Handbook of

Engine Technology and Internal Combustion Engines

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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.

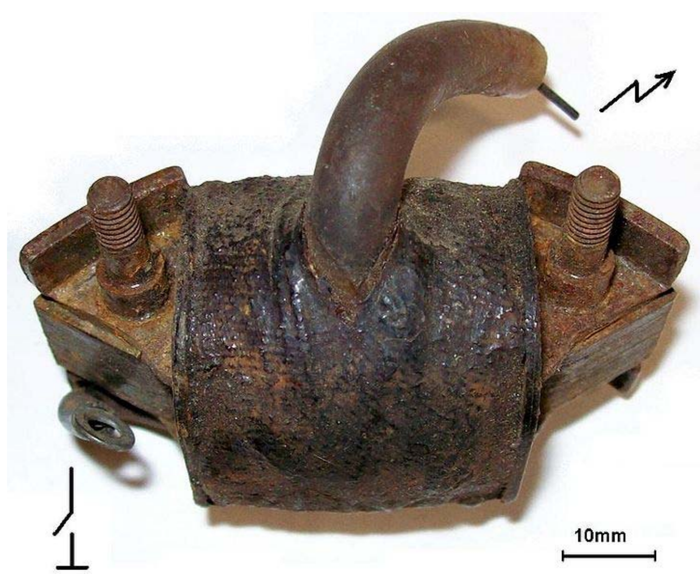
Chapter 2

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



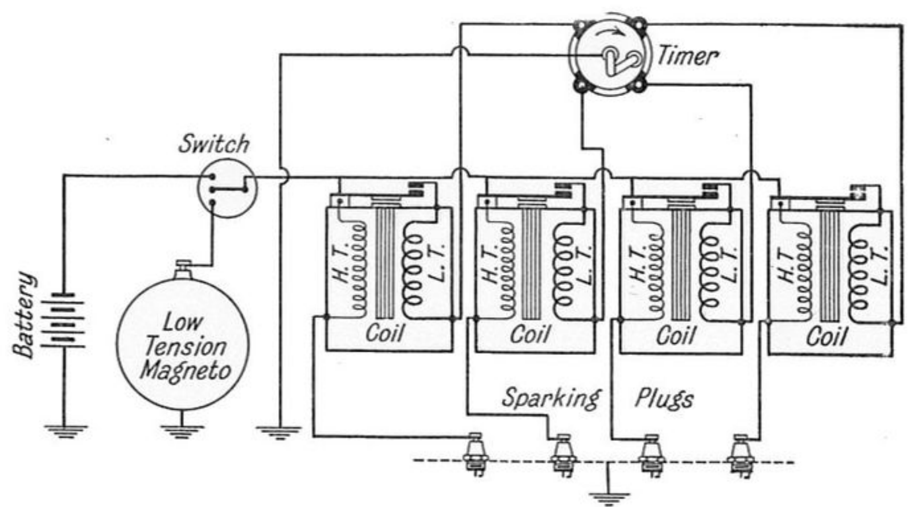
Magneto ignition coil

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.

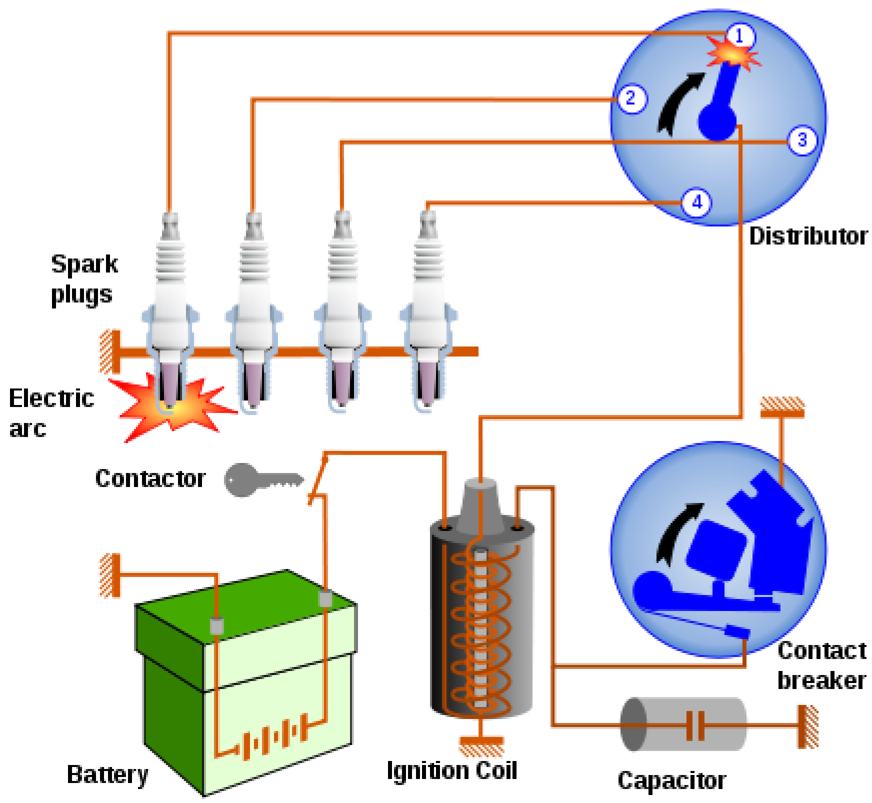
Mechanically timed ignition

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.

