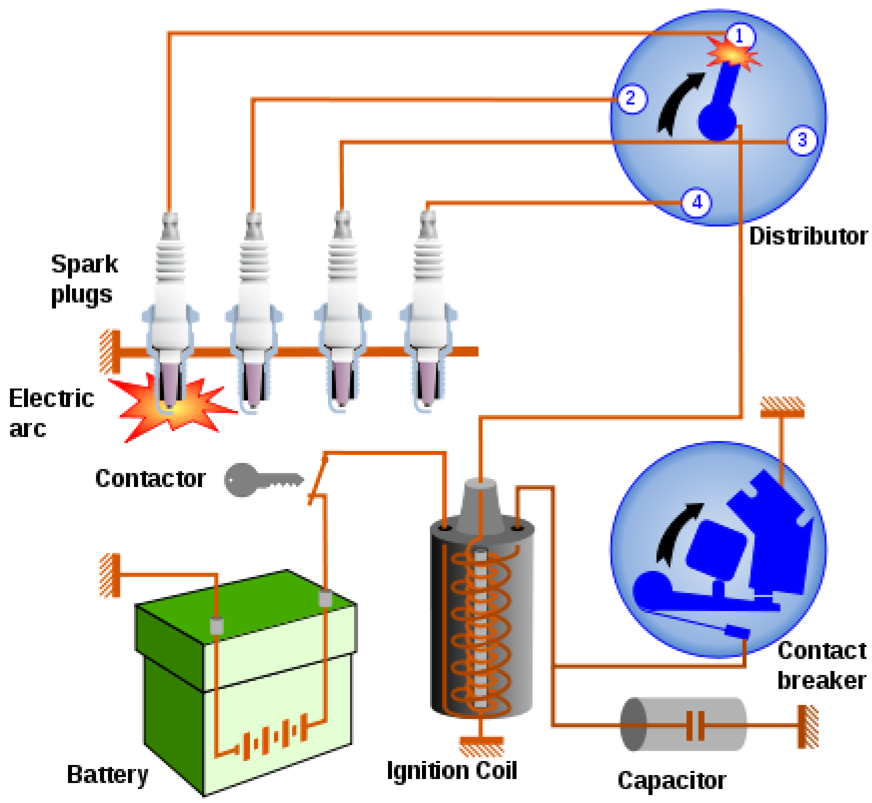
Mechanically timed ignition

Distributor cap

Most four-stroke engines have used a mechanically timed electrical ignition system. The heart of the system is the distributor. The distributor contains a rotating cam driven by the engine's drive, a set of breaker points, a condenser, a rotor and a distributor cap. External to the distributor is the ignition coil, the spark plugs and wires linking the distributor to the spark plugs and ignition coil.

The system is powered by a lead-acid battery, which is charged by the car's electrical system using a dynamo or alternator. The engine operates contact breaker points, which interrupt the current to an induction coil (known as the ignition coil).

The ignition coil consists of two transformer windings sharing a common magnetic core—the primary and secondary windings. An alternating current in the primary induces alternating magnetic field in the coil's core. Because the ignition coil's secondary has far more windings than the primary, the coil is a step-up transformer which induces a much higher voltage across the secondary windings. For an ignition coil, one end of windings of both the primary and secondary are connected together. This common point is connected to the battery (usually through a current-limiting ballast resistor). The other end of the primary is connected to the points within the distributor. The other end of the secondary is connected, via the distributor cap and rotor, to the spark plugs.



Ignition Circuit Diagram - Mechanically Timed Ignition

The ignition firing sequence begins with the points (or contact breaker) closed. A steady charge flows from the battery, through the current-limiting resistor, through the coil primary, across the closed breaker points and finally back to the battery. This steady current produces a magnetic field within the coil's core. This magnetic field forms the energy reservoir that will be used to drive the ignition spark.

As the engine turns, so does the cam inside the distributor. The points ride on the cam so that as the engine turns and reaches the top of the engine's compression cycle, a high point in the cam causes the breaker points to open. This breaks the primary winding's circuit and abruptly stops the current through the breaker points. Without the steady current through the points, the magnetic field generated in the coil immediately and rapidly collapses. This change in the magnetic field induces a high voltage in the coil's secondary windings.

At the same time, current exits the coil's primary winding and begins to charge up the capacitor ("condenser") that lies across the now-open breaker points. This capacitor and the coil's primary windings form an oscillating LC circuit. This LC circuit produces a damped, oscillating current which bounces energy between the capacitor's electric field and the ignition coil's magnetic field. The oscillating current in the coil's primary, which produces an oscillating magnetic field in the coil, extends the high voltage pulse at the output of the secondary windings. This high voltage thus continues beyond the time of the initial field collapse pulse. The oscillation continues until the circuit's energy is consumed.

The ignition coil's secondary windings are connected to the distributor cap. A turning rotor, located on top of the breaker cam within the distributor cap, sequentially connects the coil's secondary windings to one of the several wires leading to each cylinder's spark plug. The extremely high voltage from the coil's secondary -– often higher than 1000 volts—causes a spark to form across the gap of the spark plug. This, in turn, ignites the compressed air-fuel mixture within the engine. It is the creation of this spark which consumes the energy that was originally stored in the ignition coil's magnetic field.

High performance engines with eight or more cylinders that operate at high r.p.m. (such as those used in motor racing) demand both a higher rate of spark and a higher spark energy than the simple ignition circuit can provide. This problem is overcome by using either of these adaptations:

- **Two complete sets of coils, breakers and condensers** can be provided - one set for each half of the engine, which is typically arranged in V-8 or V-12 configuration. Although the two ignition system halves are electrically independent, they typically share a single distributor which in this case contains two breakers driven by the rotating cam, and a rotor with two isolated conducting planes for the two high voltage inputs.
- A single breaker driven by a cam and a return spring is limited in spark rate by the onset of contact bounce or float at high rpm. This limit can be overcome by substituting for the breaker a **pair of breakers** that are connected electrically in series but spaced on opposite sides of the cam so they are driven out of phase. Each breaker then switches at half the rate of a single breaker and the "dwell" time for current buildup in the coil is maximized since it is shared between the breakers. The Lamborghini V-12 engine has both these adaptations and therefore uses two ignition coils and a single distributor that contains 4 contact breakers.

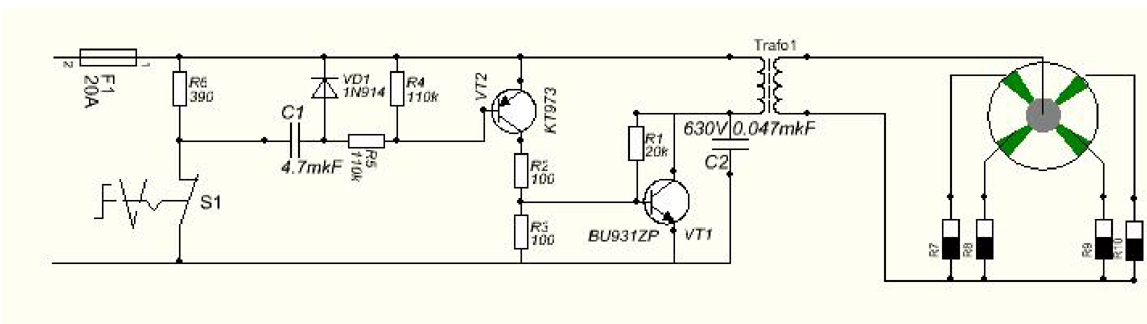
A distributor-based system is not greatly different from a magneto system except that more separate elements are involved. There are also advantages to this arrangement. For example, the position of the contact breaker points relative to the engine angle can be changed a small amount dynamically, allowing the ignition timing to be automatically advanced with increasing revolutions per minute (RPM) and/or increased manifold vacuum, giving better efficiency and performance.

However it is necessary to check periodically the maximum opening gap of the breaker(s), using a feeler gauge, since this mechanical adjustment affects the "dwell" time during which the coil charges, and breakers should be re-dressed or replaced when they have become pitted by electric arcing. This system was used almost universally until the late 1970s, when electronic ignition systems started to appear.

Electronic ignition

The disadvantage of the mechanical system is the use of breaker points to interrupt the low-voltage high-current through the primary winding of the coil; the points are subject to mechanical wear where they ride the cam to open and shut, as well as oxidation and burning at the contact surfaces from the constant sparking. They require regular adjustment to compensate for wear, and the opening of the contact breakers, which is responsible for spark timing, is subject to mechanical variations.

In addition, the spark voltage is also dependent on contact effectiveness, and poor sparking can lead to lower engine efficiency. A mechanical contact breaker system cannot control an average ignition current of more than about 3 A while still giving a reasonable service life, and this may limit the power of the spark and ultimate engine speed.



Example of a basic electronic ignition system

Electronic ignition (EI) solves these problems. In the initial systems, points were still used but they handled only a low current which was used to control the high primary current through a solid state switching system. Soon, however, even these contact breaker points were replaced by an angular sensor of some kind - either optical, where a vaned rotor breaks a light beam, or more commonly using a Hall effect sensor, which responds to a rotating magnet mounted on the distributor shaft. The sensor output is shaped and processed by suitable circuitry, then used to trigger a switching device such as a thyristor, which switches a large current through the coil.

The first electronic ignition (a cold cathode type) was tested in 1948 by Delco-Remy, while Lucas introduced a transistorized ignition in 1955, which was used on BRM and Coventry Climax Formula One engines in 1962. The aftermarket began offering EI that year, with both the AutoLite Electric Transistor 201 and Tung-Sol EI-4 being available. Pontiac became the first automaker to offer an optional EI, the breakerless magnetic pulse-triggered Delcotronic, on some 1963 models; it was also available on some Corvettes. Ford fitted a Lucas system on the Lotus 25s entered at Indianapolis the next year, ran a fleet test in 1964, and began offering optional EI on some models in 1965. Beginning in 1958, Earl W. Meyer at Chrysler worked on EI, continuing until 1961 and resulting in use of EI on the company's NASCAR hemis in 1963 and 1964.

Prest-O-Lite's CD-65, which relied on capacitance discharge (CD), appeared in 1965, and had "an unprecedented 50,000 mile warranty." (This differs from the non-CD Prest-O-Lite system introduced on AMC products in 1972, and made standard equipment for the 1975 model year.) A similar CD unit was available from Delco in 1966, which was optional on Oldsmobile, Pontiac, and GMC vehicles in the 1967 model year. Also in 1967, Motorola debuted their breakerless CD system.

FIAT became the first company to offer standard EI, in 1968, followed by Chrysler (after a 1971 trial) in 1973 and by Ford and GM in 1975.

In 1967, Prest-O-Lite made a "Black Box" ignition amplifier, intended to take the load off of the distributor's breaker points during high r.p.m. runs, which was used by Dodge and Plymouth on their factory Super Stock Coronet and Belvedere and drag racers. This amp was installed on the interior-side of the cars' firewall, and had a duct which provided outside air to cool the amp. The rest of the system (distributor and spark plugs) remains as for the mechanical system. The lack of moving parts compared with the mechanical system leads to greater reliability and longer service intervals. Chrysler introduced breakerless ignition in mid-1971 as an option for its 340 V8 and the 426 Street Hemi. For the 1972 model year, the system became standard on its high-performance engines (the 340 cu in (5.6 l) and the four-barrel carburetor-equipped 400 hp (298 kW) 400 cu in (7 l)) and was an option on its 318 cu in (5.2 l), 360 cu in (5.9 l), two-barrel 400 cu in (6.6 l), and low-performance 440 cu in (7.2 l) . Breakerless Ignition was standardised across the model range for 1973. For older cars, it is usually possible to retrofit an EI system in place of the mechanical one. In some cases, a modern distributor will fit into the older engine with no other modifications, like the H.E.I. distributor made by General Motors, and the aforementioned Chrysler-built electronic ignition (with an "Orange Box" amplifier and a faster-advance curve distributor).

Other innovations are currently available on various cars. In some models, rather than one central coil, there are individual coils on each spark plug, sometimes known as direct ignition or coil on plug (COP). This allows the coil a longer time to accumulate a charge between sparks, and therefore a higher energy spark. A variation on this has each coil handle two plugs, on cylinders which are 360 degrees out of phase (and therefore reach TDC at the same time); in the four-cycle engine this means that one plug will be sparking during the end of the exhaust stroke while the other fires at the usual time, a so-called "wasted spark" arrangement which has no drawbacks apart from faster spark plug erosion; the paired cylinders are 1/4 and 2/3. Other systems do away with the distributor as a timing apparatus and use a magnetic crank angle sensor mounted on the crankshaft to trigger the ignition at the proper time.

During the 1980s, electronic ignition systems were developed alongside other improvements such as fuel injection systems. After a while it became logical to combine the functions of fuel control and ignition into one electronic system known as an engine control unit. However on older vehicles this was not possible and now a common electronic ignition system for classic cars is the Powerspark electronic ignition.

Digital electronic ignitions

At the turn of the 21st century digital electronic ignition modules became available for small engines on such applications as chainsaws, string trimmers, leaf blowers, and lawn mowers. This was made possible by low cost, high speed, and small footprint microcontrollers. Digital electronic ignition modules can be designed as either capacitor discharge ignition (CDI) or inductive discharge ignition (IDI) systems. Capacitive discharge digital ignitions store charged energy for the spark in a capacitor within the module that can be released to the spark plug at virtually any time throughout the engine cycle via a control signal from the microprocessor. This allows for greater timing flexibility, and engine performance; especially when designed hand-in-hand with the engine carburetor.

Engine management

In an Engine Management System (EMS), electronics control fuel delivery, ignition timing and firing order. Primary sensors on the system are engine angle (crank or Top Dead Center (TDC) position), airflow into the engine and throttle demand position. The circuitry determines which cylinder needs fuel and how much, opens the requisite injector to deliver it, then causes a spark at the right moment to burn it. Early EMS systems used analogue computer circuit designs to accomplish this, but as embedded systems became fast enough to keep up with the changing inputs at high revolutions, digital systems started to appear.

Some designs using EMS retain the original coil, distributor and spark plugs found on cars throughout history. Other systems dispense with the distributor and individual coils mounted directly atop each spark plug. This removes the need for both distributor and high-tension leads, both components with a poor record for long-term reliability.

Modern EMSs read in data from various sensors about the crank position, manifold temperature, manifold pressure (or air mass flow), throttle position, fuel mixture via the O2 sensor and sometimes the unit will read data from knock sensors and exhaust gas temperature sensors. The EMS then uses collected data to precisely determine how much fuel to deliver and when and thus how far to advance the ignition timing. With electronic ignition systems, individual cylinders can have their own individual ignition timing so that timing can be as aggressive as possible per cylinder without fuel detonation. As a result, sophisticated electronic ignition systems can be both more fuel efficient, and produce better performance, over their counterparts.

Turbine and jet engines

Turbine engines have a capacitor discharge ignition system using one or more ignitor plugs, which are only used at startup or in case the combustor(s) flame goes out. Rocket engines have particularly demanding ignitions systems- if prompt ignition does not occur the chamber can fill with excess fuel and oxidiser and significant overpressure can occur (a 'hard start'). Rockets often employ pyrotechnic devices that place flames across the face of the injector plate, or, alternatively, self-ignition chemicals.

Chapter 3

Supercharger

Supercharger on AMC V8 engine for dragstrip racing

A **supercharger** is an air compressor used for forced induction of an internal combustion engine.

The greater mass flow-rate provides more oxygen to support combustion than would be available in a naturally-aspirated engine, which allows more fuel to be burned and more work to be done per cycle, increasing the power output of the engine.

Power for the unit can come mechanically by a belt, gear, shaft, or chain connected to the engine's crankshaft.

When power comes from an exhaust gas turbine a supercharger is known as a *turbosupercharger* – typically referred to simply as a *turbocharger* or just *turbo*. Common usage restricts the term *supercharger* to mechanically driven units.

History

In 1860, brothers Philander and Francis Marion Roots of Connersville, Indiana, patented the design for an air mover, for use in blast furnaces and other industrial applications. By the late 19th century, it had made its way to Germany, where an engineer called Krigar invented an air pump that utilized twin rotating shafts that compressed air.

The combination of the pair of inventions resulted in a third, with the first functional supercharger attributed to German engineer Gottlieb Daimler, who received a German patent for supercharging an internal combustion engine in 1885. Louis Renault patented a centrifugal supercharger in France in 1902. An early supercharged race car was built by Lee Chadwick of Pottstown, Pennsylvania in 1908, which, it was reported, reached a speed of 100 mph (160 km/h).

Types of supercharger

There are two main types of superchargers defined according to the method of compression: positive displacement and dynamic compressors. The former deliver a fairly constant level of pressure increase at all engine speeds (RPM), whereas the latter deliver increasing pressure with increasing engine speed.

Positive displacement

An Eaton MP62 Roots-type supercharger is visible at the front of this Ecotec LSJ engine in a 2006 Saturn Ion Red Line.

Lysholm screw rotors with complex shape of each rotor which must run at high speed and with close tolerances. This makes this type of supercharger expensive. (This unit has been blued to show close contact areas.)

Positive-displacement pumps deliver a nearly fixed volume of air per revolution at all speeds (minus leakage, which is almost constant at all speeds for a given pressure, thus its importance decreases at higher speeds). The device divides the air mechanically into parcels for delivery to the engine, mechanically moving the air into the engine bit by bit.

Major types of positive-displacement pumps include:

- Roots
- Lysholm screw
- Sliding vane
- Scroll-type supercharger, also known as the G-Lader

Compression type

Positive-displacement pumps are further divided into internal compression and external compression types.

Roots superchargers are typically external compression only (although high-helix roots blowers attempt to emulate the internal compression of the Lysholm screw).

- External compression refers to pumps that transfer air at ambient pressure into the engine. If the engine is running under boost conditions, the pressure in the intake manifold is higher than that coming from the supercharger. That causes a backflow from the engine into the supercharger until the two reach equilibrium. It is the backflow that actually compresses the incoming gas. This is a highly inefficient process, and the main factor in the lack of efficiency of Roots superchargers when used at high boost levels. The lower the boost level the smaller is this loss, and Roots blowers are very efficient at moving air at low pressure differentials, which is what they were first invented for (hence the original term "blower").

All the other types have some degree of internal compression.

- Internal compression refers to the compression of air within the supercharger itself, which, already at or close to boost level, can be delivered smoothly to the engine with little or no back flow. This is more efficient than back flow compression and allows higher efficiency to be achieved. Internal compression devices usually use a fixed internal compression ratio. When the boost pressure is equal to the compression pressure of the supercharger, the back flow is zero. If the boost pressure exceeds that compression pressure, back flow can still occur as in a roots blower. Internal compression blowers must be matched to the expected boost pressure in order to achieve the higher efficiency they are capable of, otherwise they will suffer the same problems and low efficiency of the roots blowers.

Capacity rating

Positive-displacement superchargers are usually rated by their capacity per revolution. In the case of the Roots blower, the GMC rating pattern is typical. The GMC types are rated according to how many two-stroke cylinders, and the size of those cylinders, it is designed to scavenge. GMC has made 2–71, 3–71, 4–71, and the famed 6–71 blowers. For example, a 6–71 blower is designed to scavenge six cylinders of 71 cubic inches each and would be used on a two-stroke diesel of 426 cubic inches, which is designated a 6–71; the blower takes this same designation. However, because 6–71 is actually the *engine's* designation, the actual displacement is less than the simple multiplication would suggest. A 6–71 actually pumps 339 cubic inches per revolution.

Aftermarket derivatives continue the trend with 8–71 to current 14–71 blowers. From this, one can see that a 6–71 is roughly twice the size of a 3–71. GMC also made −53-cubic-inch series in 2-, 3-, 4-, 6-, and 8–53 sizes, as well as a “V71” series for use on engines using a V configuration.

Dynamic

Dynamic compressors rely on accelerating the air to high speed and then exchanging that velocity for pressure by diffusing or slowing it down.

Major types of dynamic compressor are:

- Centrifugal
- Multi-stage axial-flow
- Pressure wave supercharger

Supercharger drive types

Superchargers are further defined according to their method of drive (mechanical—or turbine).

Mechanical

- Belt (V-belt, Synchronous belt, Flat belt)
- Direct drive
- Gear drive
- Chain drive

Exhaust gas turbines

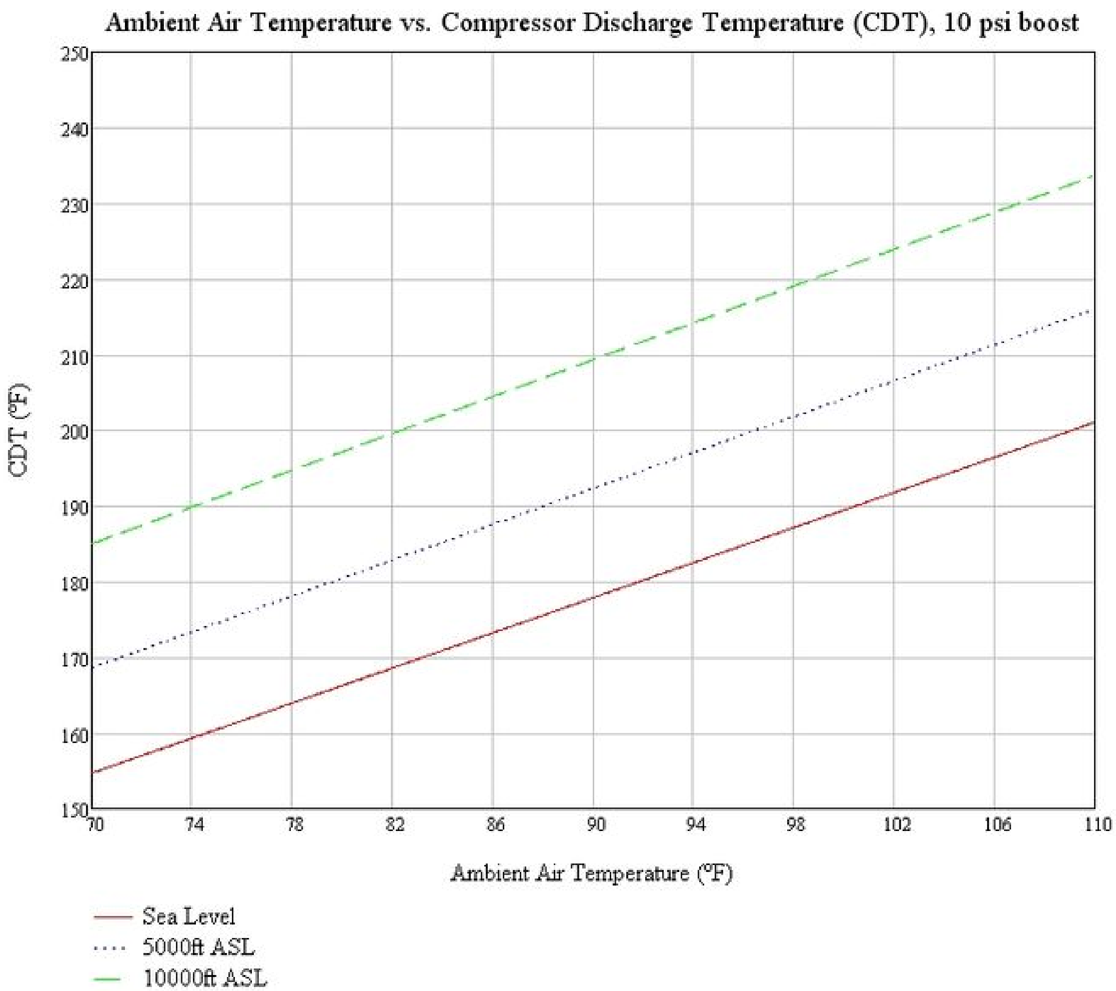
- Axial turbine
- Radial turbine

Other

- Electric motor

All types of compressor may be mated to and driven by either gas turbine or mechanical linkage. Dynamic compressors are most often matched with gas turbine drives due to their similar high-speed characteristics, whereas positive displacement pumps usually use one of the mechanical drives. However, all of the possible combinations have been tried with various levels of success. In principle, a positive displacement engine could be used in place of an exhaust turbine to improve low speed performance. Electric superchargers are all essentially fans (axial pumps). A form of regenerative braking has been tried where the car is slowed by compressing air for future acceleration.