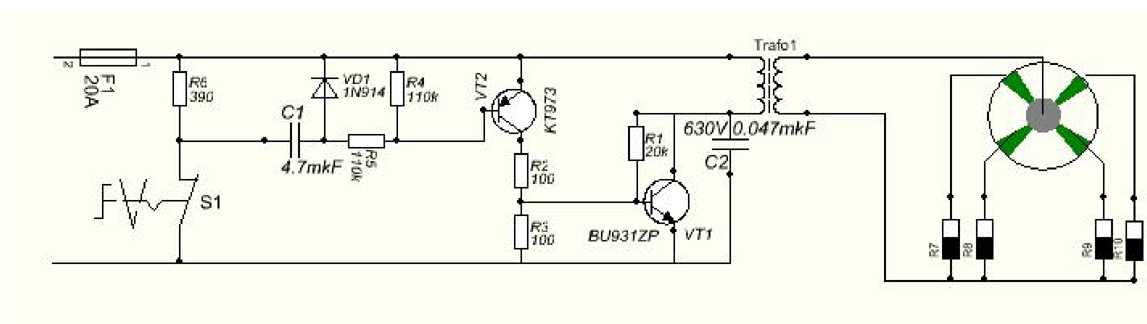
A distributor-based system is not greatly different from a magneto system except that more separate elements are involved. There are also advantages to this arrangement. For example, the position of the contact breaker points relative to the engine angle can be changed a small amount dynamically, allowing 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

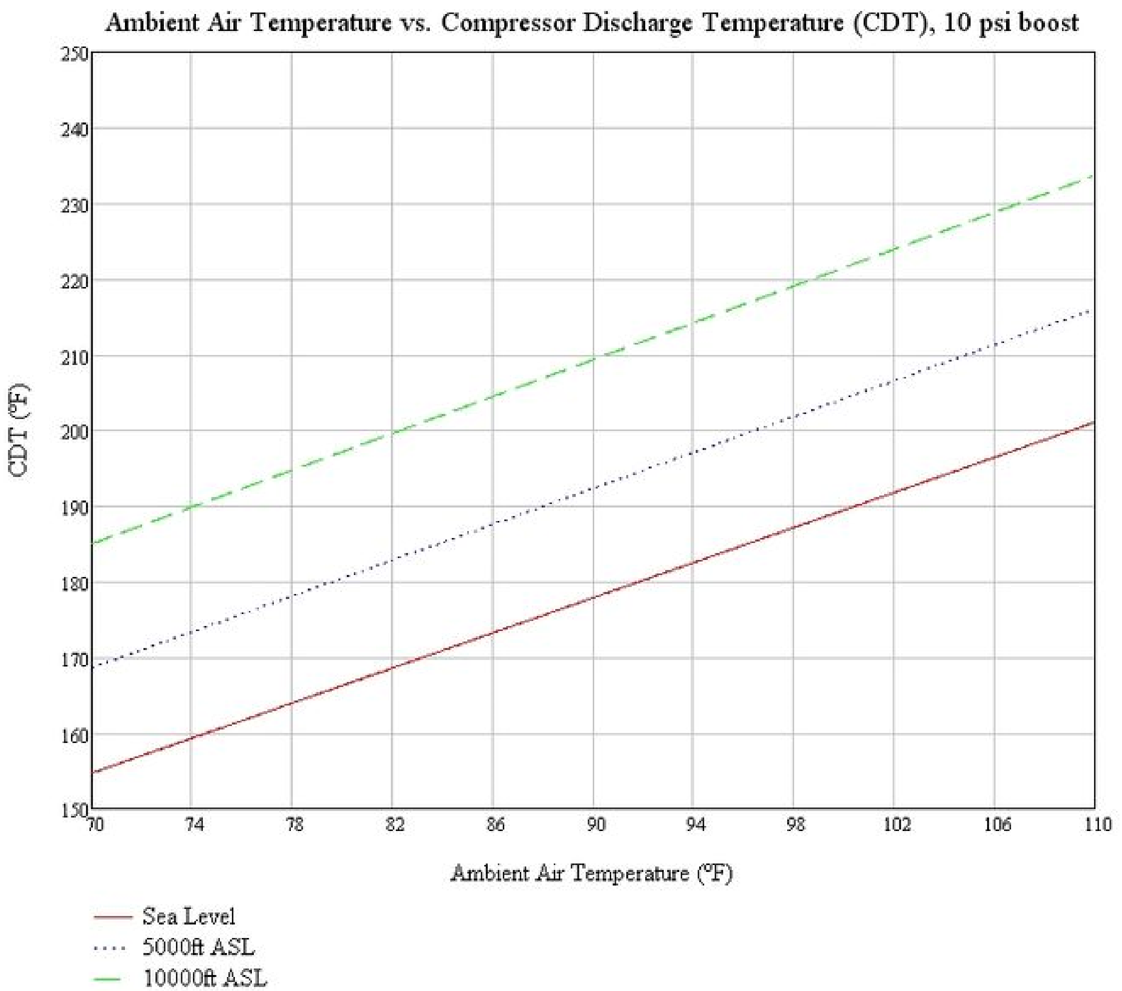
- Axial turbine
- Radial turbine

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.

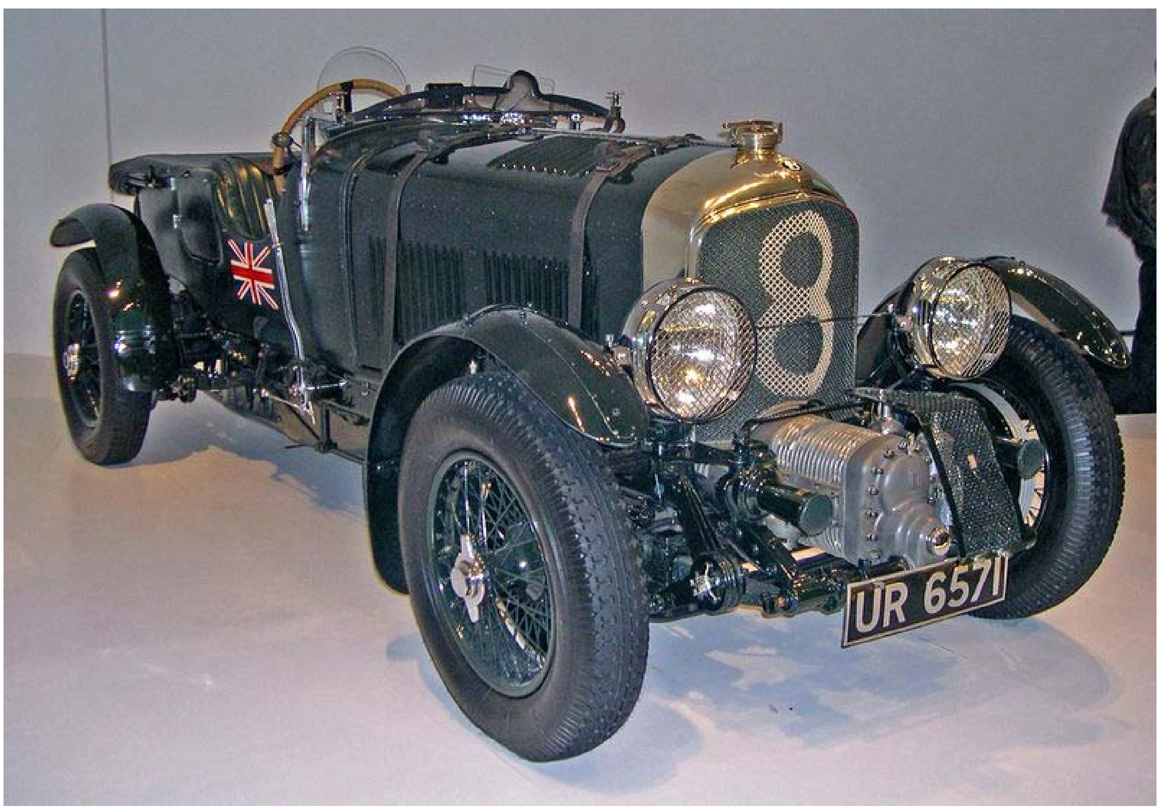
$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

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.

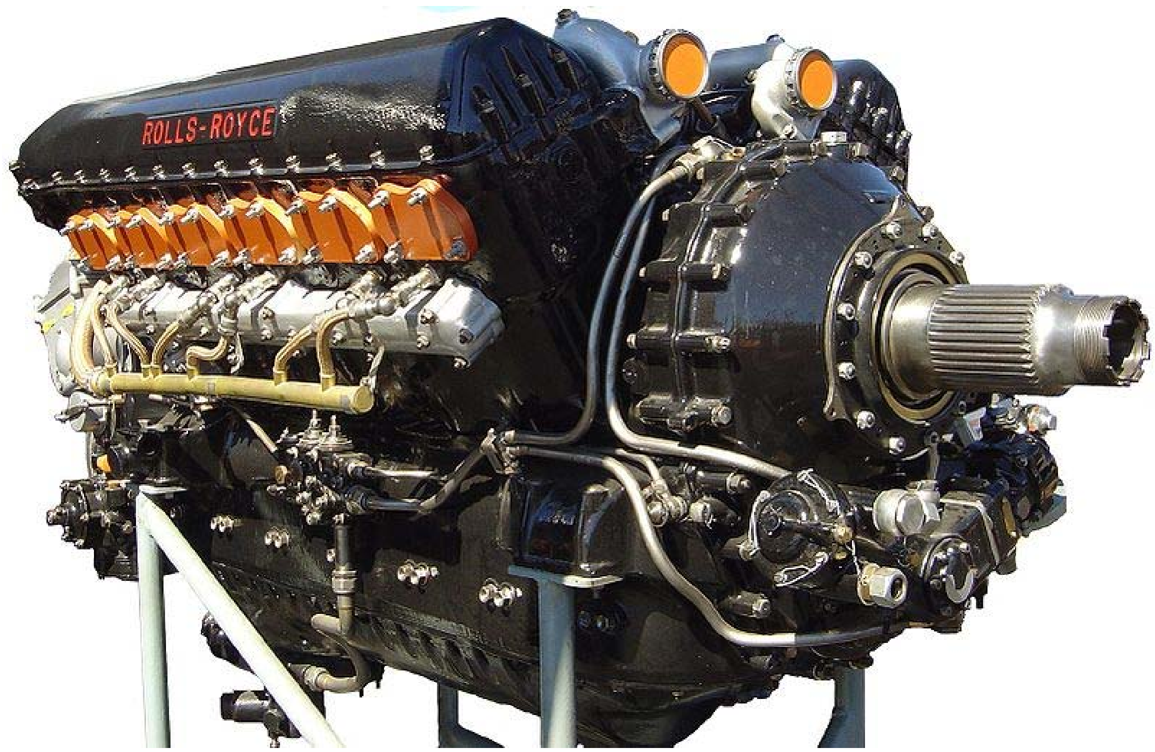
Roots blowers tend to be 40–50% efficient at high boost levels. Centrifugal superchargers are 70–85% efficient. Lysholm-style blowers can be nearly as efficient as their centrifugal counterparts over a narrow range of load/speed/boost, for which the system must be specifically designed.