Temperature effects and intercoolers



Supercharger CDT vs. Ambient Temperature. Graph shows how a supercharger's CDT varies with air temperature and altitude (absolute pressure).

One downside of supercharging is that compressing the air increases its temperature. When a supercharger is used on an internal combustion engine, the temperature of the fuel/air charge becomes a major limiting factor in engine performance. Extreme temperatures will cause detonation of the fuel-air mixture (spark ignition engines) and damage to the engine. In cars, this can cause a problem when it is a hot day outside, or when large amounts of boost are being pushed.

It is possible to estimate the temperature rise across a supercharger by modeling it as an isentropic process.

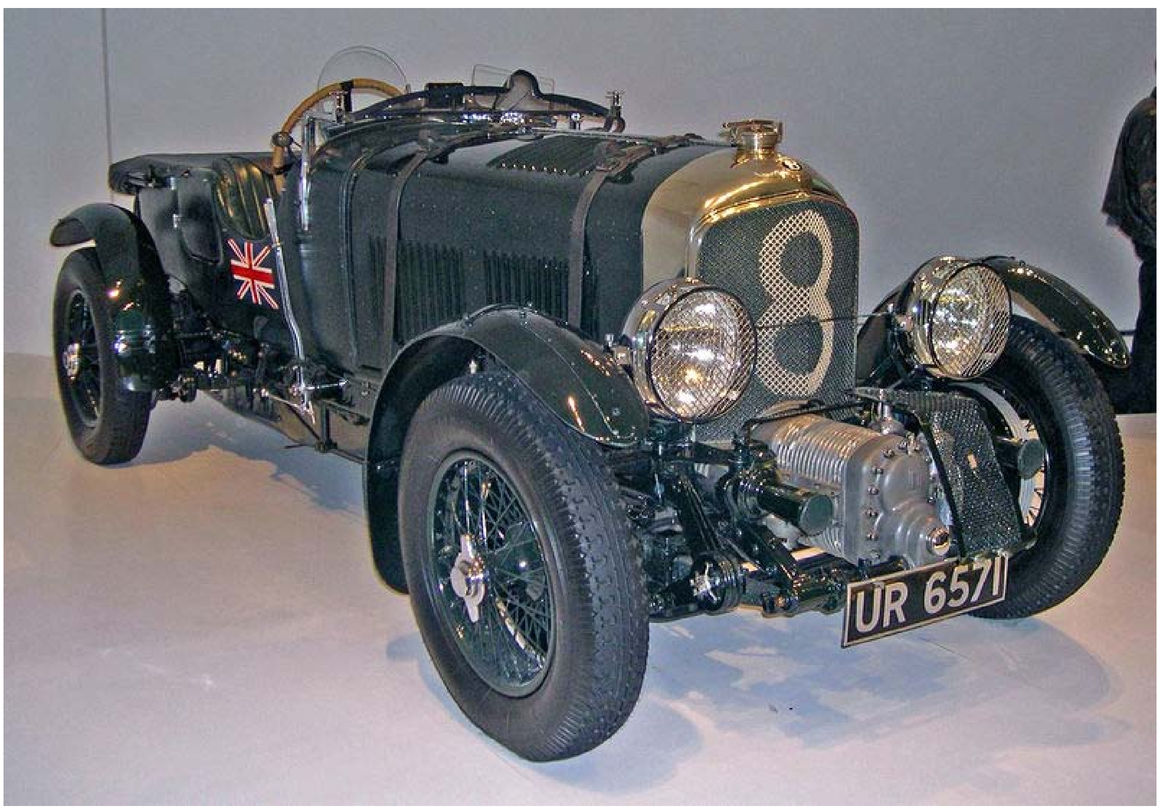
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

Where:
T_1= ambient air temperature
T_2= temperature after the compressor
p_1= ambient atmospheric pressure (absolute)
p_2= pressure after the compressor (absolute)
γ= Ratio of specific heats for air = C_p/C_v
C_p= Specific heat at constant pressure
C_v= Specific heat at constant volume

For example, if a supercharged engine is pushing 10 psi (0.69 bar) of boost at sea level (ambient pressure of 14.7 psi (1.01 bar), ambient temperature of 75 °F), the temperature of the air after the supercharger will be 160.5 °F (71.4 °C). This temperature is known as the compressor discharge temperature (CDT) and highlights why a method for cooling the air after the compressor is so important.

In addition to causing possible detonation and damage, hot intake decreases power in at least one way. At a given pressure, the hotter the air the less dense it is, so the mass of intake is decreased, or for the same mass it takes more power to drive the compressor.

Automobiles



1929 "Blower" Bentley. The large "blower" (supercharger), located in front of the radiator, gave the car its name.

In 1900, Gottlieb Daimler, of Daimler-Benz (Daimler AG), was the first to patent a forced-induction system for internal combustion engines, superchargers based the twin-rotor air-pump design, first patented by the American Francis Roots in 1860, *the* basic design for the modern Roots type supercharger.

The first supercharged cars were introduced at the 1921 Berlin Motor Show: the 6/20 hp and 10/35 hp Mercedes. These cars went into production in 1923 as the 6/25/40 hp (regarded as the first supercharged road car) and 10/40/65 hp. These were normal road cars as other supercharged cars at same time were almost all racing cars, including the 1923 Fiat 805-405, 1923 Miller 122 1924 Alfa Romeo P2, 1924 Sunbeam, 1925 Delage, and the 1926 Bugatti Type 35C. At the end of the 1920s, Bentley made a supercharged version of the Bentley 4½ Litre road car. Since then, superchargers (and turbochargers) have been widely applied to racing and production cars, although the supercharger's technological complexity and cost have largely limited it to expensive, high-performance cars.

Supercharging versus turbocharging

Positive-displacement superchargers may absorb as much as a third of the total crankshaft power of the engine, and, in many applications, are less efficient than turbochargers. In applications for which engine response and power are more important than any other consideration, such as top-fuel dragsters and vehicles used in tractor pulling competitions, positive-displacement superchargers are very common.

There are three main categories of superchargers for automotive use:

- Centrifugal turbochargers – driven from exhaust gases.
- Centrifugal superchargers – driven directly by the engine via a belt-drive.
- Positive displacement pumps – such as the Roots, Twin Screw(Lysholm), and TVS(Eaton) blowers.

The thermal efficiency, or fraction of the fuel/air energy that is converted to output power, is less with a mechanically-driven supercharger than with a turbocharger, because turbochargers are using energy from the exhaust gases that would normally be wasted. For this reason, both the economy and the power of a turbocharged engine are usually better than with superchargers. The main advantage of an engine with a mechanically-driven supercharger is better throttle response, as well as the ability to reach full-boost pressure instantaneously. With the latest turbocharging technology, throttle response on turbocharged cars is nearly as good as with mechanically-powered superchargers, but the existing lag time is still considered a major drawback, especially considering that the vast majority of mechanically-driven superchargers are now driven off clutched pulleys, much like an air compressor.

Turbochargers suffer (to a greater or lesser extent) from so-called *turbo-spool* (turbo lag; more correctly, boost lag), in which initial acceleration from low RPM is limited by the lack of sufficient exhaust gas mass flow (pressure). Once engine RPM is sufficient to start the turbine spinning, there is a rapid increase in power, as higher turbo boost causes more exhaust gas production, which spins the turbo yet faster, leading to a belated "surge" of acceleration. This makes the maintenance of smoothly-increasing RPM far harder with turbochargers than with engine-driven superchargers, which apply boost in direct proportion to the engine RPM.

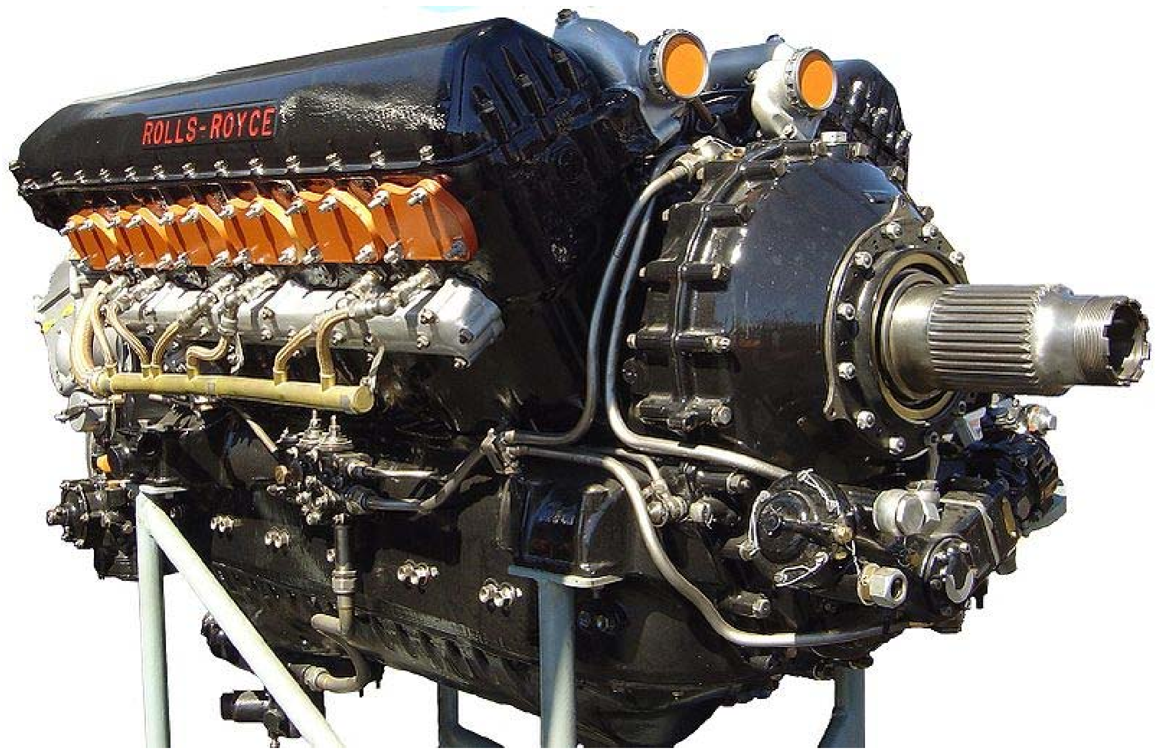
Roots blowers tend to be 40–50% efficient at high boost levels. Centrifugal superchargers are 70–85% efficient. Lysholm-style blowers can be nearly as efficient as their centrifugal counterparts over a narrow range of load/speed/boost, for which the system must be specifically designed.

Keeping the air that enters the engine cool is an important part of the design of both superchargers and turbochargers. Compressing air increases its temperature, so it is common to use a small radiator called an intercooler between the pump and the engine to reduce the temperature of the air.

In the 1985 and 1986 World Rally Championships, Lancia ran the Delta S4 which incorporated both a belt driven supercharger and exhaust driven turbocharger. The design used a complex series of bypass valves in the induction and exhaust systems, and an electromagnetic clutch so that at low engine speeds boost was derived from the supercharger, in the middle of the rev range boost was derived from both systems, whilst at the highest revs the system disconnected drive from the supercharger and isolated the associated ducting. This was done in an attempt to exploit the advantages of each of the charging systems whilst removing the disadvantages. In turn this approach brought greater complexity and impacted on the cars reliability in WRC events, whilst also increasing the weight of engine anciliaries in the finished design.

Aircraft

Altitude effects



The Rolls Royce Merlin, a supercharged aircraft engine from World War II

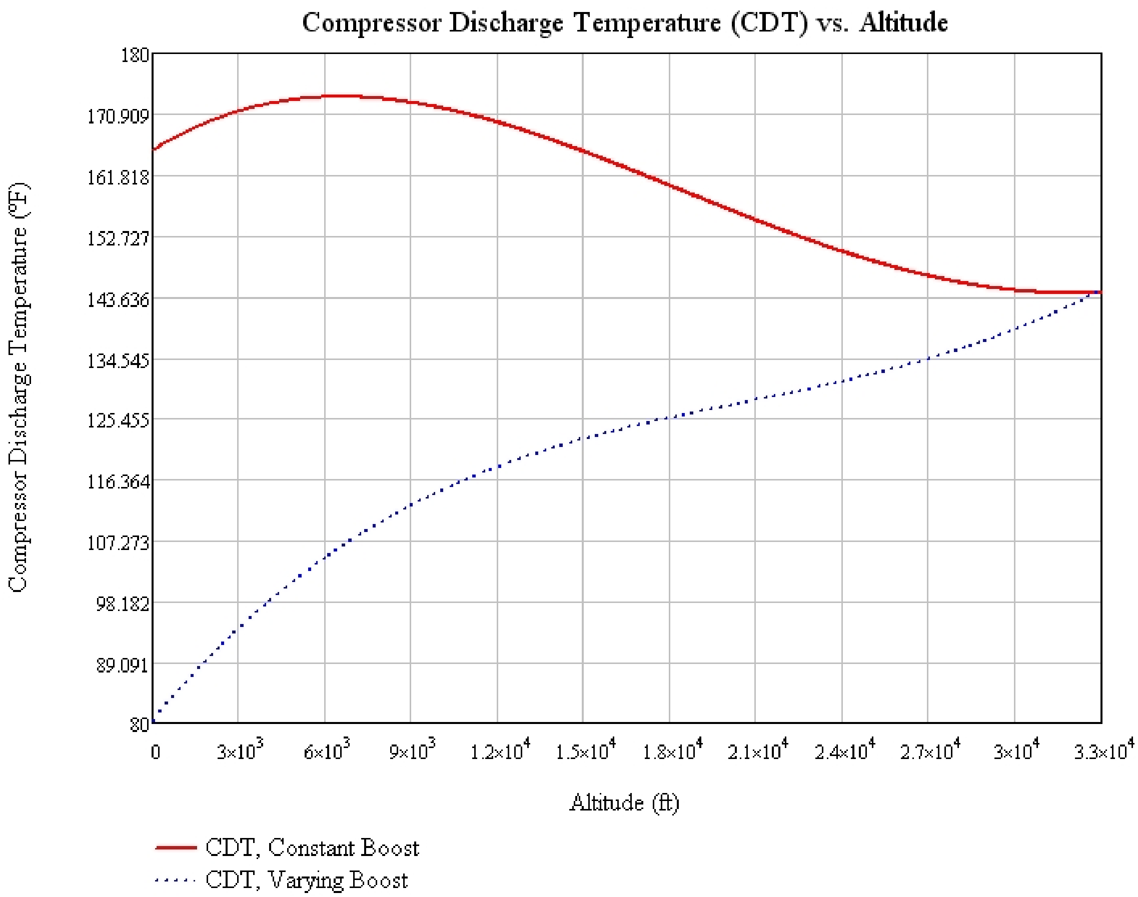
A Centrifugal supercharger of a Bristol Centaurus radial aircraft engine.

Superchargers are a natural addition to aircraft piston engines which are intended for operation at high altitudes. As an aircraft climbs to higher altitude, air pressure and air density decreases. The output of a piston engine drops because of the reduction in the mass of air that can be drawn into the engine; for example the air density at 30,000 ft (9,100 m) is $\frac{1}{3}$ of that at sea level, thus only $\frac{1}{3}$ of the amount of air can be drawn into the cylinder, with enough oxygen to provide efficient combustion for only a third as much fuel. So, at 30,000 ft (9,100 m), only $\frac{1}{3}$ of the fuel burnt at sea level can be burnt. (An advantage of the decreased air density is that the airframe only experiences about 1/3 of the aerodynamic drag. Plus there is decreased back pressure on the exhaust gases. On the other hand, more energy is consumed holding an airplane up with less air to push down on.)

A supercharger can be thought of either as artificially increasing the density of the air by compressing it – or as forcing more air than normal into the cylinder every time the piston moves down.

A supercharger compresses the air back to sea-level equivalent pressures, or even much higher, in order to make the engine produce just as much power at cruise altitude as it does at sea level. With the reduced aerodynamic drag at high altitude and the engine still producing rated power, a supercharged airplane can fly much faster at altitude than a naturally-aspirated one. The pilot controls the output of the supercharger with the throttle and indirectly via the propeller governor control. Since the size of the supercharger is chosen to produce a given amount of pressure at high altitude, the supercharger is over-sized for low altitude. The pilot must be careful with the throttle and watch the manifold pressure gauge to avoid overboosting at low altitude. As the aircraft climbs and the air density drops, the pilot must continually open the throttle in small increments to maintain full power. The altitude at which the throttle reaches full open and the engine is still producing full rated power is known as the *critical altitude.* Above the critical altitude, engine power output will start to drop as the aircraft continues to climb.

Effects of temperature



Supercharger CDT vs. Altitude. Graph shows the CDT differences between a constant-boost supercharger and a variable-boost supercharger when utilized on an aircraft.

As discussed above, supercharging can cause a spike in temperature, and extreme temperatures will cause detonation of the fuel-air mixture and damage to the engine. In the case of aircraft, this causes a problem at low altitudes, where the air is both denser and warmer than at high altitudes. With high ambient air temperatures, detonation could start to occur with the manifold pressure gauge reading far below red line.

A supercharger optimized for high altitudes causes the opposite problem on the intake side of the system. With the throttle retarded to avoid overboosting, air temperature in the carburetor can drop low enough to cause ice to form at the throttle plate. In this manner, enough ice could accumulate to cause engine failure, even with the engine operating at full rated power. For this reason, many supercharged aircraft featured a carburetor air temperature gauge or warning light to alert the pilot of possible icing conditions.

Several solutions to these problems were developed: intercoolers and aftercoolers, anti-detonant injection, two-speed superchargers, and two-stage superchargers.

Two-stage and two-speed superchargers

In the 1930s, two-speed drives were developed for superchargers. These provided more flexibility for the operation of the aircraft, although they also entailed more complexity of manufacturing and maintenance. The gears connected the supercharger to the engine using a system of hydraulic clutches, which were manually engaged or disengaged by the pilot with a control in the cockpit. At low altitudes, the low-speed gear would be used in order to keep the manifold temperatures low. At around 12,000 feet (3,700 m), when the throttle was full forward and the manifold pressure started to drop off, the pilot would retard the throttle and switch to the higher gear, then readjust the throttle to the desired manifold pressure.

Another way to accomplish the same level of control was the use of two compressors in series. After the air was compressed in the *low pressure stage*, the air flowed through an intercooler radiator where it was cooled before being compressed again by the *high pressure stage* and then *aftercooled* in another heat exchanger. In these systems, damper doors could be opened or closed by the pilot in order to bypass one stage as needed. Some systems had a cockpit control for opening or closing a damper to the intercooler/aftercooler, providing another way to control temperature. The most complex systems used a two-speed, two-stage system with both an intercooler and an aftercooler, but these were found to be prohibitive in cost and complicated. In the end, it was found that, for most engines, a single-stage two-speed setup was most suitable.

Turbocharging

A mechanically driven supercharger has to take its drive power from the engine. Taking a single-stage single-speed supercharged engine, such as the Rolls Royce Merlin, for instance, the supercharger uses up about 150 hp (110 kW). Without a supercharger, the engine would produce 750 hp (560 kW); with a supercharger, it produces 1,000 hp (750 kW), a total increase of 400 hp (750 hp — 150 + 400), or a net gain of 250 hp (190 kW). This is where the principal disadvantage of a supercharger becomes apparent: The engine has to burn extra fuel to provide power to turn the supercharger. The increased charge density increases the engine's specific power and power to weight ratio, but also increases the engine's specific fuel consumption. This increases the cost of running the aircraft and reduces its overall range.

As opposed to a supercharger driven by the engine itself, a turbocharger is driven using the exhaust gases from the engines. The amount of power in the gas is proportional to the difference between the exhaust pressure and air pressure, and this difference increases with altitude, helping a turbocharged engine to compensate for changing altitude.

The majority of WWII engines used mechanically driven superchargers, because they maintained three significant manufacturing advantages over turbochargers. Turbochargers, used by American aero engines such as the Allison V-1710, the Pratt & Whitney R-2800 were larger, involved extra piping, and required rare high-temperature alloys in the turbine and pre-turbine section of the exhaust system. The size of the piping alone was a serious issue; the Vought F4U Corsair and Republic P-47 Thunderbolt used the same engine but the huge barrel-like fuselage of the latter was, in part, a result of the necessary piping to and from the turbocharger in the rear of the plane. Turbocharged piston engines are also subject to many of the same operating restrictions as gas turbine engines. Turbocharged engines also require frequent inspections of the turbocharger and exhaust systems for damage due to the increased heat, increasing maintenance costs.

Today, most general aviation aircraft are naturally aspirated. The small number of modern aviation piston engines designed to run at high altitudes generally use a turbocharger or turbo-normalizer system rather than a supercharger driven from the crank shaft. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the supercharger has fallen out of favor. Equivalently, depending on what monetary inflation factor one uses, fuel costs have not decreased as fast as production and maintenance costs have.

Effects of fuel octane rating

Until World War II all automobile and aviation fuel was generally rated at 87 octane or less. This is the rating that was achieved by the simple distillation of "light crude" oil. Engines from around the world were designed to work with this grade of fuel, which set a limit to the amount of boosting that could be provided by the supercharger, while maintaining a reasonable compression ratio.

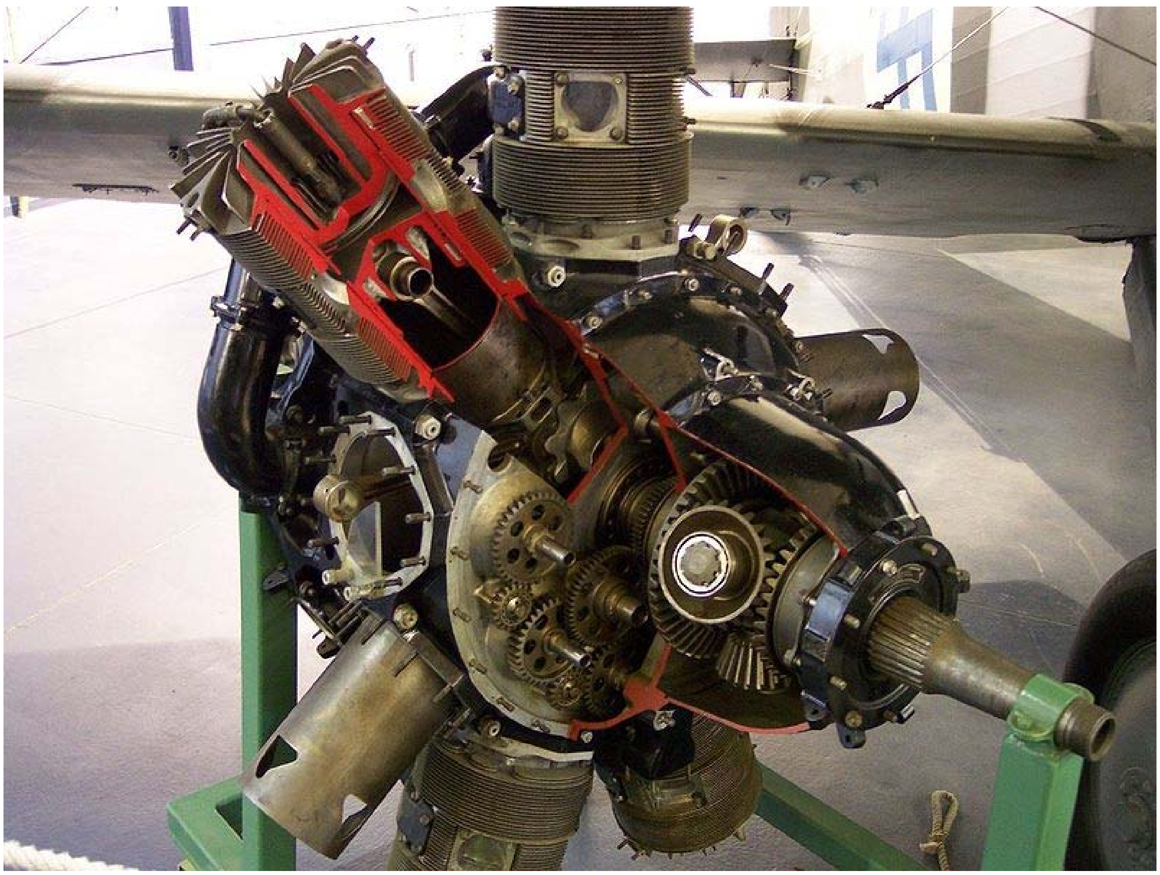
Octane rating boosting through additives was a line of research being explored at the time. Using these techniques, less valuable crude could still supply large amounts of useful gasoline, which made it a valuable economic process. However the additives were not limited to making poor-quality oil into 87-octane gasoline; the same additives could also be used to boost the gasoline to much higher octane ratings.

Higher-octane fuel resists auto ignition and detonation better than does low-octane fuel. As a result, the amount of boost supplied by the superchargers could be increased, resulting in an increase in engine output. The development of 100 octane aviation fuel, pioneered in the USA before the war, enabled the use of higher boost pressures to be used on high-performance aviation engines, and was used to develop extremely high power outputs – for short periods – in several of the pre-war speed record airplanes. Operational use of the new fuel during World War II began in early 1940 when 100-octane fuel was delivered to the British Royal Air Force from refineries in America and the East Indies. The German *Luftwaffe* also had supplies of a similar fuel.

Increasing the knocking limits of existing aviation fuels became a major focus of aero engine development during World War II. By the end of the war, fuel was being delivered at a nominal 150-octane rating, on which late-war aero engines like the Rolls-Royce Merlin 66 or the Daimler-Benz DB 605DC developed as much as 2,000 hp (1,500 kW).

Chapter 4

Sleeve Valve



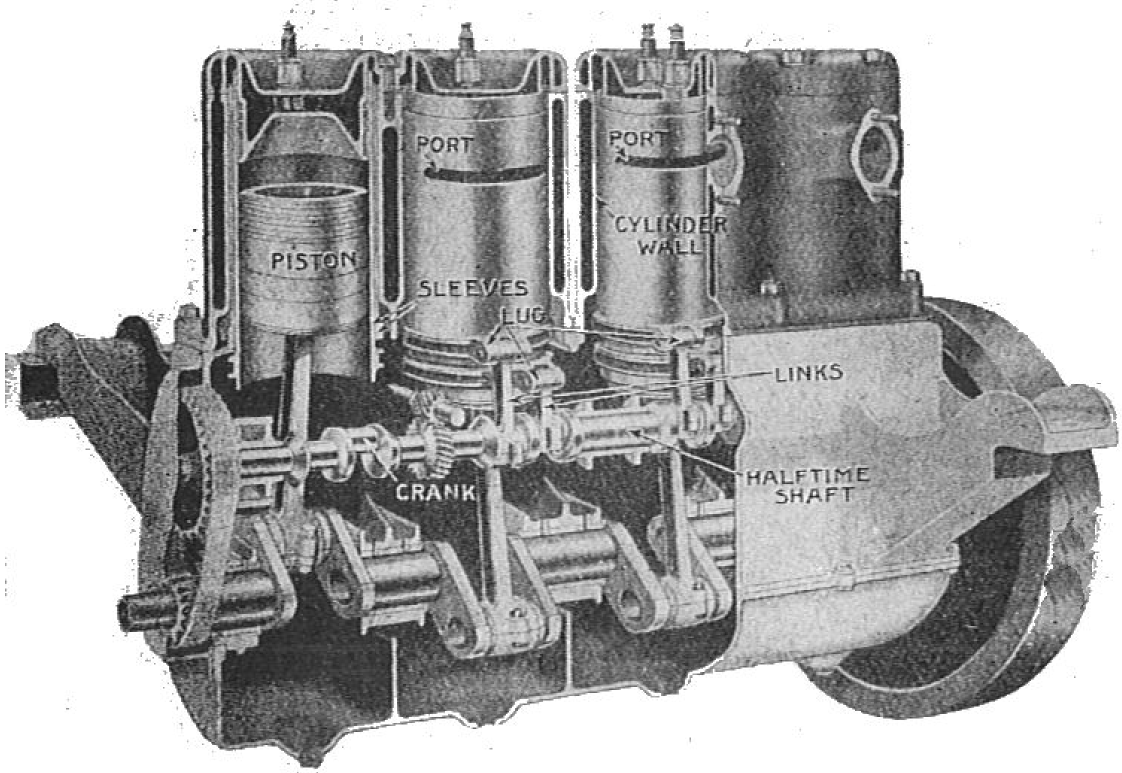
Bristol Perseus

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

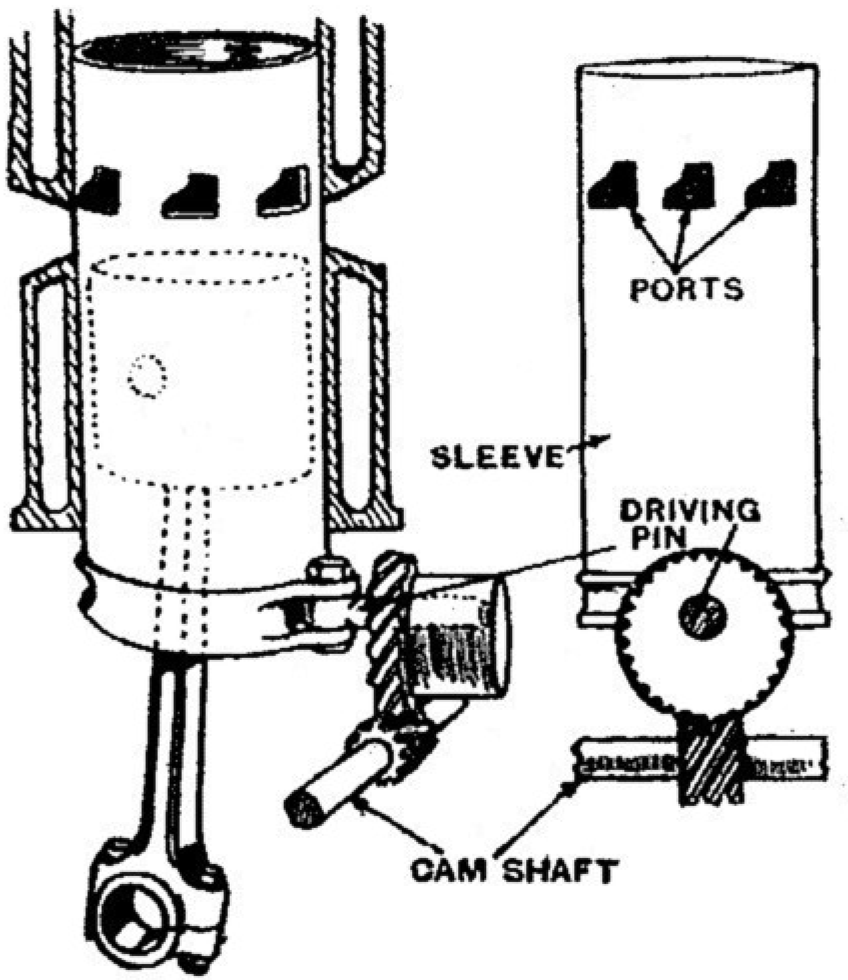
A sleeve valve takes the form of one or more machined sleeves. It fits between the piston and the cylinder wall in the cylinder of an internal combustion engine where it rotates and/or slides, ports (holes) in the side of the valve(s) aligning with the cylinder's inlet and exhaust ports at the appropriate 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 5

Thermodynamic Cycle

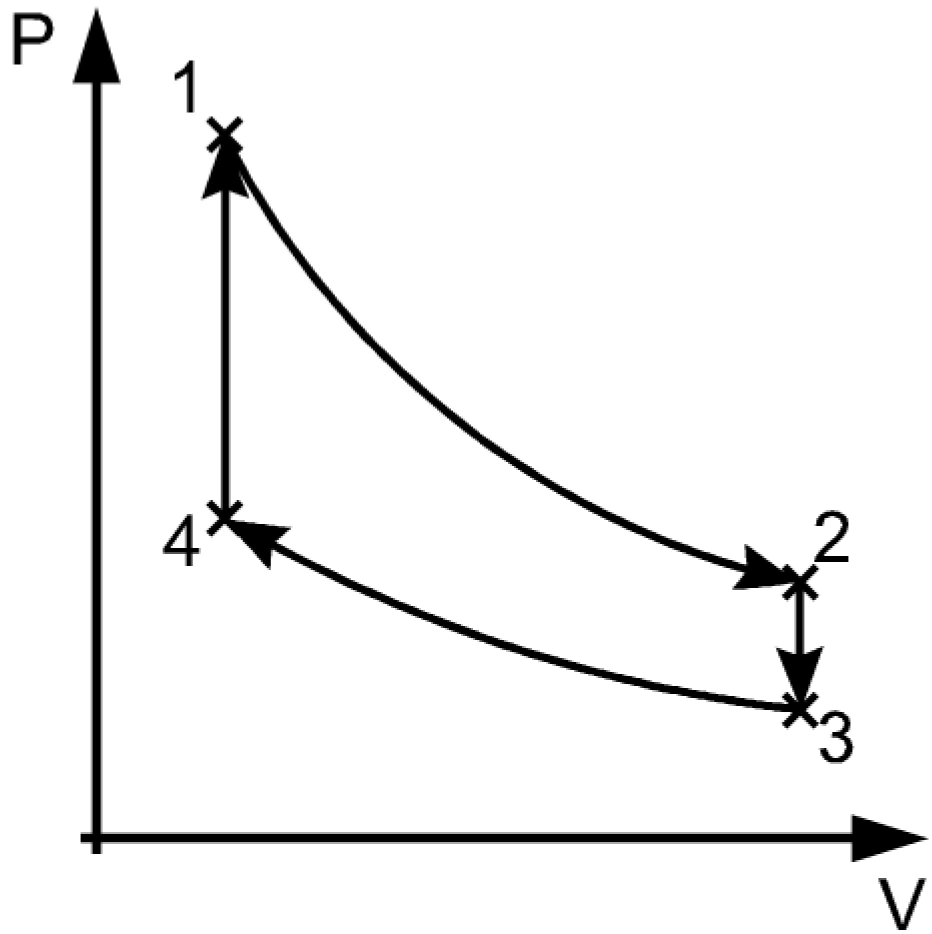
A **thermodynamic cycle** consists of a series of thermodynamic processes transferring heat and work, while varying pressure, temperature, and other state variables, eventually returning a system to its initial state. In the process of going through this cycle, the system may perform work on its surroundings, thereby acting as a heat engine.

State quantities depend only on the thermodynamic state, and cumulative variation of such properties adds up to zero during a cycle. Process quantities (or path quantities), such as heat and work are process dependent, and cumulative heat and work are non-zero. The first law of thermodynamics dictates that the net heat input is equal to the net work output over any cycle. The repeating nature of the process path allows for continuous operation, making the cycle an important concept in thermodynamics. Thermodynamic cycles often use quasistatic processes to model the workings of actual devices.

Heat and work

Two primary classes of thermodynamic cycles are **power cycles** and **heat pump cycles**. Power cycles are cycles which convert some heat input into a mechanical work output, while heat pump cycles transfer heat from low to high temperatures using mechanical work input. Cycles composed entirely of quasistatic processes can operate as power or heat pump cycles by controlling the process direction. On a pressure volume diagram or temperature entropy diagram, the clockwise and counterclockwise directions indicate power and heat pump cycles, respectively.

Relationship to work



Example of P-V diagram of a thermodynamic cycle.

Because the net variation in state properties during a thermodynamic cycle is zero, it forms a closed loop on a PV diagram. A PV diagram's *Y* axis shows pressure (*P*) and *X* axis shows volume (*V*). The area enclosed by the loop is the work (*W*) done by the process:

$$(1) \qquad W = \oint P \, dV$$

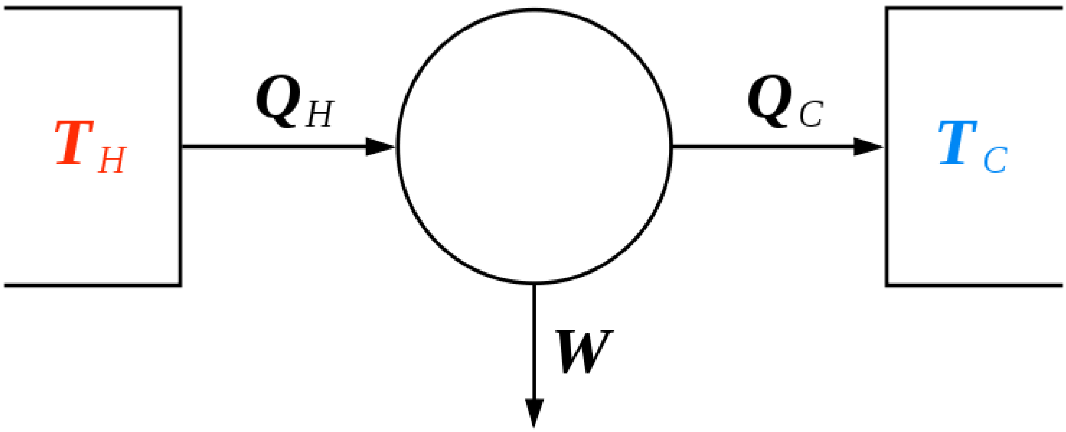
This work is equal to the balance of heat (Q) transferred into the system:

$$(2) \qquad W = Q = Q_{in} - Q_{out}$$

Equation (2) makes a cyclic process similar to an isothermal process: even though the internal energy changes during the course of the cyclic process, when the cyclic process finishes the system's energy is the same as the energy it had when the process began.

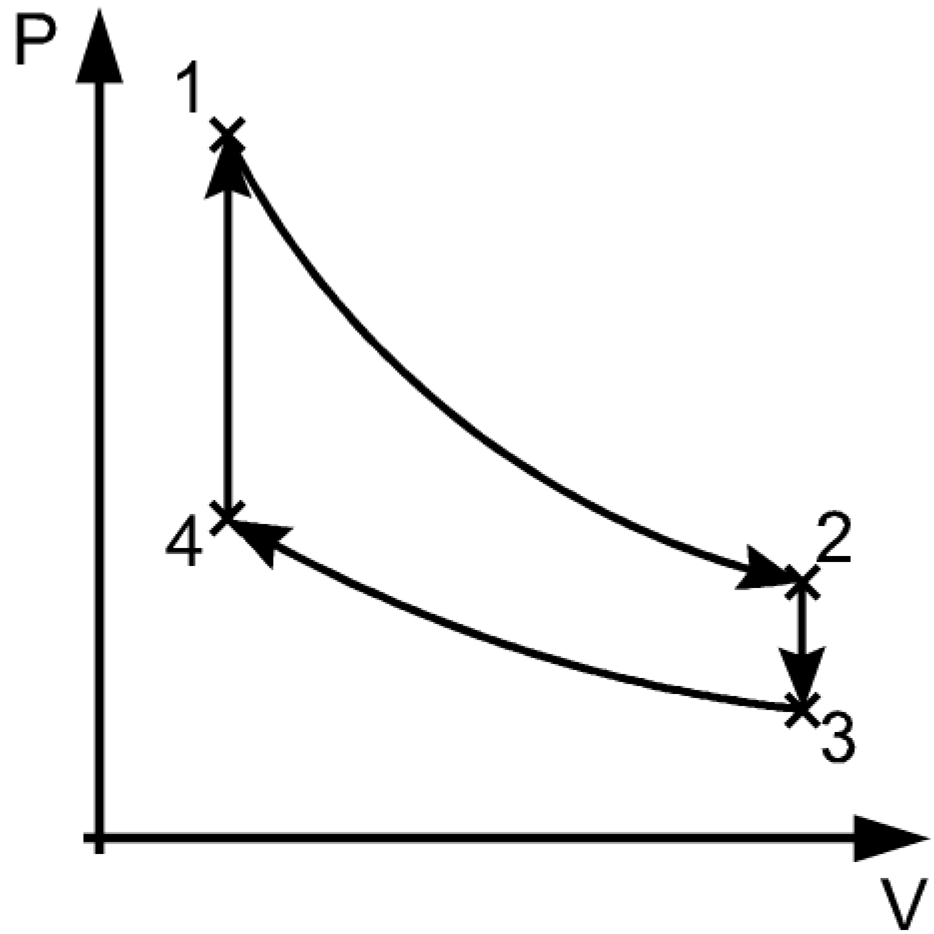
If the cyclic process moves clockwise around the loop, then W will be positive, and it represents a heat engine. If it moves counterclockwise, then W will be negative, and it represents a heat pump.

Power cycles



Heat engine diagram.

Thermodynamic power cycles are the basis for the operation of heat engines, which supply most of the world's electric power and run almost all motor vehicles. Power cycles can be divided according to the type of heat engine they seek to model. The most common cycles that model internal combustion engines are the Otto cycle, which models gasoline engines and the Diesel cycle, which models diesel engines. Cycles that model external combustion engines include the Brayton cycle, which models gas turbines, and the Rankine cycle, which models steam turbines.



The clockwise thermodynamic cycle indicated by the arrows shows that the cycle represents a heat engine. The cycle consists of four states (the point shown by crosses) and four thermodynamic processes (lines).

For example the pressure-volume mechanical work done in the heat engine cycle, consisting of 4 thermodynamic processes, is:

$$(3) \qquad W = W_{1\to2} + W_{2\to3} + W_{3\to4} + W_{4\to1}$$

$$W_{1\to2} = \int_{V_1}^{V_2} P\,dV, \text{ negative, work done by system}$$

$$W_{2\to3} = \int_{V_2}^{V_3} P\,dV, \text{ zero work if V2 equal V3}$$

$$W_{3\to4} = \int_{V_3}^{V_4} P\,dV, \text{ positive, work done on system}$$

$$W_{4\to 1} = \int_{V_4}^{V_1} P\,dV, \text{ zero work if V4 equal V1}$$

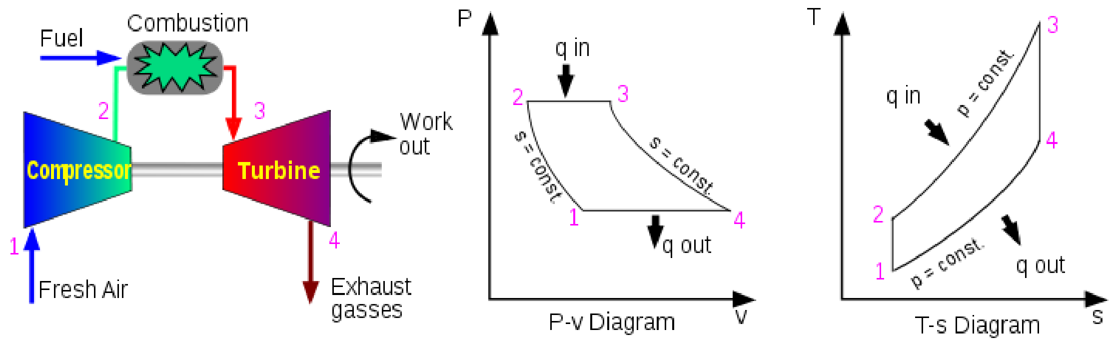
If no volume change happens in process 4->1 and 2->3, equation (3) simplifies to:

$$(4) \qquad W = W_{1\to 2} + W_{3\to 4}$$

Heat pump cycles

Thermodynamic heat pump cycles are the models for heat pumps and refrigerators. The difference between the two is that heat pumps are intended to keep a place warm while refrigerators are designed to cool it. The most common refrigeration cycle is the vapor compression cycle, which models systems using refrigerants that change phase. The absorption refrigeration cycle is an alternative that absorbs the refrigerant in a liquid solution rather than evaporating it. Gas refrigeration cycles include the reversed Brayton cycle and the Hampson-Linde cycle. Regeneration in gas refrigeration allows for the liquefaction of gases.