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

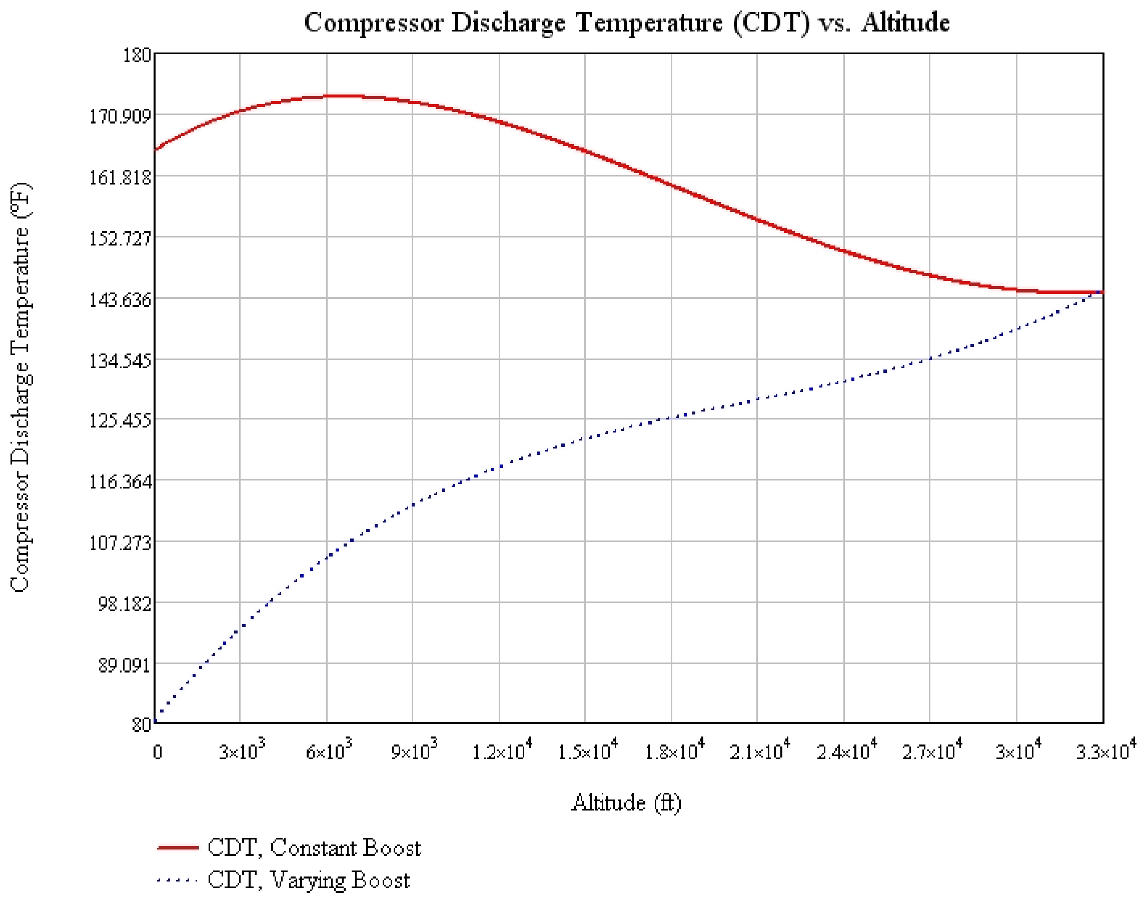
A Centrifugal supercharger of a Bristol Centaurus radial aircraft engine.

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.

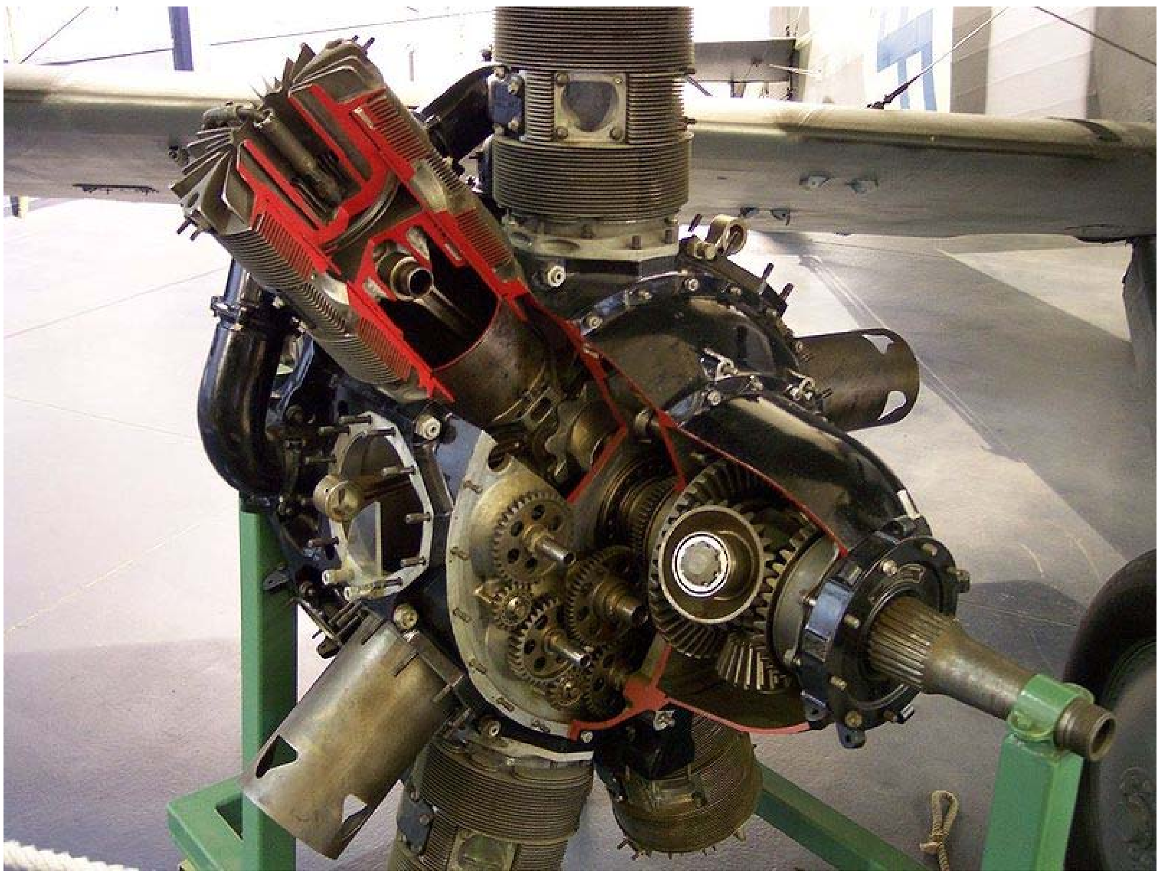
Octane rating boosting through additives was a line of research being explored at the time. Using these techniques, less valuable crude could still supply large amounts of useful gasoline, which made it a valuable economic process. However the additives were not limited to making poor-quality oil into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



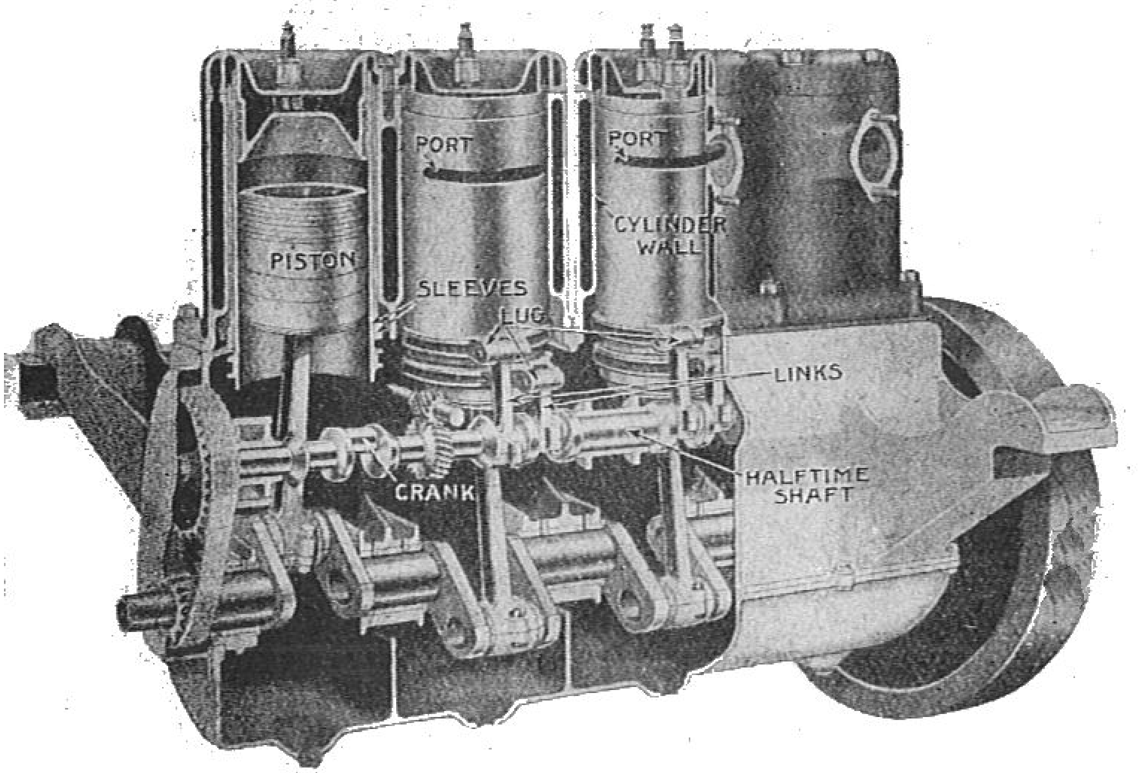
Bristol Perseus

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

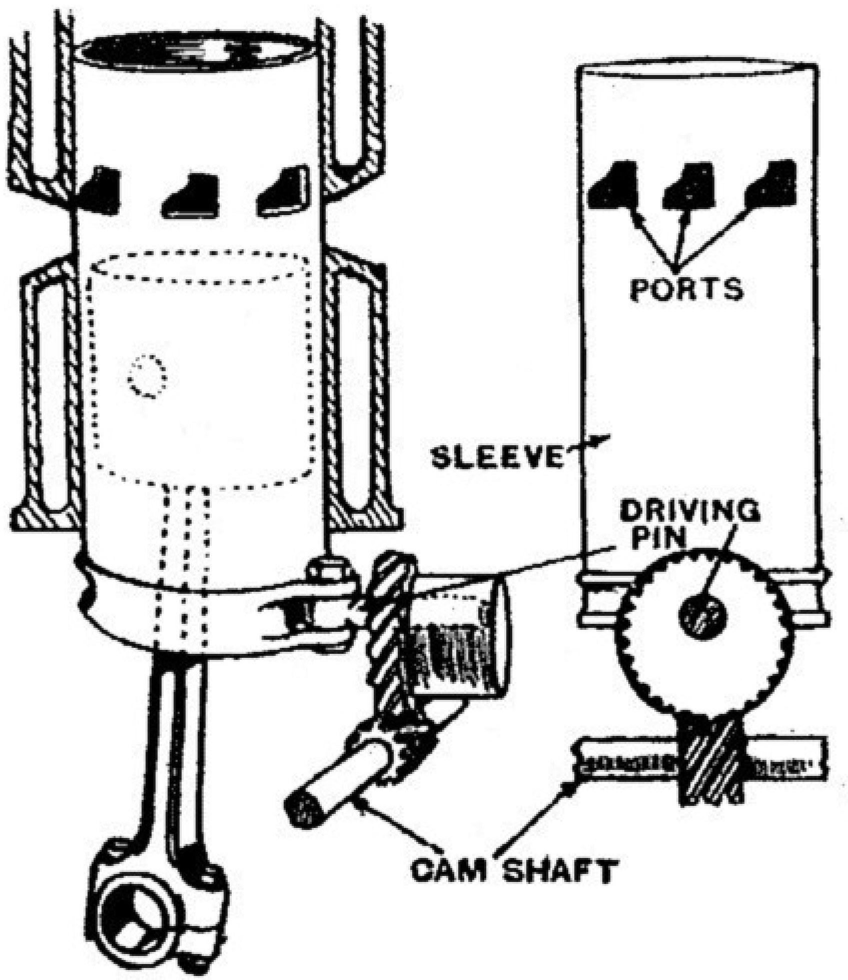
A sleeve valve takes the form of one or more machined sleeves. It fits between the piston and the cylinder wall in the cylinder of an internal combustion engine where it rotates and/or slides, ports (holes) in the side of the valve(s) aligning with the cylinder's inlet and exhaust ports at the appropriate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