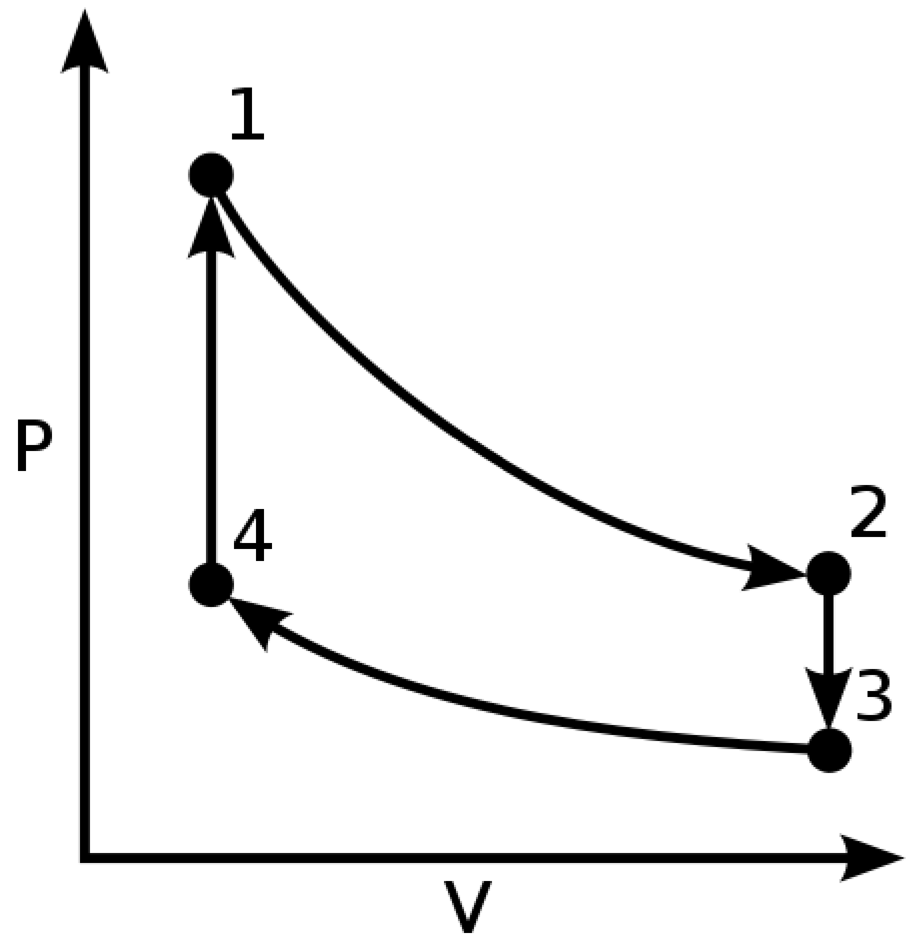
Modelling real systems



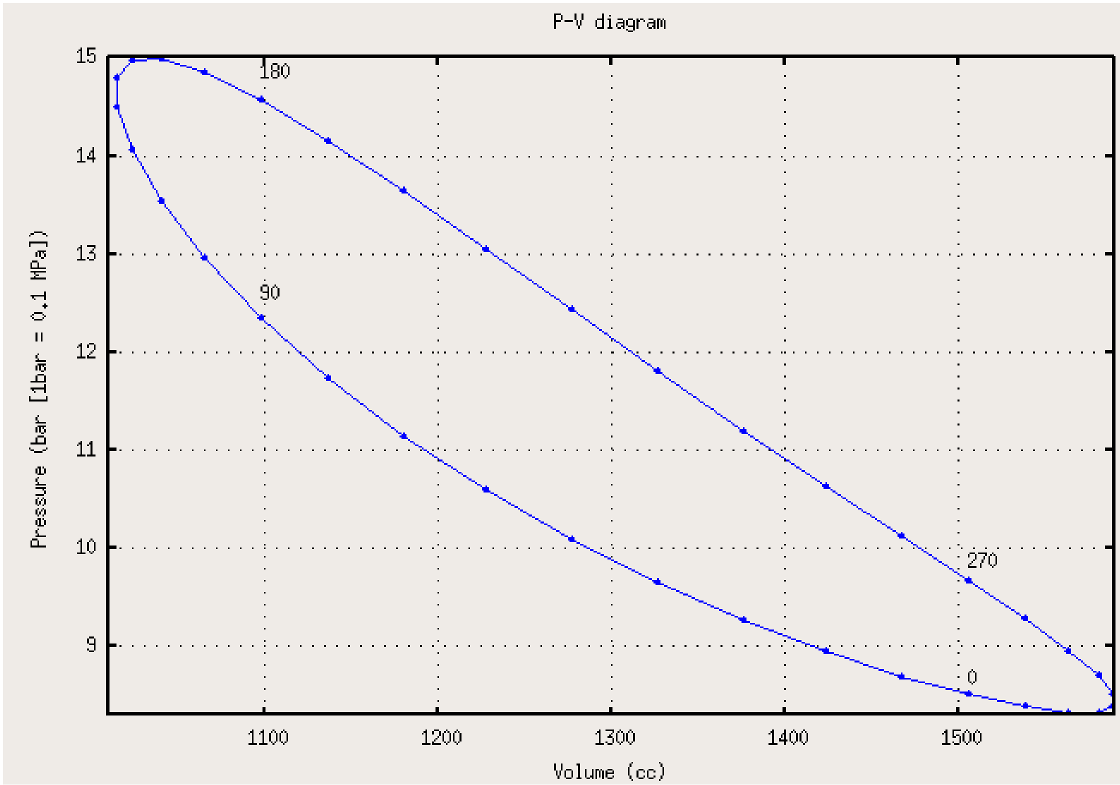
Example of a real system modelled by an idealized process: PV and TS diagrams of a Brayton cycle mapped to actual processes of a gas turbine engine

Thermodynamic cycles may be used to model real devices and systems, typically by making a series of assumptions. simplifying assumptions are often necessary to reduce the problem to a more manageable form. For example, as shown in the figure, devices such a gas turbine or jet engine can be modelled as a Brayton cycle. The actual device is made up of a series of stages, each of which is itself modelled as an idealized thermodynamic process. Although each stage which acts on the working fluid is a complex real device, they may be modelled as idealized processes which approximate their real behavior. A further assumption is that the exhaust gases would be passed back through the inlet with a corresponding loss of heat, thus completing the idealized cycle.

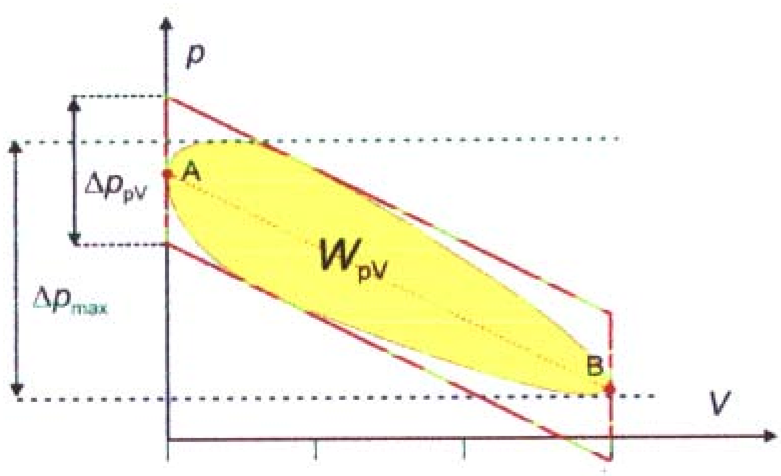
The difference between an idealized cycle and actual performance may be significant. For example, the following images illustrate the differences in work output predicted by an ideal Stirling cycle and the actual performance of a Stirling engine:



Ideal Stirling cycle



Actual performance



Actual and ideal overlaid, showing difference in work output

As work output is represented by the interior of the cycle, there is a significant difference between the predicted work output of the ideal cycle and the actual work output shown by a real engine. It may also be observed that the real individual processes diverge from their idealized counterparts; e.g., isochoric expansion (process 1-2) occurs with some actual volume change.

Well-known thermodynamic cycles

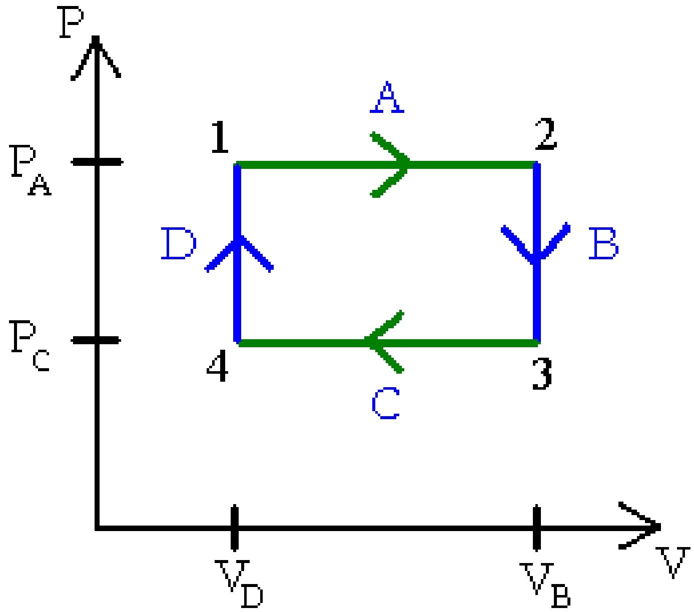
In practice, simple idealized thermodynamic cycles are usually made out of four thermodynamic processes. Any thermodynamic processes may be used. However, when idealized cycles are modeled, often processes where one state variable is kept constant are used, such as an isothermal process (constant temperature), isobaric process (constant pressure), isochoric process (constant volume), isentropic process (constant entropy), or an isenthalpic process (constant enthalpy). Often adiabatic processes are also used, where no heat is exchanged.

Some example thermodynamic cycles and their constituent processes are as follows:

Cycle	Process 1-2 (Compression)	Process 2-3 (Heat Addition)	Process 3-4 (Expansion)	Process 4-1 (Heat Rejection)	Notes
Power cycles normally with external combustion - or heat pump cycles:					
Bell Coleman	adiabatic	isobaric	adiabatic	isobaric	A reversed Brayton cycle
Brayton	adiabatic	isobaric	adiabatic	isobaric	Jet engines aka first Ericsson cycle from 1833
Carnot	isentropic	isothermal	isentropic	isothermal	
Ericsson	isothermal	isobaric	isothermal	isobaric	the second Ericsson cycle from 1853
Scuderi	adiabatic	variable pressure and volume	adiabatic	isochoric	
Stirling	isothermal	isochoric	isothermal	isochoric	
Stoddard	adiabatic	isobaric	adiabatic	isobaric	
Power cycles normally with internal combustion:					
Diesel	adiabatic	isobaric	adiabatic	isochoric	
Lenoir	isobaric	isochoric	adiabatic	isobaric	Pulse jets (Note: 3 of the 4 processes are different)
Otto	adiabatic	isochoric	adiabatic	isochoric	Gasoline / petrol engines

Rankine	adiabatic	isobaric	adiabatic	isobaric	Steam engine

Ideal cycle



An illustration of an ideal cycle heat engine (arrows clockwise).

An ideal cycle is constructed out of:

1. TOP and BOTTOM of the loop: a pair of parallel **isobaric** processes
2. LEFT and RIGHT of the loop: a pair of parallel **isochoric** processes

Carnot cycle

The Carnot cycle is a cycle composed of the totally reversible processes of isentropic compression and expansion and isothermal heat addition and rejection. The thermal efficiency of a Carnot cycle depends only on the absolute temperatures of the two reservoirs in which heat transfer takes place, and for a power cycle is:

$$\eta = 1 - \frac{T_L}{T_H}$$

where T_L is the lowest cycle temperature and T_H the highest. For Carnot power cycles the coefficient of performance for a heat pump is:

$$COP = 1 + \frac{T_L}{T_H - T_L}$$

and for a refrigerator the coefficient of performance is:

$$COP = \frac{T_L}{T_H - T_L}$$

The second law of thermodynamics limits the efficiency and COP for all cyclic devices to levels at or below the Carnot efficiency. The Stirling cycle and Ericsson cycle are two other reversible cycles that use regeneration to obtain isothermal heat transfer.

Stirling cycle

A Stirling cycle is like an Otto cycle, except that the adiabats are replaced by isotherms. It is also the same as an Ericsson cycle with the isobaric processes substituted for constant volume processes.

1. TOP and BOTTOM of the loop: a pair of quasi-parallel **isothermal** processes
2. LEFT and RIGHT sides of the loop: a pair of parallel **isochoric** processes

Heat flows into the loop through the top isotherm and the left isochore, and some of this heat flows back out through the bottom isotherm and the right isochore, but most of the heat flow is through the pair of isotherms. This makes sense since all the work done by the cycle is done by the pair of isothermal processes, which are described by $Q=W$. This suggests that all the net heat comes in through the top isotherm. In fact, all of the heat which comes in through the left isochore comes out through the right isochore: since the top isotherm is all at the same warmer temperature T_H and the bottom isotherm is all at the same cooler temperature T_C, and since change in energy for an isochore is proportional to change in temperature, then all of the heat coming in through the left isochore is cancelled out exactly by the heat going out the right isochore.

State functions and entropy

If Z is a state function then the balance of Z remains unchanged during a cyclic process:

$$\oint dZ = 0 .$$

Entropy is a state function and is defined as

$$S = \frac{Q}{T}$$

so that

$$\Delta S = \frac{\Delta Q}{T} ,$$

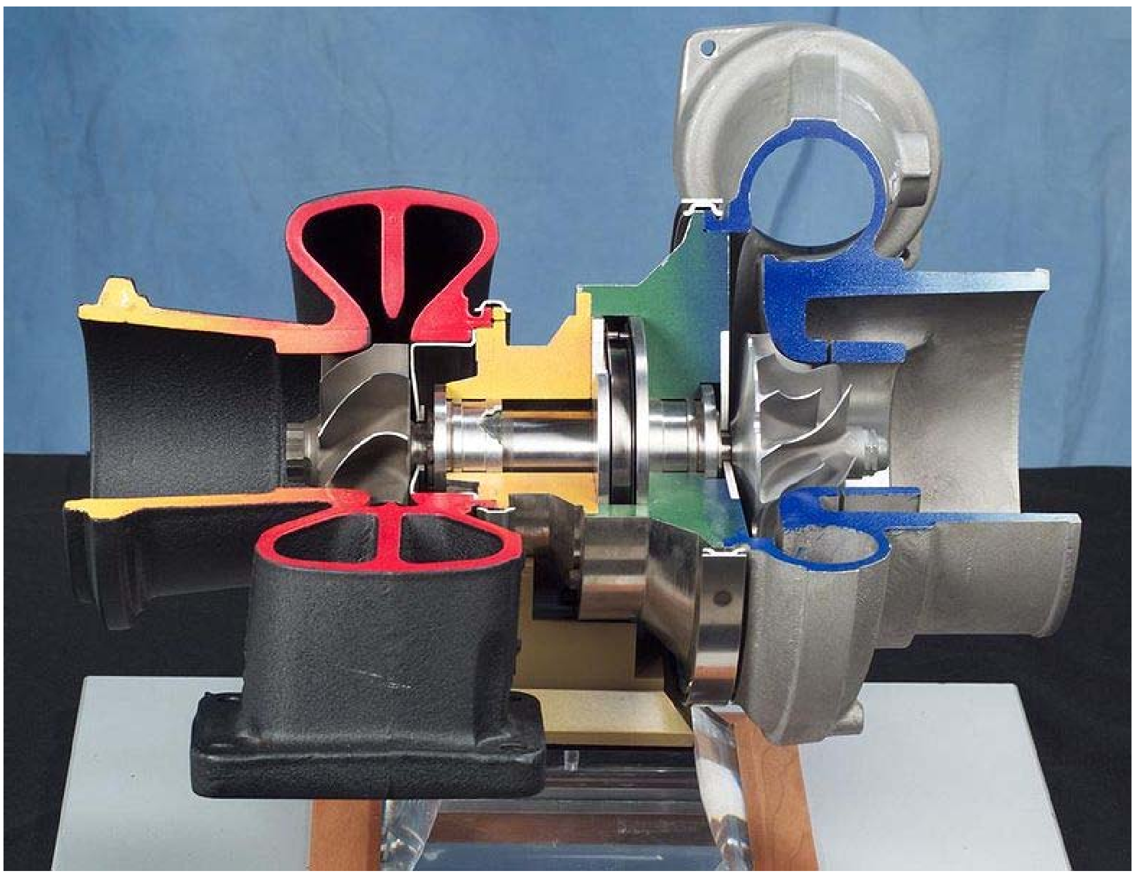
then it is clear that for any cyclic process,

$$\oint dS = \oint \frac{dQ}{T} = 0$$

meaning that the net entropy change over a cycle is 0.

Chapter 6

Turbocharger



Cut-away view of an air foil bearing-supported turbocharger made by Mohawk Innovative Technology

A **turbocharger**, or **turbo**, is a gas compressor used for forced induction of an internal combustion engine. A form of supercharger, the turbocharger increases the pressure of air entering the engine to create more power. A turbocharger has the compressor powered by a turbine which is driven by the engine's own exhaust gases rather than direct mechanical drive. This allows a turbocharger to achieve a higher degree of efficiency than other types of forced induction compressors which are more vulnerable to parasitic loss.

Nomenclature

Early manufacturers of turbochargers referred to them as "turbosuperchargers". A supercharger is an air compressor used for forced induction of an engine. Logically then, adding a turbine to turn the supercharger would yield a "turbosupercharger". However, the term was soon shortened to "turbocharger". This is now a source of confusion, as the term "turbosupercharged" is sometimes used to refer to an engine that uses both a crankshaft-driven supercharger and an exhaust-driven turbocharger, often referred to as twincharging.

Aviation engine manufacturers such as Teledyne Continental Motors still use the term *turbosupercharged* to refer to turbo chargers that are used to boost manifold pressure above 1 ATM. Turbochargers that maintain 1 ATM of manifold pressure to a specific altitude are considered turbo-normalized. Though these represent true turbochargers, they should not be confused with some aircraft engines that employ actual engine-driven superchargers.

Operating principle

A turbocharger is a small centrifugal pump driven by the energy of the exhaust gases of an engine. A turbocharger consists of a turbine and a compressor on a shared shaft. The turbine converts kinetic energy from the engine exhaust's velocity and potential energy from the exhaust's higher-than-atmospheric pressure into rotational kinetic energy, which is in turn used to drive the compressor. The compressor draws in ambient air and pumps it into the intake manifold at increased pressure, resulting in a greater mass of air entering the cylinders on each intake stroke.

The objective of a turbocharger is the same as that of a supercharger; to improve an engine's volumetric efficiency by solving one of its cardinal limitations. A naturally aspirated automobile engine relies mostly on the downward stroke of a piston to create an area of low pressure in order to draw air into the cylinder through one or more intake valves. The pressure in the atmosphere is no more than 1 atm (approximately 14.7 psi, or 1 bar), so there ultimately will be a limit to the pressure difference across the intake valves and thus the amount of airflow entering the combustion chamber. Since the turbocharger increases the pressure at the point where air is entering the cylinder, a greater mass of air (oxygen) will be forced in as the inlet manifold pressure increases. The presence of additional air mass in the cylinder makes it possible to create a bigger explosion if more fuel is injected, increasing the power and torque output of the engine.

To avoid detonation and physical damage to the host engine, the intake manifold pressure must not get too high, thus the pressure at the intake manifold of the engine must be controlled by some means. A Wastegate, which vents excess exhaust gas so that it will bypass the exhaust turbine is the most common boost control device. An actuator, connected to the compressor outlet via a signal hose, and usually controlled via a solenoid by the car's Engine Control Unit, forces the wastegate to open as the boost pressure rises. The reduction in turbine speed results in the compressor slowing, and in less air pressure at the intake manifold.

Modern Group N Rally cars are forced by the rules to use a 34mm restrictor at the compressor inlet, which effectively limits the maximum boost (pressure above atmospheric) that the cars can achieve at high rpm. Interestingly, at low rpm they can reach boost pressures of above 22psi (1.5bar).

History

The turbocharger was invented by Swiss engineer Alfred Büchi. His patent for a turbocharger was applied for use in 1905. Diesel ships and locomotives with turbochargers began appearing in the 1920s.

Aviation

During the First World War French engineer Auguste Rateau fitted turbochargers to Renault engines powering various French fighters with some success.

In 1918, General Electric engineer Sanford Moss attached a turbo to a V12 *Liberty* aircraft engine. The engine was tested at Pikes Peak in Colorado at 14,000 feet (4,300 m) to demonstrate that it could eliminate the power losses usually experienced in internal combustion engines as a result of reduced air pressure and density at high altitude.

Turbochargers were first used in production aircraft engines such as the Napier Lioness, in the 1920s before World War II, although they were less common than engine-driven centrifugal superchargers. The primary purpose behind most aircraft-based applications was to increase the altitude at which the airplane could fly, by compensating for the lower atmospheric pressure present at high altitude. Aircraft such as the Fw 190D, B-17 Flying Fortress, and P-47 Thunderbolt all used turbochargers to increase high altitude engine power.

Production automobiles

The first turbocharged diesel truck was produced by *Schweizer Maschinenfabrik Saurer* (Swiss Machine Works Saurer) in 1938.

The Chevrolet Corvair's turbocharged engine. The turbo, located at top right, feeds pressurized air into the engine through the chrome T-pipe spanning the engine.

The first production turbocharged automobile engines came from General Motors in 1962. The Y-body Oldsmobile Cutlass Jetfire was fitted with a Garrett AiResearch turbocharger and the Chevrolet Corvair Monza Spyder with a TRW turbocharger. At the Paris auto show in 1974, during the height of the oil crisis, Porsche introduced the 911 Turbo – the world’s first production sports car with an exhaust turbocharger and pressure regulator. This was made possible by the introduction of a wastegate to direct excess exhaust gasses away from the exhaust turbine. The world's first production turbo diesel automobiles were the Garrett-turbocharged Mercedes 300SD and the Peugeot 604, both introduced in 1978. Today, most automotive diesels are turbocharged.

- 1962 Oldsmobile Cutlass Jetfire
- 1962 Chevrolet Corvair Monza Spyder
- 1973 BMW 2002 Turbo
- 1974 Porsche 911 Turbo
- 1978 Buick Regal
- 1978 Saab 99
- 1978 Peugeot 604 turbodiesel
- 1978 Mercedes-Benz 300SD turbodiesel (United States/Canada)

- 1979 Alfa Romeo Alfetta GTV 2000 Turbodelta
- 1980 Mitsubishi Lancer GT Turbo
- 1980 Pontiac Firebird
- 1980 Renault 5 Turbo
- 1981 Volvo 240-series Turbo

Competition cars

The aircraft engineer Frank Halford experimented with turbocharging in his modified Aston Martin racing car the *Halford Special*, but it is unclear whether or not his efforts were successful. The first successful application of turbocharging in automotive racing appears to have been in 1952 when Fred Agabashian in the diesel-powered *Cummins Special* qualified for pole position at the Indianapolis 500 and led for 175 miles (282 km) before ingested tire shards disabled the compressor section of the Elliott turbocharger. Offenhauser's turbocharged engines returned to Indianapolis in 1966, with victories coming in 1968 using a Garrett AiResearch turbocharger. The Offenhauser turbo peaked at over 1,000 hp (750 kW) in 1973, which led USAC to limit boost pressure. In their turn, Porsche dominated the Can-Am series with a 1,100 hp (820 kW) 917/30. Turbocharged cars dominated the 24 Hours of Le Mans between 1976 and 1988, and then from 2000-2007.

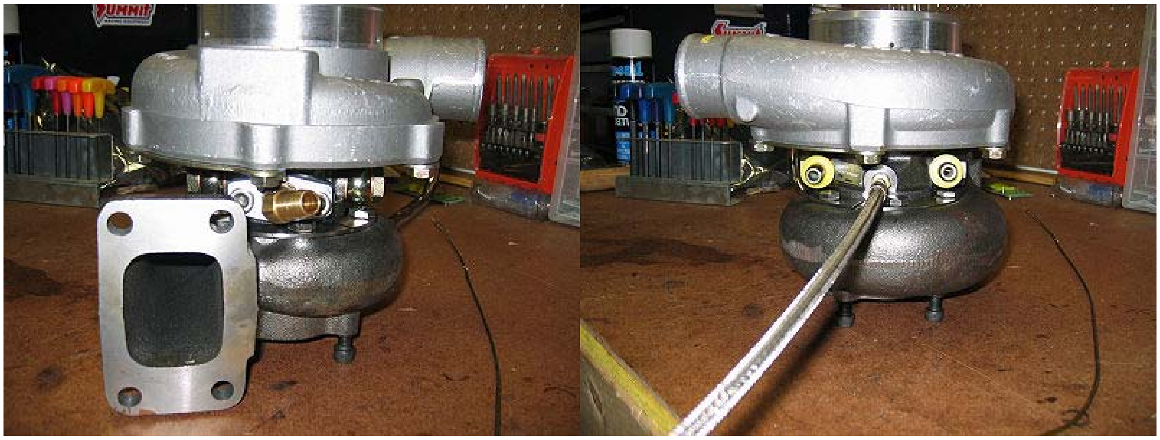
In Formula One, in the so called "Turbo Era" of 1977 until 1989, Renault, Honda, BMW, and Ferrari produced engines with a capacity of 1,500 cc (92 cu in) able to generate 1,000 to 1,500 horsepower (750 to 1,100 kW). Renault was the first manufacturer to apply turbo technology in F1. The project's high cost was compensated for by its performance, and led other engine manufacturers to follow suit. Turbocharged engines dominated and ended the Cosworth DFV era in the mid 1980s. However, the FIA decided turbochargers were making the sport too dangerous and expensive. In 1987, *FIA* decided to limit the maximum boost before the technology was banned for 1989.

In drag racing, an 1,800 hp (1,340 kW) twin-turbocharged Pontiac GTA developed by Gale Banks of Southern California, set a land speed record for the "World's Fastest Passenger Car" of 277 mph (446 km/h). This event was chronicled at the time in a 1987 cover story published by *Autoweek* magazine. Gale Banks Engineering also built and raced several diesel-powered machines, including what Banks erroneously calls the "World's Fastest Diesel Truck," a street-legal 735 hp (548 kW) Dodge Dakota pick-up that towed its own trailer to the Bonneville Salt Flats and then set an official *FIA* record of 217 mph (349 km/h) with a one-way top speed of 222 mph (357 km/h). The truck also showed the fuel economy of a turbocharged diesel engine by averaging 21.2-mpg on the Hot Rod Power Tour. If it ran 50 mph (80 km/h) faster, it would almost match the actual fastest diesel truck, the "Phoenix" of R. B. Slagle and Carl Heap.

In rallying, turbocharged engines of up to 2,000 cc (120 cu in) have long been the preferred motive power for the Group A/N World Rally Car competitors, due to the exceptional power-to-weight ratios attainable. This combines with the use of vehicles with relatively small bodyshells for maneuverability and handling. As turbo outputs rose to levels similar to F1's category, rather than banning the technology, FIA restricted turbo inlet diameter (currently 34 mm).

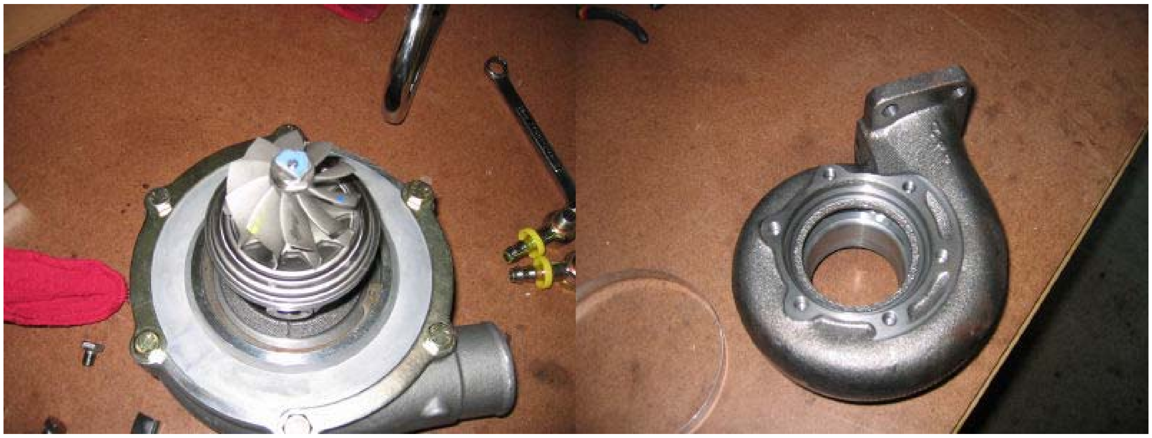
Design and installation

Components

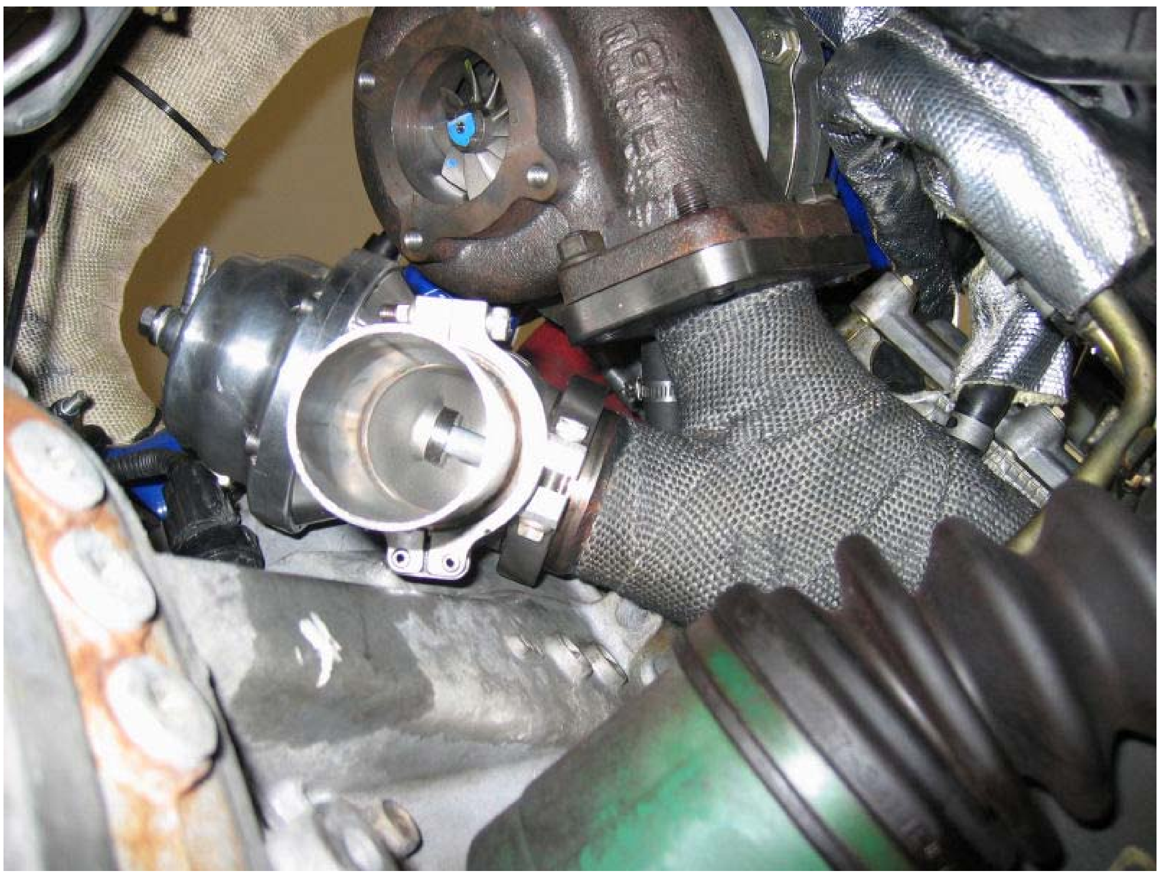


On the left, the brass oil drain connection. On the right are the braided oil supply line and water coolant line connections.

Compressor impeller side with the cover removed.



Turbine side housing removed.



A wastegate installed next to the turbocharger.

The turbocharger has four main components. The turbine (almost always a radial turbine) and impeller/compressor wheels are each contained within their own folded conical housing on opposite sides of the third component, the center housing/hub rotating assembly (CHRA).

The housings fitted around the compressor impeller and turbine collect and direct the gas flow through the wheels as they spin. The size and shape can dictate some performance characteristics of the overall turbocharger. Often the same basic turbocharger assembly will be available from the manufacturer with multiple housing choices for the turbine and sometimes the compressor cover as well. This allows the designer of the engine system to tailor the compromises between performance, response, and efficiency to application or preference. Twin-scroll designs have two valve-operated exhaust gas inlets, a smaller sharper angled one for quick response and a larger less angled one for peak performance.

The turbine and impeller wheel sizes also dictate the amount of air or exhaust that can be flowed through the system, and the relative efficiency at which they operate. Generally, the larger the turbine wheel and compressor wheel, the larger the flow capacity. Measurements and shapes can vary, as well as curvature and number of blades on the wheels. Variable geometry turbochargers are further developments of these ideas.

The center hub rotating assembly (CHRA) houses the shaft which connects the compressor impeller and turbine. It also must contain a bearing system to suspend the shaft, allowing it to rotate at very high speed with minimal friction. For instance, in automotive applications the CHRA typically uses a thrust bearing or ball bearing lubricated by a constant supply of pressurized engine oil. The CHRA may also be considered "water cooled" by having an entry and exit point for engine coolant to be cycled. Water cooled models allow engine coolant to be used to keep the lubricating oil cooler, avoiding possible oil coking (the destructive distillation of the engine oil) from the extreme heat found in the turbine. The development of air-foil bearings has removed this risk. Adaptation of turbochargers on naturally aspirated internal combustion engines, either on petrol or diesel, can yield power increases of 30% to 40%.

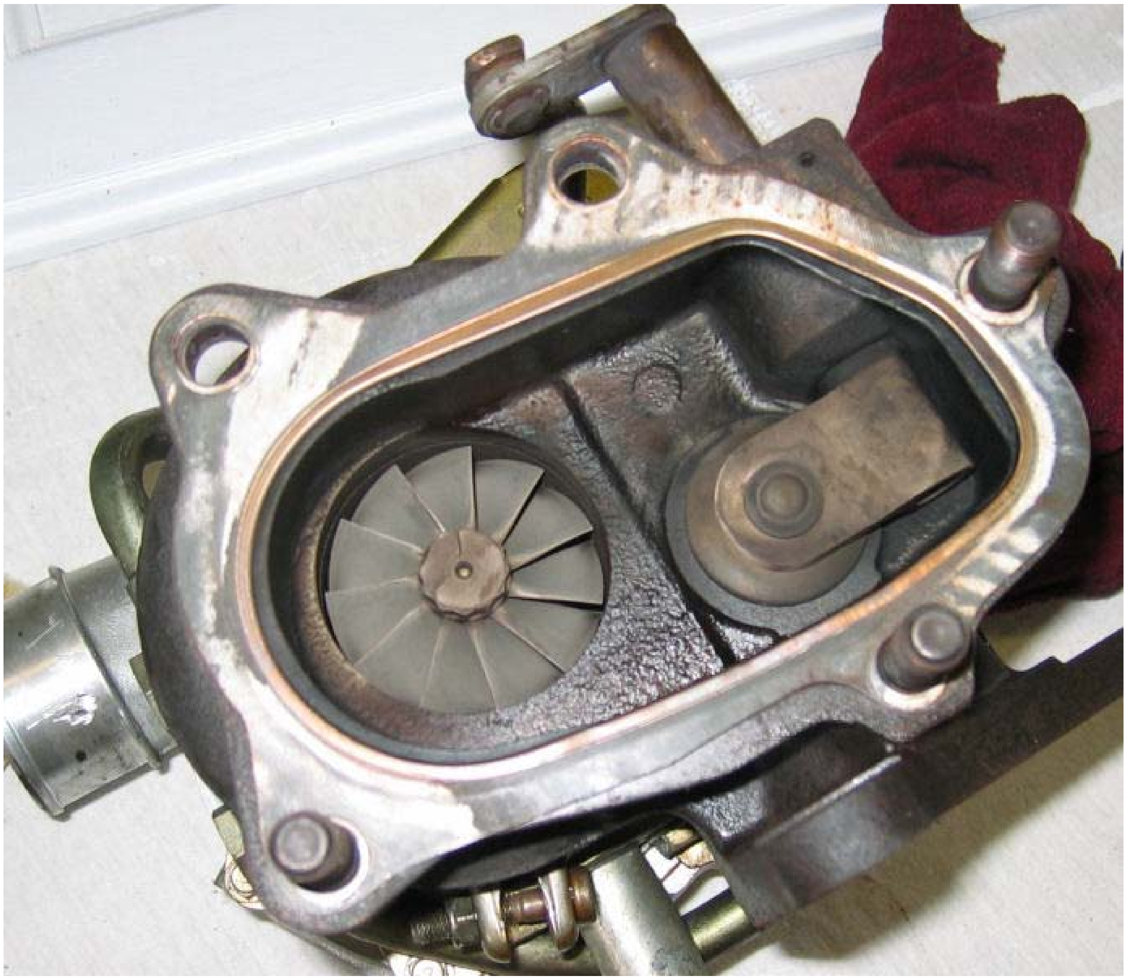
Pressure increase

In the automotive world, boost refers to the increase in pressure that is generated by the turbocharger in the intake manifold that exceeds normal atmospheric pressure. Atmospheric pressure is approximately 14.7 psi or 1.0 bar, and anything above this level is considered to be boost. The level of boost may be shown on a pressure gauge, usually in bar, psi or possibly kPa. This is representative of the extra air pressure that is achieved over what would be achieved without the forced induction. Manifold pressure should not be confused with the volume of air that a turbo can flow.

In aircraft engines the main benefit of turbochargers is to maintain manifold pressure as altitude increases. Since atmospheric pressure reduces as the aircraft climbs, power drops as a function of altitude in normally aspirated engines. Aircraft manifold pressure in western built aircraft is expressed in inches of mercury (Hg) where 29.92 inches is the standard sea level pressure. In high performance aircraft, turbo chargers will provide takeoff manifold pressures in the 30 - 42 inches Hg range. (1 to 1.4 bar). This varies according to aircraft and engine types. In contrast, the takeoff manifold pressure of a normally aspirated engine is about 27 in. Hg, even at sea level, due to losses in the induction system (air filter, ducting, throttle body, etc.). As the turbocharged aircraft climbs, however, the pilot (or automated system) can close the waste gate forcing more exhaust gas through the turbocharger turbine thereby maintaining manifold pressure during the climb, at least until the critical pressure altitude is reached (when the waste gate is fully closed) after which manifold pressure will fall. With such systems, modern high performance piston engine aircraft can cruise at altitudes above 20,000 feet where low air density results in lower drag and higher true airspeeds. Most importantly, this allows flying "above the weather". In manually controlled wastegate systems the pilot must take care not to overboost the engine which will cause pre-ignition leading to engine damage. Further, since most aircraft turbocharger systems do not include an intercooler, the engine is typically operated on the rich side of peak exhaust temperature in order to avoid overheating the turbocharger. In non high performance turbo charged aircraft, the turbocharger is solely used to maintain sea-level manifold pressure during the climb (this is called turbo-normalizing).

Boost pressure is limited to keep the entire engine system, including the turbo, inside its thermal and mechanical design operating range. The speed and thus the output pressure of the turbo is controlled by the wastegate, a bypass which shunts the gases from the cylinders around the turbine directly to the exhaust pipe. The maximum possible boost depends on the fuel's octane rating and the inherent tendency of any particular engine towards detonation. Premium gasoline or racing gasoline can be used to prevent detonation within reasonable limits. Ethanol, methanol, liquefied petroleum gas (LPG) and compressed natural gas (CNG) allow higher boost than gasoline, because of their higher resistance to autoignition (lower tendency to knock). Diesel engines can also tolerate much higher levels of boost pressure than Otto cycle engines, because only air is being compressed during the compression phase, and fuel is injected later, removing the knocking issue entirely. High performance racing diesel engines routinely run boost pressures from 3 to above 10 bar. To obtain more power from higher boost levels and maintain reliability, many engine components have to be replaced or upgraded such as the fuel pump, fuel injectors, pistons, valves, head-gasket, and head bolts.

Wastegate



View of a turbocharger from the turbine exhaust side, clearly showing the integral wastegate to the right

By spinning at a relatively high speed, the compressor draws in a large volume of air and forces it into the engine. As the turbocharger's output flow volume exceeds the engine's volumetric flow, air pressure in the intake system begins to build. The speed at which the assembly spins is proportional to the pressure of the compressed air and total mass of air flow being moved. Since a turbo can spin to rpm far beyond what is needed, or of what it is safely capable of, the speed must be controlled. A wastegate is the most common mechanical speed control system, and is often further augmented by an electronic or manual boost controller. The main function of a wastegate is to allow some of the exhaust to bypass the turbine when the set intake pressure is achieved. Most modern passenger car engines have wastegates that are internal to the turbocharger, although some earlier engines (such as the Audi Inline-5 in the UrS4 and S6) have external wastegates. External wastegates are more accurate and efficient than internal wastegates, but are far more expensive, and thus are generally only found in racing cars (Where precise control of turbo boost is a necessity and any efficiency increase is welcomed)

Anti-surge/dump/blow off valves

A recirculating type anti-surge valve

Turbocharged engines operating at wide open throttle and high rpm require a large volume of air to flow between the turbo and the inlet of the engine. When the throttle is closed compressed air will flow to the throttle valve without an exit (*i.e.* the air has nowhere to go).

This causes a surge which can raise the pressure of the air to a level which can damage the turbo. If the pressure rises high enough, a compressor stall will occur, where the stored pressurized air decompresses backwards across the impeller and out the inlet. The reverse flow back across the turbocharger causes the turbine shaft to reduce in speed more quickly than it would naturally, possibly damaging the turbocharger. In order to prevent this from happening, a valve is fitted between the turbo and inlet which vents off the excess air pressure. These are known as an anti-surge, diverter, bypass, blow-off valve(BOV) or dump valve. It is basically a pressure relief valve, and is normally operated by the vacuum in the intake manifold.

The primary use of this valve is to maintain the turbo spinning at a high speed. The air is usually recycled back into the turbo inlet (diverter or bypass valves) but can also be vented to the atmosphere (blow off valve). Recycling back into the turbocharger inlet is required on an engine that uses a mass-airflow fuel injection system, because dumping the excessive air overboard downstream of the mass airflow sensor will cause an excessively rich fuel mixture (this is because the mass-airflow sensor has already accounted for the extra air which is no longer being used). Valves which recycle the air will also shorten the time needed to re-spool the turbo after sudden engine deceleration, since the load on the turbo when the valve is active is much lower than if the air charge is vented to atmosphere.

Ported shroud/map width enhancement

The flow range of a turbocharger compressor can also be increased by allowing air to bleed from a ring of holes or a circular groove around the compressor at a point slightly downstream of the compressor inlet (but far nearer to the inlet than to the outlet). The Ported shroud is an efficiency increasing enhancement. Increases in compressor efficiency result in colder (more dense) intake air, which improves power. The escaping air flow is directed back into the compressor inlet pipe. In contrast to blow off valves which are electronically controlled, this is a passive structure which is constantly open (which is one reason that it does not open to atmosphere). Allowing some air to escape at this location inhibits the onset of surge and widens the compressor map. The ability of the compressor to accommodate high mass flows (high boost at low rpm) is also increased marginally (because near choke conditions the compressor draws air inward through the bleed path). This technology is widely used by turbocharger manufacturers such as Honeywell Turbo Technologies, Cummins Turbo Technologies, and GReddy. When implemented appropriately, it has a reasonable impact on compressor map width while not compromising the top of the maximum efficiency island.

Charge cooling

Compressing air in the turbocharger increases the air's temperature, which can cause a number of problems. Excessive charge air temperature can lead to detonation, which is extremely destructive to engines. When a turbocharger is installed on an engine, it is common practice to fit the engine with an intercooler (also known as a charge air cooler, or CAC), a type of heat exchanger which gives up heat energy in the charge to the ambient air. Over time an intercooler can develop leaks, losing boost pressure, and reducing fuel economy. It is common practice to leak test the intercooler during routine service, particularly in trucks where a leaking intercooler can result in a 20% reduction in fuel economy.

In addition to the use of intercoolers, it is common practice to introduce extra fuel into the charge for the sole purpose of cooling. The amount of extra fuel varies, but typically reduces the air-fuel ratio to between 11 and 13, instead of the stoichiometric 14.7 (in gasoline engines). The extra fuel is not burned, as there is insufficient oxygen to complete the chemical reaction, and instead undergoes a phase change from vapor(liquid) to gas. This reaction absorbs heat(the latent heat of vaporization), and the added mass of the extra fuel reduces the average kinetic energy of the charge and exhaust gas. The gaseous hydrocarbons generated are oxidized to carbon dioxide, carbon monoxide, and water in the catalytic converter.

Multiple turbochargers

A pair of turbochargers mounted to an Inline 6 engine (2JZ-GTE from a MkIV Toyota Supra) in a dragster.

Parallel

Some engines, such as V-type engines, utilize two identically-sized but smaller turbos, each fed by a separate set of exhaust streams from the engine. The two smaller turbos produce the same (or more) aggregate amount of boost as a larger single turbo, but since they are smaller they reach their optimal RPM, and thus optimal boost delivery, more quickly. Such an arrangement of turbos is typically referred to as a parallel twin-turbo system. The first production automobile with parallel twin turbochargers was the Maserati Biturbo of the early 1980s. Later such installations include Porsche 911 TT, Nissan GT-R, Mitsubishi 3000GT VR-4, Nissan 300ZXTT, Audi RS6, and **BMW twin-turbo 3.0 liter inline N54 6 cylinder**[N54 uses two different in size turbos, a sequential setup] cars (E90, E81, E60).

Sequential

Some car makers combat lag by using two small turbos. A typical arrangement for this is to have one turbo active across the entire rev range of the engine and one coming on-line at higher RPM. Below this RPM, both exhaust and air inlet of the secondary turbo are closed. Being individually smaller they do not suffer from excessive lag and having the second turbo operating at a higher RPM range allows it to get to full rotational speed before it is required. Such combinations are referred to as a sequential twin-turbo. Porsche first used this technology in 1985 in the Porsche 959. Sequential twin-turbos are usually much more complicated than a single or parallel twin-turbo systems because they require what amounts to three sets of intake and waste gate pipes for the two turbochargers as well as valves to control the direction of the exhaust gases. Many new diesel engines use this technology to not only eliminate lag but also to reduce fuel consumption and reduce emissions.

Remote installations

Turbochargers are sometimes mounted well away from the engine, in the tailpipe of the exhaust system. Such remote turbochargers require a smaller aspect ratio due to the slower, lower-volume, denser exhaust gas passing through them. For low-boost applications, an intercooler is not required; often the air charge will cool to near-ambient temperature en route to the engine. A remote turbo can run 300 to 600 degrees cooler than a close-coupled turbocharger, so oil coking (forming solid residue) in the bearings is of much less concern. Remote turbo systems can incorporate multiple turbochargers in series or parallel.