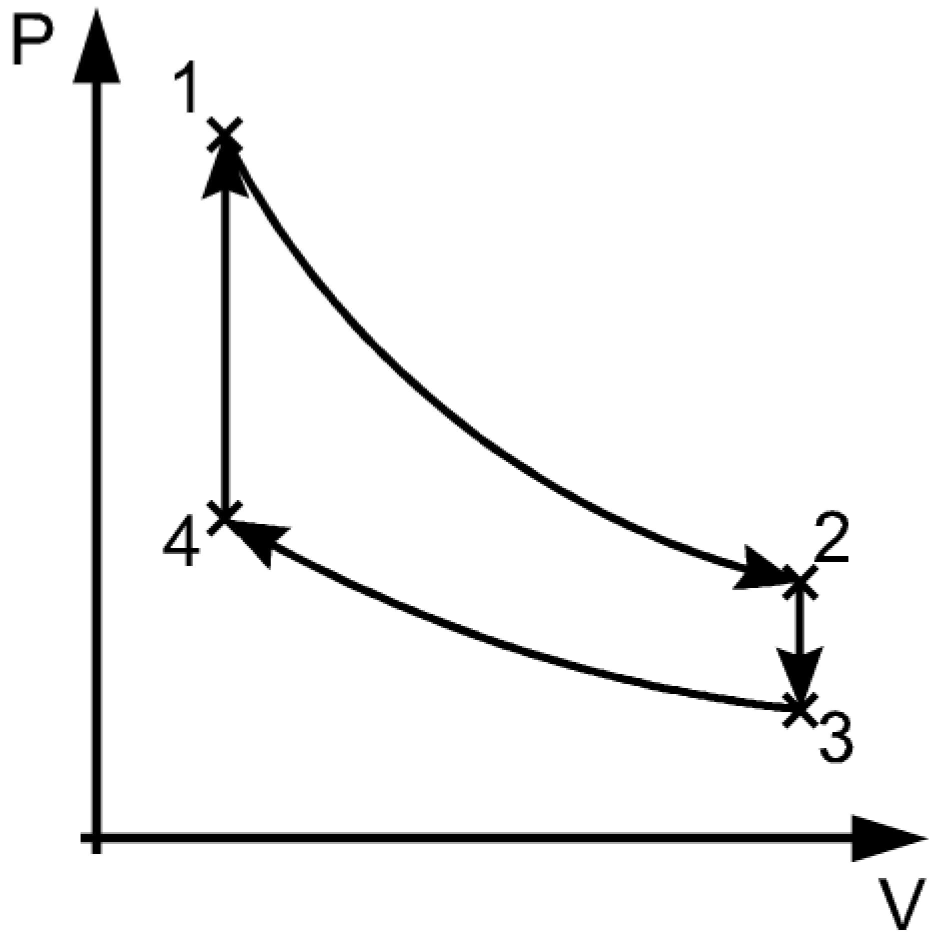
A **thermodynamic cycle** consists of a series of thermodynamic processes transferring heat and work, while varying pressure, temperature, and other state variables, eventually returning a system to its initial state. In the process of going through this cycle, the system may perform work on its surroundings,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