Automotive applications

To manage the pressure of the air coming from the turbo (known as the 'upper-deck air pressure'), the turbocharger's exhaust gas flow is regulated with a wastegate that bypasses excess exhaust gas entering the turbocharger's turbine. This regulates the rotational speed of the turbine and thus the output of the compressor. The wastegate is opened and closed by the compressed air from turbo and can be raised by using a solenoid to regulate the pressure fed to the wastegate membrane. This solenoid can be controlled by Automatic Performance Control, the engine's electronic control unit or a boost control computer. Another method of raising the boost pressure is through the use of check and bleed valves to keep the pressure at the membrane lower than the pressure within the system.

A medium-sized six-cylinder marine Diesel-engine, with turbocharger and exhaust in the foreground

Turbocharging is very common on diesel engines in automobiles, trucks, locomotives, boats and ships, and heavy machinery. For current automotive applications, non-turbocharged diesel engines are becoming increasingly rare. Diesels are particularly suitable for turbocharging for several reasons:

- Turbocharging can dramatically improve an engine's specific power and power-to-weight ratio, performance characteristics which are normally poor in non-turbocharged diesel engines.
- Truck and industrial Diesel engines run mostly at their maximum power, reducing problems with turbo lag caused by sudden accelerations and decelerations.
- Lacking a throttle valve, compressor stall is essentially non-existent.
- Diesel engines have no detonation because diesel fuel is injected at the end of the compression stroke, ignited by compression heat. Because of this, diesel engines can use much higher boost pressures than spark ignition engines, limited only by the engine's ability to withstand the additional heat and pressure.

The turbocharger's small size and low weight have production and marketing advantage to vehicle manufacturers. By providing naturally-aspirated and turbocharged versions of one engine, the manufacturer can offer two different power outputs with only a fraction of the development and production costs of designing and installing a different engine. Usually increased piston cooling is provided by spraying more lubrication oil on the bottom of the piston. The compact nature of a turbocharger mean that bodywork and engine compartment layout changes to accommodate the more powerful engine are not needed. The use of parts common to the two versions of the same engine reduces production and servicing costs.

Today, turbochargers are most commonly used on gasoline engines in high-performance automobiles and diesel engines in transportation and other industrial equipment. Small cars in particular benefit from this technology, as there is often little room to fit a large engine. Volvo, Saab, Audi, Volkswagen and Subaru have produced turbocharged cars for many years; the turbo Porsche 944's acceleration performance was very similar to that of the larger-engined non-turbo Porsche 928; and Chrysler Corporation built numerous turbocharged cars in the 1980s and 1990s. Buick also developed a turbocharged V-6 during the energy crisis in the late 1970s as a fuel efficient alternative to the enormous eight cylinder engines that powered the famously large cars and produced them through most of the next decade as a performance option. Recently, several manufacturers have returned to the turbocharger in an attempt to improve the tradeoff between performance and fuel economy by using a smaller turbocharged engine in place of a larger normally-aspirated engine. The Ford EcoBoost engine is one such design.

Motorcycle applications

The 1982 Honda CX500 Turbo, the world's first turbo-charged production bike

Using turbochargers to gain performance without a large gain in weight was very appealing to the Japanese factories in the 1980s. The first example of a turbocharged bike is the 1978 Kawasaki Z1R TC. It used a Rayjay ATP turbo kit to build 0.35 bar (5 lb) of boost, bringing power up from c. 90 hp (67 kW) to c. 105 hp (78 kW). However, it was only marginally faster than the standard model. A US Kawasaki importer came up with the idea of modifying the Z1-R with a turbocharging kit as a solution to the Z1-R being a low selling bike. The 112 hp (84 kW) Kawasaki GPz750 Turbo was manufactured from 1983 to 1985. This motorcycle had little in common with the normally aspirated Kawasaki GPz750. Nearly every component was altered or strengthened for this GPz 750 Turbo to handle the 20 hp (15 kW) increase in power.

In 1982, Honda released the CX500T featuring a carefully developed turbo (as opposed to the Z1-R's bolt-on approach). It has a rotation speed of 200,000 rpm. The development of the CX500T was riddled with problems; due to being a V-twin engine the intake periods in the engine rotation are staggered leading to periods of high intake and long periods of no intake at all. Designing around these problems increased the price of the bike, and the performance still was not as good as the cheaper CB900(a 16 valve in-line four) During these years, Suzuki produced the XN85, a 650 cc in-line four producing 85 bhp (63 kW), and Yamaha produced the Seca Turbo. The XN85 was fuel injected, while the Yamaha Seca Turbo relied on pressurized carburetors.

Since the mid 1980s, no manufactures have produced turbocharged motorcycles making these bikes a bit of an educational experience; as of 2007 no factories offer turbocharged motorcycles (although the Suzuki B-King prototype featured a supercharged Hayabusa engine). The Dutch manufacturer EVA motorcycles builds a small series of turbocharged diesel motorcycle with an 800cc smart cdi engine.

Aircraft applications

A natural use of the turbocharger is with aircraft engines. As an aircraft climbs to higher altitudes the pressure of the surrounding air quickly falls off. At 5,486 m (18,000 ft) the air is at half the pressure of sea level, and the airframe only experiences half the aerodynamic drag. However, since the charge in the cylinders is being pushed in by this air pressure, it means that the engine will normally produce only half-power at full throttle at this altitude. Pilots would like to take advantage of the low drag at high altitudes in order to go faster, but a naturally aspirated engine will not produce enough power at the same altitude to do so.

Altitude effects

A turbocharger remedies this problem by compressing the air back to sea-level pressures; or even much higher; in order to produce rated power at high altitude. Since the size of the turbocharger is chosen to produce a given amount of pressure at high altitude, the turbocharger is over-sized for low altitude. The speed of the turbocharger is controlled by a wastegate. Early systems used a fixed wastegate, resulting in a turbocharger that functioned much like a supercharger. Later systems utilized an adjustable wastegate, controlled either manually by the pilot or by an automatic hydraulic or electric system. When the aircraft is at low altitude the wastegate is usually fully open, venting all the exhaust gases overboard. As the aircraft climbs and the air density drops, the wastegate must continually close in small increments to maintain full power. The altitude at which the wastegate is full closed and the engine is still producing full rated power is known as the *critical altitude.* When the aircraft climbs above the critical altitude, engine power output will decrease as altitude increases just as it would in a naturally-aspirated engine.

Temperature considerations

One adverse effect of turbocharging is that compressing the air increases its temperature, which is true for any method of forced induction. This causes multiple problems. Increased temperatures can lead to pre-ignition or detonation because of excessive cylinder head temperatures. In addition, hotter air is less dense, so fewer air molecules enter the cylinders on each intake stroke, resulting in an effective drop in volumetric efficiency which works against the efforts of the turbocharger to increase volumetric efficiency.

A Subaru Impreza WRX STI engine bay, clearly showing the top mounted intercooler to the back of the engine. Cold fresh air enters through a bonnet scoop

A method of generally coping with this problem is in one of several ways. The most common one is to add an intercooler or aftercooler somewhere in the air stream between the compressor outlet of the turbocharger and the engine intake manifold. Intercoolers and aftercoolers are types of heat exchangers which cause the compressed air to give up some of its heat energy to the ambient air. In the past, some aircraft featured anti-detonant injection for takeoff and climb phases of flight, which performs the function of cooling the fuel/air charge before it reaches the cylinders.

In contrast, modern turbocharged aircraft usually forego any kind of temperature compensation, because the turbochargers are generally small and the manifold pressures created by the turbocharger are not very high. Thus the added weight, cost, and complexity of a charge cooling system are considered to be unnecessary penalties. In those cases the turbocharger is limited by the temperature at the compressor outlet, and the turbocharger and its controls are designed to prevent a large enough temperature rise to cause detonation. Even so, in many cases the engines are designed to run rich in order to use the evaporating fuel for charge cooling.

Comparison to supercharging

A supercharger inevitably requires some energy to be bled from the engine to drive the supercharger. On the single-stage single-speed supercharged Rolls Royce Merlin engine for instance, the supercharger uses up about 150 horsepower (110 kW). Yet the benefits outweigh the costs, for that 150 hp (110 kW), the engine generates an additional 400 horsepower and delivers 1,000 hp (750 kW) when it would otherwise deliver 750 hp (560 kW), a net gain of 250 hp (190 kW). This is where the principal disadvantage of a supercharger becomes apparent: The engine has to burn extra fuel to provide power to turn the supercharger. The increased charge density increases the engine's specific power and power to weight ratio, but also increases the engine's specific fuel consumption. This increases the cost of running the aircraft and reduces its overall range. On the other hand, a turbocharger is driven using the exhaust gases. Otherwise-wasted heat is extracted from the exhaust gas, and converted to useful power to compress the intake air. The turbine section of the turbocharger is actually a heat engine in itself. It converts the heat of the exhaust into power used to drive the compressor, thereby providing a more efficient compression of the intake air than can happen with supercharger, which uses up net engine power to drive its air compressor.

With older supercharged aircraft, the pilot must continually adjust the throttle to maintain the required manifold pressure during ascent or descent. The pilot must also take great care to avoid overboosting the engine and causing damage, especially during emergencies such as go-arounds. In contrast, modern turbocharger systems use an automatic wastegate which controls the manifold pressure within parameters preset by the manufacturer. For these systems, as long as the control system is working properly and the pilot's control commands are smooth and deliberate, a turbocharger will not overboost the engine and damage it.

Yet the majority of World War II engines used superchargers, because they maintained three significant manufacturing advantages over turbochargers, which were larger, involved extra piping, and required exotic high-temperature materials in the turbine and pre-turbine section of the exhaust system. The size of the piping alone is a serious issue; American fighters Vought F4U and Republic P-47 used the same engine but the huge barrel-like fuselage of the latter was, in part, needed to hold the piping to and from the turbocharger in the rear of the plane. Turbocharged piston engines are also subject to many of the same operating restrictions as gas turbine engines. Pilots must make smooth, slow throttle adjustments to avoid overshooting their target manifold pressure. The fuel mixture must often be adjusted far on the rich side of the peak exhaust gas temperature to avoid overheating the turbine when running at high power settings. In systems using a manually-operated wastegate, the pilot must be careful not to exceed the turbocharger's maximum RPM. Turbocharged engines require a cooldown period after landing to prevent cracking of the turbo or exhaust system from thermal shock. Turbocharged engines require frequent inspections of the turbocharger and exhaust systems for damage due to the increased heat, increasing maintenance costs.

Today, most general aviation aircraft are naturally aspirated. The small number of modern aviation piston engines designed to run at high altitudes generally use a turbocharger or turbo-normalizer system rather than a supercharger. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the supercharger has fallen out of favor.

Turbocharged aircraft often occupy a performance range in between that of normally-aspirated piston-powered aircraft and turbine-powered aircraft. The increased maintenance costs of a turbo-charged engine are considered worthwhile for this purpose, as a turbocharged piston engine is still far cheaper than any turbine engine.

Relationship to gas turbine engines

Prior to World War II, Sir Frank Whittle started his experiments on early turbojet engines. Due to a lack of sufficient materials as well as funding, initial progress was slow. However, turbochargers were used extensively in military aircraft during World War II to enable them to fly very fast at very high altitudes. The demands of the war led to constant advances in turbocharger technology, particularly in the area of materials. This area of study eventually crossed over into the development of early gas turbine engines. Those early turbine engines were little more than a very large turbocharger with the compressor and turbine connected by a number of combustion chambers. The cross over between the two has been shown in an episode of the TV show Scrapheap Challenge where contestants were able to build a functioning jet engine using an ex-automotive turbocharger as a compressor.

General Electric manufactured turbochargers for military aircraft and held several patents on their electric turbo controls during World War II, then used that expertise to very quickly carve out a dominant share of the gas turbine market which they have held ever since.

Properties and applications

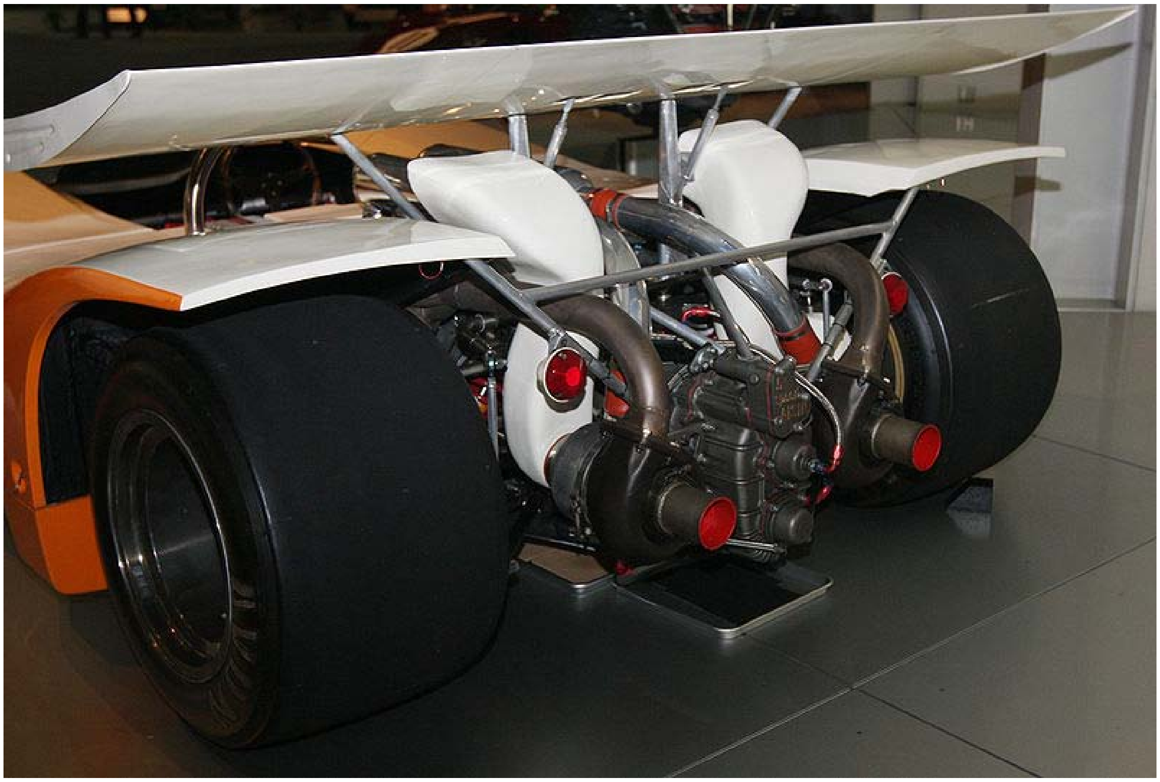
Reliability

Turbochargers can be damaged by dirty or ineffective oil, and most manufacturers recommend more frequent oil changes for turbocharged engines. Many owners and some companies recommend using synthetic oils, which tend to flow more readily when cold and do not break down as quickly as conventional oils. Because the turbocharger will heat when running, many recommend letting the engine idle for up to three minutes before shutting off the engine if the turbocharger was used shortly before stopping. This gives the oil and the lower exhaust temperatures time to cool the turbo rotating assembly, and ensures that oil is supplied to the turbocharger while the turbine housing and exhaust manifold are still very hot; otherwise coking of the lubricating oil trapped in the unit may occur when the heat soaks into the bearings, causing rapid bearing wear and failure when the car is restarted. Even small particles of burnt oil will accumulate and lead to choking the oil supply and failure. This problem is less pronounced in diesel engines, due to higher quality oil typically being specified.

A turbo timer can keep an engine running for a pre-specified period of time, to automatically provide this cool-down period. Oil coking is also eliminated by foil bearings. A more complex and problematic protective barrier against oil coking is the use of water-cooled bearing cartridges. The water boils in the cartridge when the engine is shut off and forms a natural recirculation to drain away the heat. Nevertheless, it is not a good idea to shut the engine off while the turbo and manifold are still glowing.

In custom applications utilizing tubular headers rather than cast iron manifolds, the need for a cooldown period is reduced because the lighter headers store much less heat than heavy cast iron manifolds.

Turbo lag

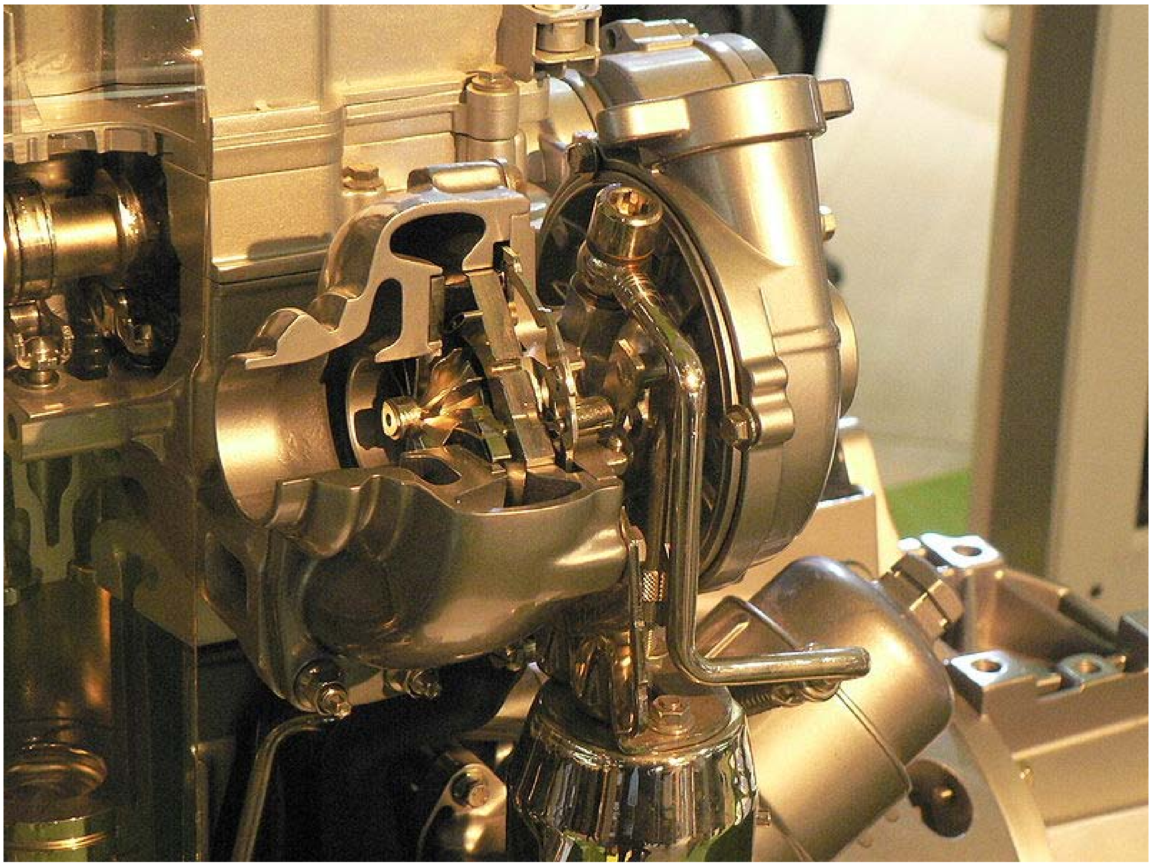


1970 Toyota 7, twin turbo-charged racing car

The time required to bring the turbo up to a speed where it can function effectively is called *turbo lag*. This is noticed as a hesitation in throttle response when coming off idle. This is symptomatic of the time taken for the exhaust system driving the turbine to come to high pressure and for the turbine rotor to overcome its rotational inertia and reach the speed necessary to supply boost pressure. The directly-driven compressor in a supercharger does not suffer from this problem. (Centrifugal superchargers do not build boost at low rpm as a positive displacement supercharger will). Conversely on light loads or at low RPM a turbocharger supplies less boost and the engine acts like a naturally aspirated engine.

Lag can be reduced by lowering the rotational inertia of the turbine, for example by using lighter parts to allow the spool-up to happen more quickly. Ceramic turbines are of benefit in this regard. Unfortunately, their relative fragility limits the maximum boost they can supply. Another way to reduce lag is to change the aspect ratio of the turbine by reducing the diameter and increasing the gas-flow path-length. Increasing the upper-deck air pressure and improving the wastegate response helps but there are cost increases and reliability disadvantages that car manufacturers are not happy about. Lag is also reduced by using a foil bearing rather than a conventional oil bearing. This reduces friction and contributes to faster acceleration of the turbo's rotating assembly. Variable-nozzle turbochargers (discussed below) greatly reduce lag.

Other engines use two turbochargers - a small and a large. Because of its weight, the smaller turbo will have a shorter lag, but when the car is reaching higher speeds, the volume of air going into the inlet manifold will be too high. When the volume of air is becoming too high, the smaller turbo will not be able to provide much boost, and the turbine and compressor will be in danger of spinning too quickly. When this happens, the larger turbocharger will take over, so more boost can be provided.



Porsche variable-geometry turbocharger

Instead of using two turbochargers in different sizes, some engines use a single turbocharger, called variable-geometry or variable-nozzle turbos, these turbos use a set of vanes in the exhaust housing to maintain a constant gas velocity across the turbine, the same kind of control as used on power plant turbines. Such turbochargers have minimal lag like a small conventional turbocharger and can achieve full boost as low as 1,500 engine rpm, yet remain efficient as a large conventional turbocharger at higher engine speeds. In many setups these turbos do not use a wastegate. The vanes are controlled by a membrane identical to the one on a wastegate, but the mechanism operates the variable vane system instead. These variable turbochargers are commonly used in diesel engines.

Lag is not to be confused with the boost threshold. The boost threshold of a turbo system describes the lower bound of the region within which the compressor will operate. Below a certain rate of flow at any given pressure multiplier, a given compressor will not produce significant boost. This has the effect of limiting boost at particular rpm regardless of exhaust gas pressure. Newer turbocharger and engine developments have caused boost thresholds to steadily decline.

Electrical boosting ("E-boosting") is a new technology under development; it uses a high speed electrical motor to drive the turbocharger to speed before exhaust gases are available, *e.g.* from a stop-light. An alternative to e-boosting is to completely separate the turbine and compressor into a turbine-generator and electric-compressor as in the hybrid turbocharger. This allows the compressor speed to become independent to that of the turbine. A similar system utilising a hydraulic drive system and overspeed clutch arrangement was fitted in 1981 to accelerate the turbocharger of the MV *Canadian Pioneer* (Doxford 76J4CR engine).

Race cars often utilize an Anti-Lag System to completely eliminate lag at the cost of reduced turbocharger life.

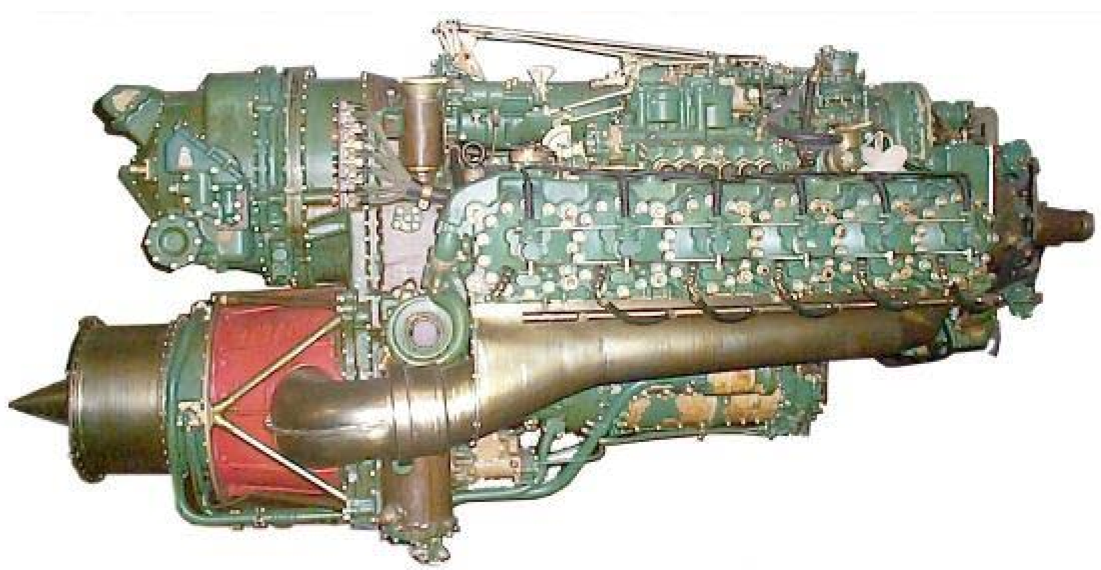
Boost threshold

Turbochargers start producing boost only above a certain exhaust mass flow rate. The boost threshold is determined by the engine displacement, rpm, throttle opening and the size of the turbo. Without adequate exhaust gas flow to spin the drive blades, the turbo cannot produce the necessary force needed to compress the air going into the engine. The point at full throttle in which the mass flow in the exhaust is strong enough to force air into the engine is known as the boost threshold rpm. Engineers have, in some cases, been able to reduce the boost threshold rpm to idle speed to allow for instant response. Both Lag and Threshold characteristics can be acquired through the use of a compressor map and a mathematical equation.

Chapter 7

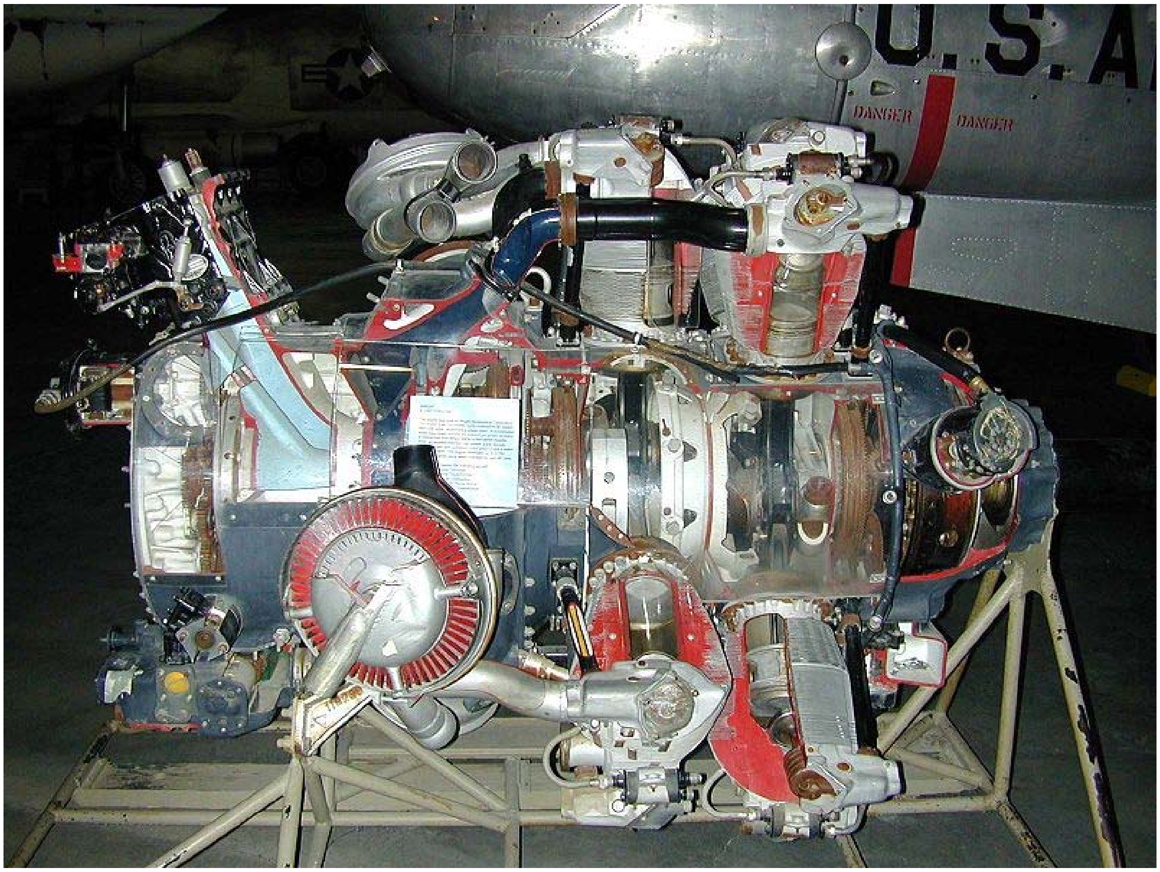
Turbo-Compound Engine & Opposed-Piston Engine

Turbo-Compound Engine



The Napier Nomad engine. The power-recovery turbine sits underneath a two-stroke diesel engine.

A **Turbo-compound engine** is a reciprocating engine that employs a blowdown turbine to recover energy from the exhaust gases. The turbine is usually mechanically connected to the crankshaft but electric and hydraulic systems have been investigated as well. The turbine increases the output of the engine without increasing its fuel consumption, thus reducing the specific fuel consumption. The turbine is referred to as a blowdown turbine (or power-recovery turbine), as it recovers the energy developed in the exhaust manifold during blowdown, that is the first period of the exhaust process when the piston still is on its expansion stroke (this is possible since the exhaust valves open before bottom dead center).



Wright R-3350 Turbo-Compound radial engine.

When a blowdown turbine is attached to an engine it will not reduce power due to exhaust gas flow restriction, since a blowdown turbine is a velocity turbine, not a pressure turbine as is a turbo supercharger. The exhaust restriction imparted by the three blowdown turbines used on the Wright 3350 Duplex Cyclone is equal to a well-designed jet stack system used on a conventional radial engine. However, the blowdown turbines recover about 550 horsepower at METO (maximum continuous except for take-off) power.

Turbo-compounding was used on on several airplane engines after World War II, the Napier Nomad and the Wright R-3350 being examples. In the case of the R-3350, maintenance crews sometimes nicknamed the turbine the "Parts Recovery Turbine" due to its negative effect on engine reliability. Turbo-compound versions of the Napier Deltic, Rolls-Royce Crecy, and Allison V-1710 were constructed but none was developed beyond the prototype stage. It was realized that in many cases the power produced by the simple turbine was approaching that of the enormously complex and maintenanceintensive piston engine to which it was attached. As a result, turbo-compound aero engines were soon supplanted by turboprop and turbojet engines.

Some modern heavy truck diesel manufacturers have incorporated turbo-compounding into their modern designs. Examples include: the Detroit Diesel DD15 engine that claims 5 percent better fuel economy with an additional 50 hp "free" compared to their previous engines, and Scania , in production from 2001

Turbo-compound engines

Detroit Diesel

- DD15

Napier

- Napier Nomad

Wright Aeronautical

- Wright R-3350 - The turbo-compound version was the only turbo-compound aero-engine to see mass production and widespread usage.

Dobrynin

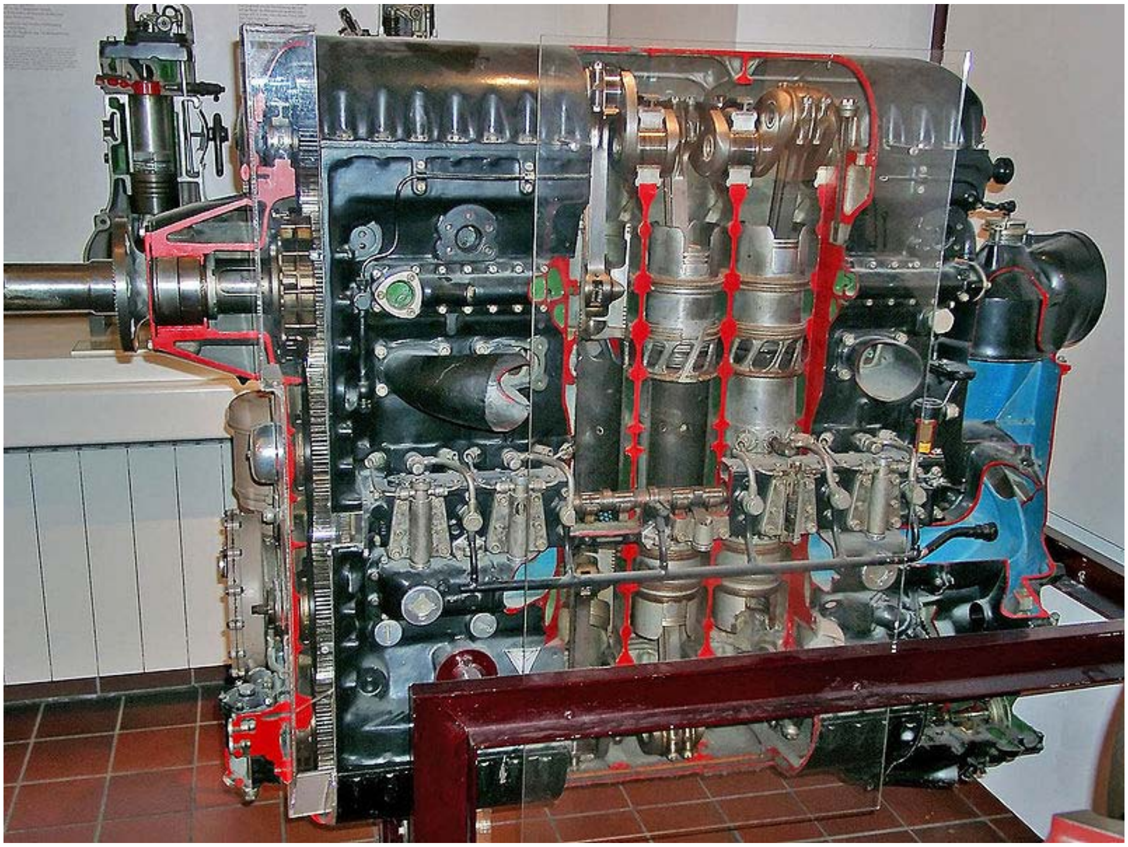
Dobrynin VD-4K

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

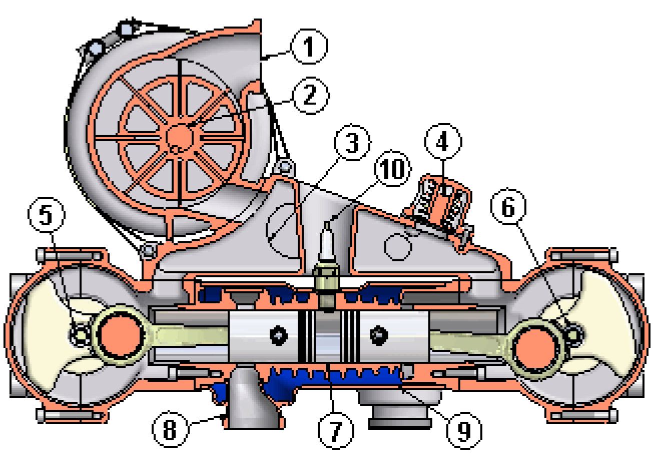
The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently 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.

Chapter 8

Hypereutectic Piston & Exhaust Gas Recirculation

Hypereutectic Piston

A **hypereutectic piston** is an internal combustion engine piston cast using a hypereutectic alloy–that is, a metallic alloy which has a composition beyond the eutectic point. In materials science, the word eutectic refers to a specific ratio of chemical composition at which the constituent elements will form a single, homogeneous phase when cooled. Above or below this ratio, separate chemical phases will form during cooling due to insolubility of one constituent in the other. Most metals are not eutectic, and have different phases present in their cooled form. Hypereutectic pistons are made of an aluminum alloy which has much more silicon present than is soluble in aluminum at the operating temperature. Hypereutectic aluminum has a lower coefficient of thermal expansion, which allows engine designers to specify much tighter tolerances.

The most common material used for automotive pistons is aluminum due to its light weight, low cost, and acceptable strength. Although other elements may be present in smaller amounts, the alloying element of concern in aluminum for pistons is silicon. The point at which silicon is fully and exactly soluble in aluminum at operating temperatures is around 12%. Either more or less silicon than this will result in two separate phases in the solidified crystal structure of the metal. This is very common. When significantly more silicon is added to the aluminum than 12%, the properties of the aluminum change in a way that is useful for the purposes of pistons for combustion engines. However, at a blend of 25% silicon there is a significant reduction of strength in the metal, so hypereutectic pistons commonly use a level of silicon between 16% and 19%. Special moulds, casting, and cooling techniques are required to obtain uniformly dispersed silicon particles throughout the piston material.

Hypereutectic pistons are stronger than more common cast aluminum pistons and used in many high performance applications. They are not as strong as forged pistons, but are much lower cost due to being cast.

Advantages

Most automotive engines use aluminium pistons that move in an iron cylinder. The average temperature of a piston crown in a gasoline engine during normal operation is typically about 300 °C (570 °F), and the coolant that runs through the engine block is usually regulated at approximately 90 °C (190 °F). Aluminium expands more than iron at this temperature range, so for the piston to fit the cylinder properly when at a normal operating temperature, the piston must have a loose fit when cold.

In the 1970s, increasing concern over exhaust pollution caused the U.S. government to form the Environmental Protection Agency (EPA), which began passing legislation that forced automobile manufacturers to introduce changes that made their engines run cleaner. By the late 1980s, automobile exhaust pollution had been noticeably improved, but more stringent regulations forced car manufacturers to adopt the use of electronically controlled fuel injection and hypereutectic pistons. Regarding pistons, it was discovered that when an engine was cold during start-up, a small amount of fuel became trapped between the piston rings. As the engine warmed up, the piston expanded and expelled this small amount of fuel which added to the amount of unburnt hydrocarbons in the exhaust.

By adding silicon to the piston's alloy, the piston expansion was dramatically reduced. This allowed engineers to specify a much tighter cold-fit between the piston and the cylinder liner. Silicon itself expands less than aluminium, but it also acts as an insulator to prevent the aluminium from absorbing as much of the operational heat as it otherwise would. Another benefit of adding silicon is that the piston becomes harder and is less susceptible to scuffing which can occur when a soft aluminium piston is cold-revved in a relatively dry cylinder on start-up or during abnormally high operating temperatures.

The biggest drawback of adding silicon to pistons is that the piston becomes more brittle as the ratio of silicon is added. This makes the piston more susceptible to cracking if the engine experiences pre-ignition or detonation.

Performance replacement alloys

When auto enthusiasts want to increase the power of the engine, they may add some type of forced induction. By compressing more air and fuel into each intake cycle, the power of the engine can be dramatically increased. This also increases the heat and pressure in the cylinder.

The normal temperature of gasoline engine exhaust is approximately 650 °C (1,200 °F). This is also approximately the melting point of most aluminum alloys and it is only the constant influx of ambient air that prevents the piston from deforming and failing. Forced induction increases the operating temperatures while "under boost", and if the excess heat is added faster than engine can shed it, the elevated cylinder temperatures will cause the air and fuel mix to auto-ignite on the compression stroke before the spark event. This is one type of engine knocking that causes a sudden shockwave and pressure spike, which can result in an immediate and catastrophic failure of the piston and connecting rod.

The "4032" performance piston alloy has a silicon content of approximately 11%. This means that it expands less than a piston with no silicon, but since the silicon is fully alloyed on a molecular level (eutectic), the alloy is less brittle and more flexible than a stock hypereutectic "smog" piston. These pistons can survive mild detonation with less damage than stock pistons.

The "2618" performance piston alloy has less than 2% silicon, and could be described as hypo (under) eutectic. This alloy is capable of experiencing the most detonation and abuse while suffering the least amount of damage. Pistons made of this alloy are also typically made thicker and heavier because of their most common applications in commercial diesel engines. Both because of the higher than normal temperatures that these pistons experience in their usual application, and the low-silicon content causing the extra heat-expansion, these pistons have their cylinders bored to a very loose cold-fit. This leads to a condition known as "piston slap" which is when the piston rocks in the cylinder and it causes an audible tapping noise that continues until the engine has warmed to operational temperatures. These engines should not be revved when cold, or excessive scuffing can occur.

Forged versus cast

When a piston is cast, the alloy is heated until liquid, then poured into a mould to create the basic shape. After the alloy cools and solidifies it is removed from the mould and the rough casting is machined to its final shape. For applications which require stronger pistons, a forging process is used.

In the forging process, the rough casting is placed in a die set while it is still hot and semi-solid. A hydraulic press is used to place the rough slug under tremendous pressure. This removes any possible porosity, and also pushes the alloy grains together tighter than can be achieved by simple casting alone. The end result is a much stronger material.

Hypereutectic pistons can be forged, but typically are only cast, because the extra expense of forging is not justified when cast pistons are considered strong enough for stock applications.

Aftermarket performance pistons made from the most common 4032 and 2618 alloys are typically forged.

Exhaust Gas Recirculation

EGR valve on top of the inlet manifold of a Saab H engine in a 1987 Saab 90

In internal combustion engines, **exhaust gas recirculation** (**EGR**) is a nitrogen oxide (NOx) emissions reduction technique used in petrol/gasoline and diesel engines.

EGR works by recirculating a portion of an engine's exhaust gas back to the engine cylinders. In a gasoline engine, this inert exhaust displaces the amount of combustible matter in the cylinder. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture.

Because NOx forms primarily when a mixture of nitrogen and oxygen is subjected to high temperature, the lower combustion chamber temperatures caused by EGR reduces the amount of NOx the combustion generates.

EGR in spark-ignited engines

The exhaust gas, added to the fuel, oxygen, and combustion products, increases the specific heat capacity of the cylinder contents, which lowers the adiabatic flame temperature.

In a typical automotive spark-ignited (SI) engine, 5 to 15 percent of the exhaust gas is routed back to the intake as EGR. The maximum quantity is limited by the requirement of the mixture to sustain a contiguous flame front during the combustion event; excessive EGR in poorly set up applications can cause misfires and partial burns. Although EGR does measurably slow combustion, this can largely be compensated for by advancing spark timing. The impact of EGR on engine efficiency largely depends on the specific engine design, and sometimes leads to a compromise between efficiency and NOx emissions. A properly operating EGR can theoretically increase the efficiency of gasoline engines via several mechanisms:

- **Reduced throttling losses**. The addition of inert exhaust gas into the intake system means that for a given power output, the throttle plate must be opened further, resulting in increased inlet manifold pressure and reduced throttling losses.
- **Reduced heat rejection**. Lowered peak combustion temperatures not only reduces NOx formation, it also reduces the loss of thermal energy to combustion chamber surfaces, leaving more available for conversion to mechanical work during the expansion stroke.
- **Reduced chemical dissociation**. The lower peak temperatures result in more of the released energy remaining as sensible energy near TDC, rather than being bound up (early in the expansion stroke) in the dissociation of combustion products. This effect is minor compared to the first two.

It also decreases the efficiency of gasoline engines via at least one more mechanism:

- **Reduced specific heat ratio**. A lean intake charge has a higher specific heat ratio than an EGR mixture. A reduction of specific heat ratio reduces the amount of energy that can be extracted by the piston.

EGR is typically not employed at high loads because it would reduce peak power output. This is because it reduces the intake charge density. EGR is also omitted at idle (low-speed, zero load) because it would cause unstable combustion, resulting in rough idle. The EGR valve also cools the exhaust valves and makes them last far longer (a very important benefit under light cruise conditions)

EGR implementations

Usually, an engine recirculates exhaust gas by piping it from the exhaust manifold to the inlet manifold. This design is called *external* EGR. A control valve (EGR Valve) within the circuit regulates and times the gas flow. Some engines incorporate a camshaft with relatively large overlap during which both the intake valve and the exhaust valve are open, thus trapping exhaust gas within the cylinder by not fully expelling it during the exhaust stroke. A form of internal EGR is used in the rotary Atkinson cycle engine.

EGR can also be implemented by using a variable geometry turbocharger (VGT) which uses variable inlet guide vanes to build sufficient backpressure in the exhaust manifold. For EGR to flow, a pressure difference is required across the intake and exhaust manifold and this is created by the VGT.

Another method that has been experimented with, is using a throttle in a turbocharged diesel engine to decrease the intake pressure, thereby initiating EGR flow.

The first EGR systems were crude; some were as simple as an orifice jet between the exhaust and intake tracts which admitted exhaust to the intake tract whenever the engine was running. Difficult starting, rough idling, and reduced performance and fuel economy resulted. By 1973, an **EGR valve** controlled by manifold vacuum opened or closed to admit exhaust to the intake tract only under certain conditions. Control systems grew more sophisticated as automakers gained experience; Chrysler's "Coolant Controlled Exhaust Gas Recirculation" system of 1973 exemplified this evolution: a coolant temperature sensor blocked vacuum to the EGR valve until the engine reached normal operating temperature. This prevented driveability problems due to unnecessary exhaust induction; NOx forms under elevated temperature conditions generally not present with a cold engine. Moreover, the EGR valve was triggered by reference to vacuum within the carburetor's venturi, which allowed more precise constraint of EGR flow to only those engine load conditions under which NOx is likely to form. Later, backpressure transducers were added to the EGR valve control to further tailor EGR flow to engine load conditions.

Modern systems utilizing electronic engine control computers, multiple control inputs, and servo-driven EGR valves typically *improve* performance/efficiency with no impact on drivability.

In most modern engines, a faulty or disabled EGR system will cause the computer to display a check engine light and the vehicle to fail an emissions test.

Disadvantages in diesel engines

Recirculating exhaust into the intake tract of a medium- or heavy-duty diesel engine can reduce power output, increase fuel consumption, and add abrasive contaminants and increase engine oil acidity, which in turn can reduce engine longevity.

Chapter 9

Two-Stroke Engine

Brons two-stroke V8 Diesel engine driving a Heemaf generator.