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

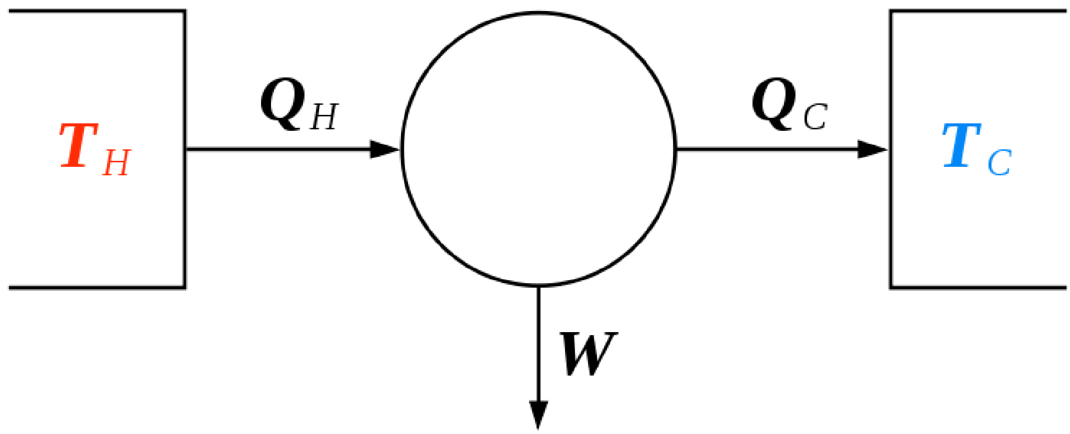
This work is equal to the balance of heat (Q) transferred into the system:

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

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.

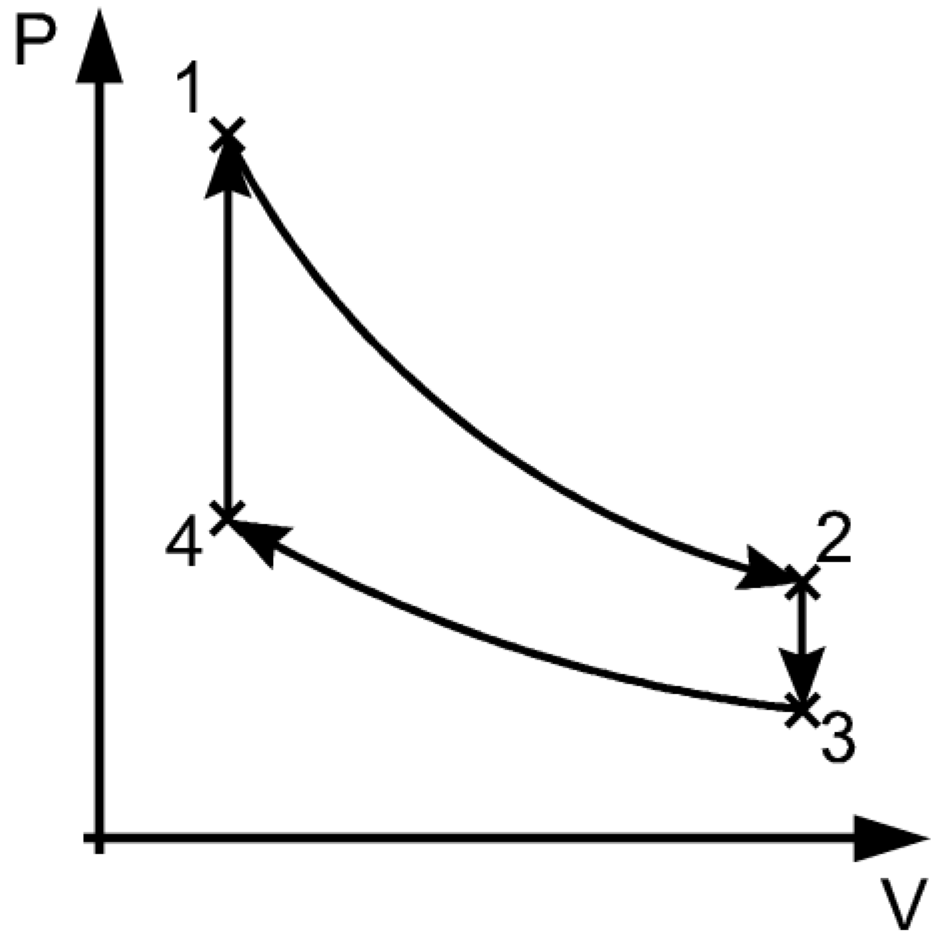
If the cyclic process moves clockwise around the loop, then W will be positive, and it represents a heat engine. If it moves counterclockwise, then W will be negative, and it represents a heat pump.

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:

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

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

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

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

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

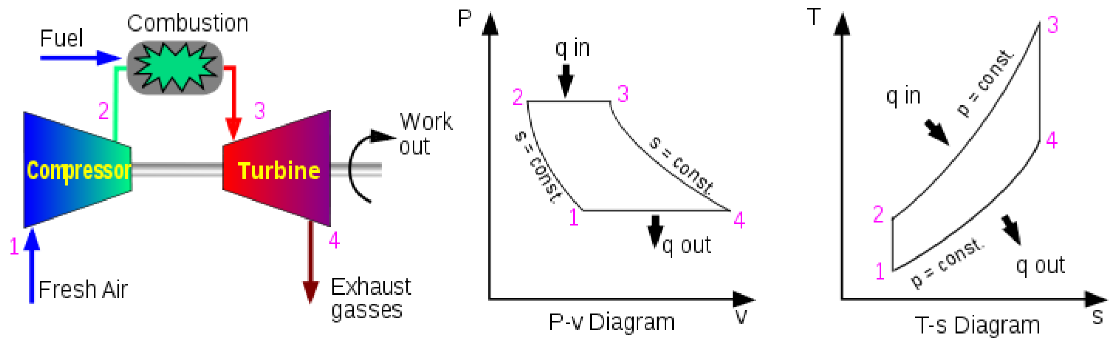
If no volume change happens in process 4->1 and 2->3, equation (3) simplifies to:

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

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.