A **two-stroke** engine is an internal combustion engine that completes the process cycle in one revolution of the crank shaft (an up stroke and a down stroke of the piston, compared to twice that number for a four-stroke engine). This is accomplished by using the beginning of the compression stroke and the end of the combustion stroke to perform simultaneously the intake and exhaust (or scavenging) functions. In this way two-stroke engines often provide strikingly high specific power, at least in a narrow range of rotations speeds. The functions of some or all of the valves required by a four-stroke engine are usually served in a two-stroke engine by ports that are opened and closed by the motion of the pistons, greatly reducing the number of moving parts. Gasoline (spark ignition) versions are particularly useful in lightweight (portable) applications such as chainsaws and the concept is also used in diesel compression ignition engines in large and non-weight sensitive applications such as ships and locomotives.

Invention of the two-stroke cycle is attributed to Scottish engineer Dugald Clerk who in 1881 patented his design, his engine having a separate charging cylinder. The crankcase-scavenged engine, employing the area below the piston as a charging pump, is generally credited to Englishman Joseph Day (and Frederick Cock for the piston-controlled inlet port).

Applications

A two-stroke minibike.

Lateral view of a two-stroke Forty series British Seagull outboard engine. The serial number dates it to 1954/1955

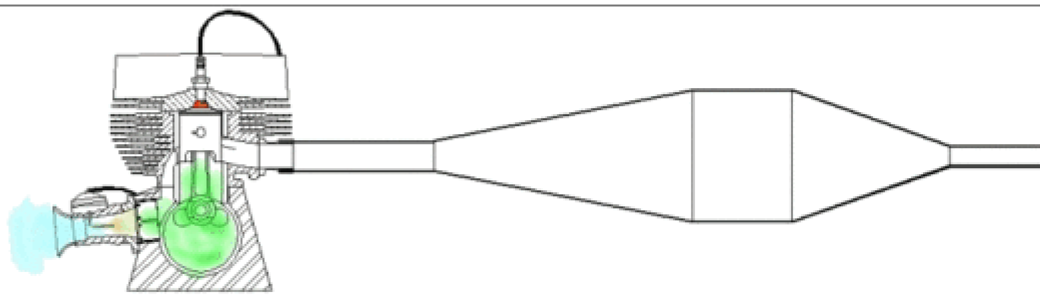
The two-stroke engine was very popular throughout the 20th century in motorcycles, small engined devices such as chainsaws and outboard motors and was also used in some cars, a few tractors and many ships. Part of their appeal was due to their simple design (and resulting low cost) and often high power-to-weight ratio. Many designs use total-loss lubrication, with the oil being burnt in the combustion chamber, causing "blue smoke" and other types of exhaust pollution. This is a major reason for two-stroke engines losing out to and being replaced by four-stroke engines in many applications.

Two-stroke engines continue to be commonly used in high-power, handheld applications such as string trimmers and chainsaws. The light overall weight, and light-weight spinning parts give important operational and even safety advantages. Only a two-stroke running on a gasoline-oil mixture can power a chainsaw running in any position.

These engines are still used for small, portable, or specialized machine applications such as outboard motors, high-performance, small-capacity motorcycles, mopeds, underbones, scooters, tuk-tuks, snowmobiles, karts, ultralights, model airplanes (and other model vehicles) and lawnmowers. The two-stroke cycle is used in many diesel engines, most notably large industrial and marine engines, as well as some trucks and heavy machinery.

A number of mainstream automobile manufacturers have used two-stroke engines in the past, including the Swedish Saab and German manufacturers DKW and Auto-Union. The Japanese manufacturer Suzuki did the same in the 1970s. Production of two-stroke cars ended in the 1980s in the West, but Eastern Bloc countries continued until around 1991, with the Trabant and Wartburg in East Germany. Lotus of Norfolk, UK, has a prototype direct-injection two-stroke engine intended for alcohol fuels called the Omnivore which it is demonstrating in a version of the Exige.

Different two-stroke design types



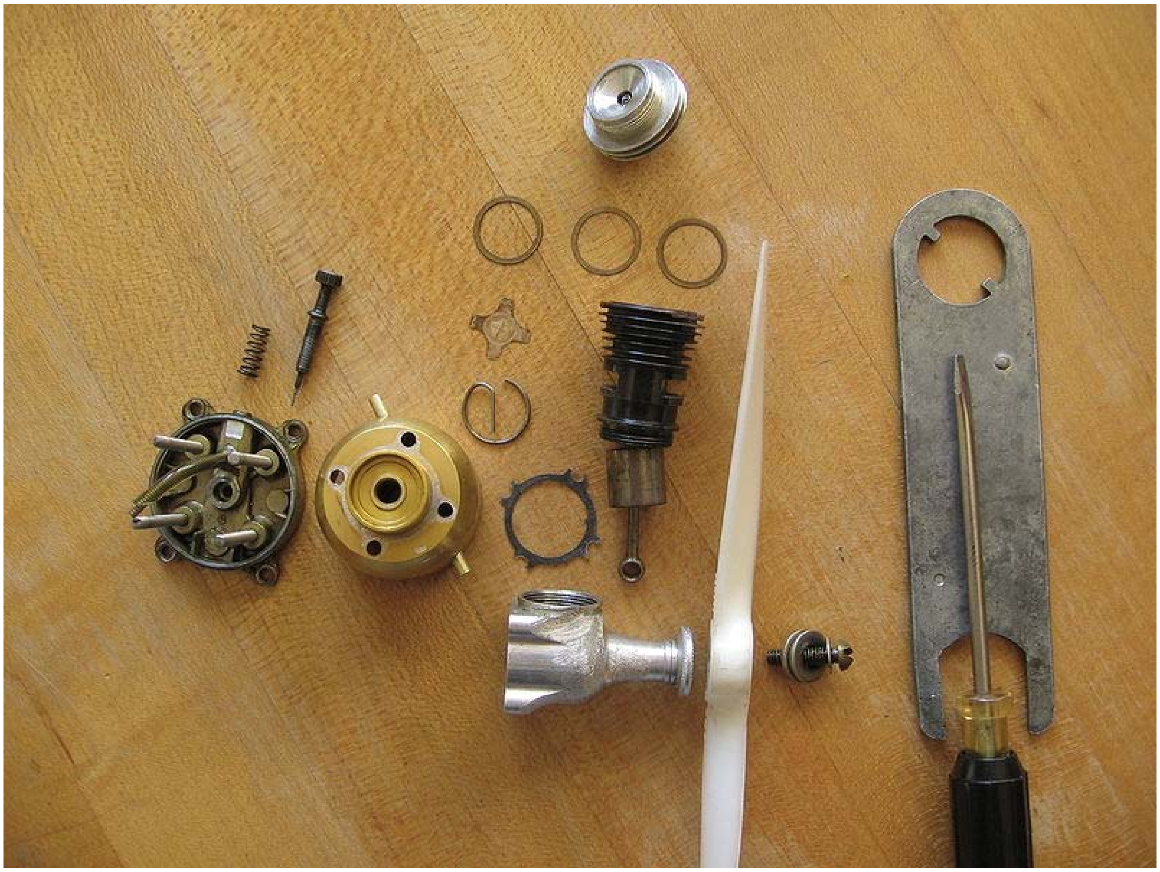
A two-stroke engine, in this case with a tuned expansion pipe illustrating the effect of a reflected pressure wave on the fuel charge. This feature is essential for maximum charge pressure (volumetric efficiency) and fuel efficiency. It is used on most high-performance engine designs.

Although the principles remain the same, the mechanical details of various two-stroke engines differ depending on the type. The design types of the two-stroke engine vary according to the method of introducing the charge to the cylinder, the method of scavenging the cylinder (exchanging burnt exhaust for fresh mixture) and the method of exhausting the cylinder.

Piston controlled inlet port

Piston port is the simplest of the designs. All functions are controlled solely by the piston covering and uncovering the ports as it moves up and down in the cylinder. A fundamental difference from typical four-stroke engines is that the crankcase is sealed and forms part of the induction process in gasoline and hot bulb engines. Diesel engines have mostly a roots blower or piston pump for scavenging.

Reed inlet valve



A Cox Babe Bee 0.049 cubic inch (0.8 cubic cm.) reed valve engine disassembled. It uses glow plug ignition. The mass is 64 grams.

The reed valve is a simple but highly effective form of check valve commonly fitted in the intake tract of the piston-controlled port. They allow asymmetric intake of the fuel-charge, improving power and economy, while widening the power band. They are widely used in ATVs, and marine outboard engines.

Rotary inlet valve

The intake pathway is opened and closed by a rotating member. A familiar type sometimes seen on small motorcycles is a slotted disk attached to the crankshaft which covers and uncovers an opening in the end of the crankcase, allowing charge to enter during one portion of the cycle.

Another form of rotary inlet valve used on two-stroke engines employs two cylindrical members with suitable cutouts arranged to rotate one within the other - the inlet pipe having passage to the crankcase only when the two cutouts coincide. The crankshaft itself may form one of the members, as in most Glowplug model engines. In another embodiment, the crank disc is arranged to be a close-clearance fit in the crankcase and is provided with a cutout which lines up with an inlet passage in the crankcase wall at the appropriate time, as in the Vespa motor scooter.

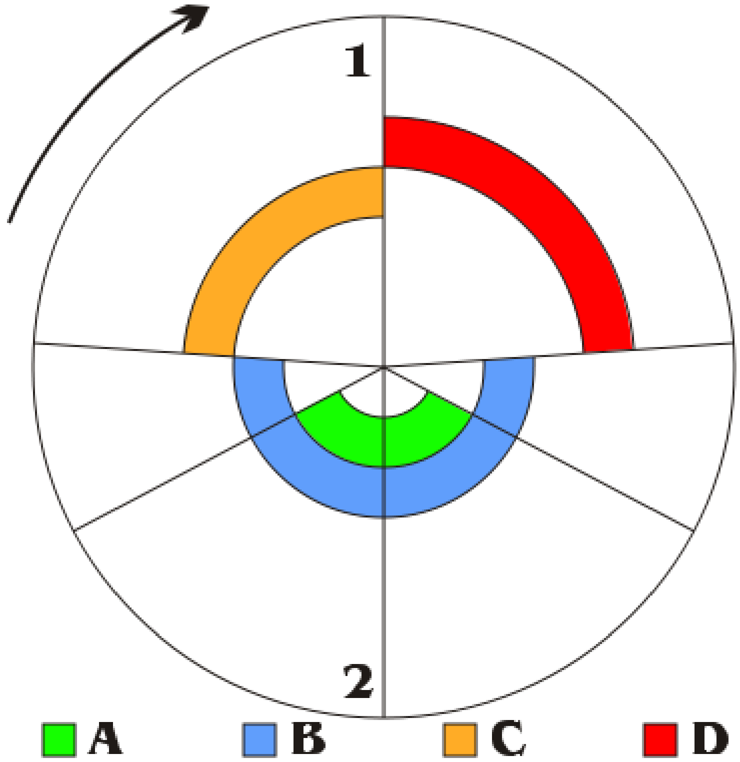
The advantage of a rotary valve is that it enables the two-stroke engine's intake timing to be asymmetrical which is not possible with two-stroke piston port type engines. The two-stroke piston port type engine's intake timing opens and closes before and after top dead center at the same crank angle making it symmetrical whereas the rotary valve allows the opening to begin earlier and close earlier.

Rotary valve engines can be tailored to deliver power over a wider speed range or higher power over a narrower speed range than either piston port or reed valve engine. Where a portion of the rotary-valve is a portion of the crankcase itself it is particularly important that no wear is allowed to take place.

Crossflow-scavenged

In a crossflow engine the transfer ports and exhaust ports are on opposite sides of the cylinder and a deflector on the top of the piston directs the fresh intake charge into the upper part of the cylinder pushing the residual exhaust gas down the other side of the deflector and out of the exhaust port. The deflector increases piston's weight and its exposed surface area, and also makes it difficult to achieve an efficient combustion chamber shape. This design has been largely superseded by loop scavenging method (below), although for smaller or slower engines the crossflow-scavenged design can be an acceptable approach.

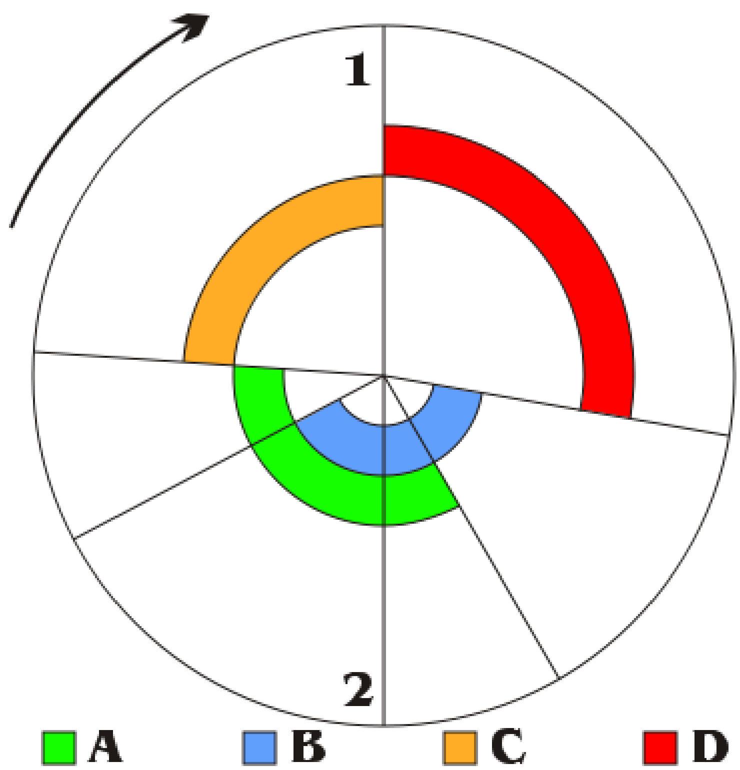
Loop-scavenged



The Two-stroke cycle
1=TDC
2=BDC
A: intake/scavenging
B: Exhaust
C: Compression
D: Expansion(power)

This method of scavenging uses carefully shaped and positioned transfer ports to direct the flow of fresh mixture toward the combustion chamber as it enters the cylinder. The fuel/air mixture strikes the cylinder head then follows the curvature of the combustion chamber then is deflected downward. This not only prevents the fuel/air mixture from traveling directly out the exhaust port but creates a swirling turbulence which improves combustion efficiency, power and economy. Usually a piston deflector is not required, so this approach has a distinct advantage over the cross flow scheme (above). Often referred to as "Schnuerle" (or "Schnürl") loop scavenging after the German inventor of an early form in the mid 1920s, it became widely adopted in that country during the 1930s and spread further afield after World War II. Loop scavenging is the most common type of fuel/air mixture transfer used on modern two stroke engines. Suzuki was one of the first manufacturers outside of Europe to adopt loop scavenged two stroke engines. This operational feature was used in conjunction with the expansion chamber exhaust developed by German motorcycle manufacturer, MZ and Walter Kaaden. Loop scavenging, disc valves and expansion chambers worked in a highly coordinated way that saw a significant increase in the power output of two-stroke engines, particularly from the Japanese manufacturers Suzuki, Yamaha and Kawasaki. Suzuki and Yamaha enjoyed success in grand Prix motorcycle racing in the 1960s due in no small way to the increased power afforded by loop scavenging. An additional benefit of loop scavenging was that the piston could be made nearly flat or slightly dome shaped. This enabled the piston to be appreciably lighter and stronger and consequently tolerated higher engine speeds. The "flat top" piston also has better thermal properties and is less prone to uneven heating, expansion, piston seizures, dimensional changes and compression losses.

Uniflow-scavenged



The Uniflow Two-stroke cycle
1=TDCdg
2=Bbb
A: Intake(effective scavenging ≈140°-250°)
B: Exhaust
C: Compression
D: Expansion(power)

In a uniflow engine the mixture, or air in the case of a diesel, enters at one end of the cylinder controlled by the piston and the exhaust exits at the other end controlled by an exhaust valve or piston. The scavenging gas-flow is therefore in one direction only, hence the name uniflow. The valved arrangement is common in diesel locomotives (Electro-

Motive Diesel) and large marine two-stroke engines (Wärtsilä). Ported types are represented by the opposed piston design in which there are two pistons in each cylinder, working in opposite directions such as the Junkers Jumo and Napier Deltic. The once-popular split-single design falls into this class being effectively a folded uniflow. With advanced angle exhaust timing uniflow engines can be supercharged with a crankshaft driven (piston or Roots) blower.

In Japan. Nissan Diesel Motor was manufacturing **Uniflow Two-stroke Diesel Engine**(ja:ユニフロー掃気ディーゼルエンジン) from General Motors from under a license of Detroit Diesel Series 71.

The latest invention, called the Reversed Uniflow two-stroke engine, has a large intake valve for compressed intake air without fuel-oil mixture. Direct fuel injection is to be used for gasoline or diesel fuel, pending intake air pressure. This engine will work on the Miller cycle. US Patent #6889636.

Stepped piston engine

The piston of this engine is "top-hat" shaped, the upper section forming the regular cylinder. and the lower section performing a scavenging function. The units run in pairs, the lower half of one piston charging an adjacent combustion chamber.

This system is still partially dependent on total loss lubrication (for the upper part of the piston), the other parts being sump lubricated with cleanliness and reliability benefits. The piston weight is only about 20% heavier than a loop-scavenged piston because skirt thicknesses can be less. The patents on this design are held by Bernard Hooper Engineering Ltd (BHE).

Power valve systems

Many modern two-stroke engines employ a power valve system. The valves are normally in or around the exhaust ports. They work in one of two ways: either they alter the exhaust port by closing off the top part of the port which alters port timing such as Ski-doo R.A.V.E, Yamaha YPVS, Honda RC-Valve, Cagiva C.T.S., Suzuki AETC system or by altering the volume of the exhaust which changes the resonant frequency of the expansion chamber, such as Honda V-TACS system. The result is an engine with better low-speed power without sacrificing high-speed power.

Direct injection

Direct injection has considerable advantages in two-stroke engines, eliminating some of the waste and pollution caused by carbureted two-strokes where a proportion of the fuel/air mixture entering the cylinder goes directly out, unburned, through the exhaust port. Two systems are in use, low-pressure air-assisted injection, and high pressure injection.

Since the fuel does not pass through the crank case, a separate source of lubrication is needed.

Two-stroke diesel engines

Diesel engines rely solely on the heat of compression for ignition. In the case of Schnuerle ported and loop-scavenged engines, intake and exhaust happens via piston-controlled ports. A uniflow diesel engine takes in air via scavenge ports, and exhaust gases exit through an overhead poppet valve. Two-stroke diesels are all scavenged by forced induction. Some designs utilize a mechanically driven Roots blower, whilst marine diesel engines normally use exhaust-driven turbochargers, with electrically-driven auxiliary blowers for low-speed operation when exhaust turbochargers are unable to deliver enough air.

Marine two-stroke diesel engines directly coupled to the propeller are able to start and run in either direction as required. The fuel injection and valve timing is mechanically readjusted by using a different set of cams on the camshaft. Thus the engine can be run in reverse to move the vessel backwards.

Lubrication

Most small petrol two-stroke engines cannot be lubricated by oil contained in their crankcase and sump, since the crankcase is already being used to pump fuel-air mixture into the cylinder. Traditionally the moving parts (both rotating crankshaft and sliding piston) were lubricated by a pre-mixed fuel-oil mixture (at a ratio between 16:1 and 50:1). As late as the 1960s petrol stations would often have a separate pump that would deliver such a pre-mix fuel to motorcycles. Even then, in many cases the rider would carry a bottle of his own two-stroke oil. Taking care to close the fuel-tap first, he or she would meter in a little oil (using the cap of the bottle) and then put in the petrol, this action mixing the two liquids.

Modern two-stroke engines pump lubrication from a separate tank of oil. This is still a total-loss system with the oil being burnt the same as in the older system, but at a lower and more economical rate. It is also cleaner, reducing the problem of oil-fouling of the spark-plugs and coke formation in the cylinder and the exhaust. Almost the only motors still using pre-mix are hand-held two-stroke devices such as chainsaws (which must operate in any attitude) and some of the smallest model engines.

All two-stroke engines running on a petroil mix will suffer oil-starvation if forced to rotate at speed with the throttle closed, e.g. motorcycles descending long hills and perhaps when decelerating gradually from high-speed by changing down through the gears. Two-stroke cars (such as those that were popular in Eastern Europe in mid-20th century) were in particular danger and were usually fitted with freewheel mechanisms in the powertrain, allowing the engine to idle when the throttle was closed, requiring the use of the brakes in all slowing down situations.

Large two-stroke engines, including diesels, normally use a sump lubrication system similar to four-stroke engines. The cylinder must still be pressurized but this is not done from the crankcase but by a pump or supercharger. A turbo-charger is not suitable for this purpose as it does not provide any starting pressure.

Two-stroke reversibility

For the purpose of this discussion, it is convenient to think in motorcycle terms, where the exhaust pipe faces into the cooling air stream, and the crankshaft commonly spins in the same axis and direction as do the wheels i.e. "forwards". Some of the considerations discussed here apply to four-stroke engines (which cannot reverse their direction of rotation without considerable modification) almost all of which spin forwards too.

Regular gasoline two-stroke engines will run backwards for short periods and under light load with little problem, and this has been used to provide a reversing facility in microcars such as the Messerschmitt KR200 that lacked reverse gearing. Where the vehicle has electric starting, the motor will be turned off and re-started backwards by turning the key in the opposite direction. Two-stroke golf carts have used a similar kind of system. Traditional flywheel magnetos (using contact-breaker "points" but no external coil) worked equally well in reverse because the cam controlling the points is symmetrical, breaking contact before TDC equally well whether running forwards or backwards. Reed-valve engines will run backwards just as well as piston-controlled porting, though rotary valve engine have asymmetrical inlet timing and will not run very well.

There are serious disadvantages to running any engine backwards under load for any length of time, and some of these reasons are general, applying equally to both two-stroke and four-stroke engines. Some of this disadvantage is intrinsic, unavoidable even in the case of a complete re-design. The problem comes about because in "forwards" running the major thrust face of the piston is on the back face of the cylinder which, in a two-stroke particularly, is the coolest and best lubricated part. The forward face of the piston is less well-suited to be the major thrust face since it covers and uncovers the exhaust port in the cylinder, the hottest part of the engine, where piston lubrication is at its most marginal. The front face of the piston is also more vulnerable since the exhaust port, the largest in the engine, is in the front wall of the cylinder. Piston skirts and rings risk being extruded into this port, so it is always better to have them pressing hardest on the back wall (where there are only the transfer ports) and there is good support. In some engines, the small end is offset to reduce thrust in the intended rotational direction and the forward face of the piston has been made thinner and lighter to compensate - but when running backwards, this weaker forward face suffers increased mechanical stress it was not designed to resist.

Large two-stroke ship diesels are sometimes made to be reversible. Like four-stroke ship engines (some of which are also reversible) they use mechanically operated valves and so require additional camshaft mechanisms.

On top of other considerations, the oil-pump of a modern two-stroke may not work in reverse, in which case the engine will suffer oil starvation within a short time. Running a motorcycle engine backwards is relatively easy to initiate and in rare cases can be triggered by a back-fire. It is not advisable.

Model airplane engines with reed-valves can be mounted in either tractor or pusher configuration without needing to change the propeller. These motors are compression ignition, so there are no ignition timing issues and little difference between running forwards and running backwards.