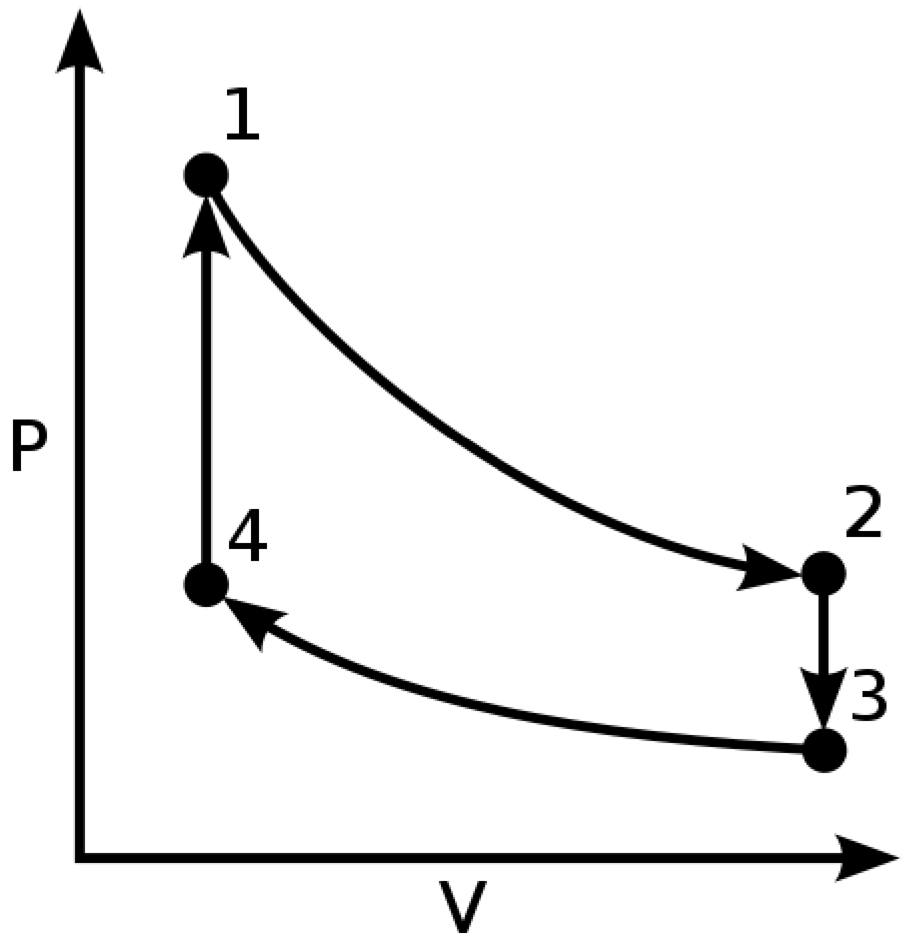
Modelling real systems



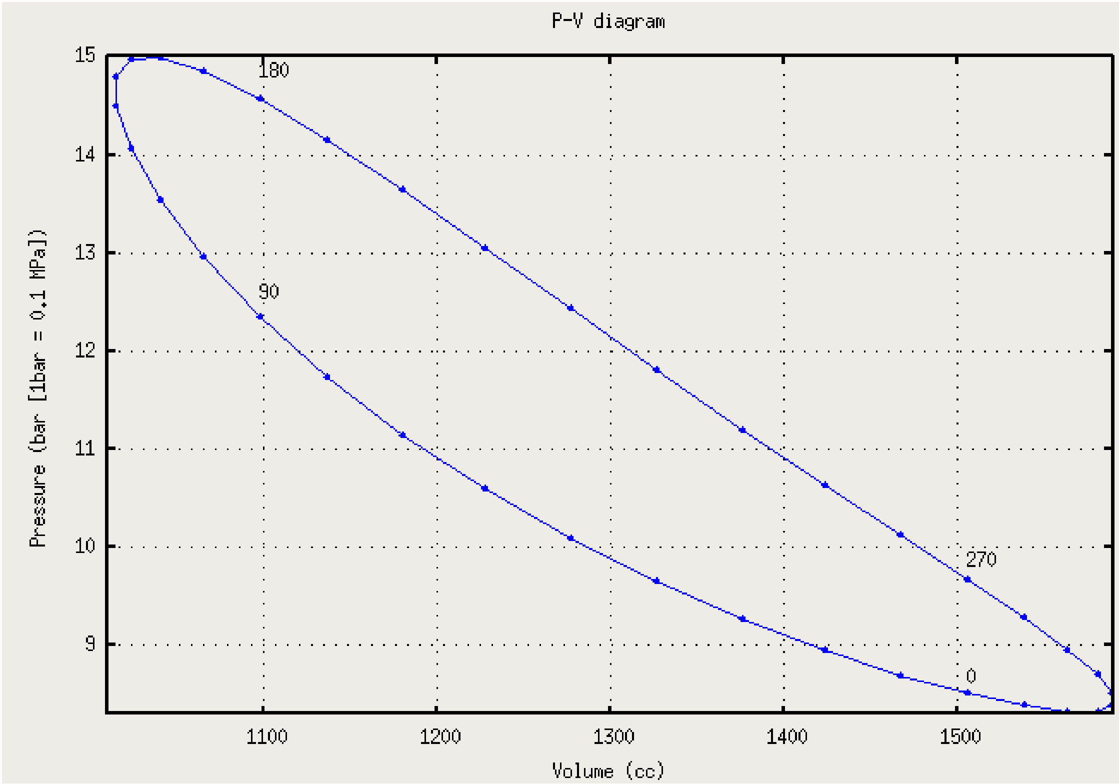
Example of a real system modelled by an idealized process: PV and TS diagrams of a Brayton cycle mapped to actual processes of a gas turbine engine

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.

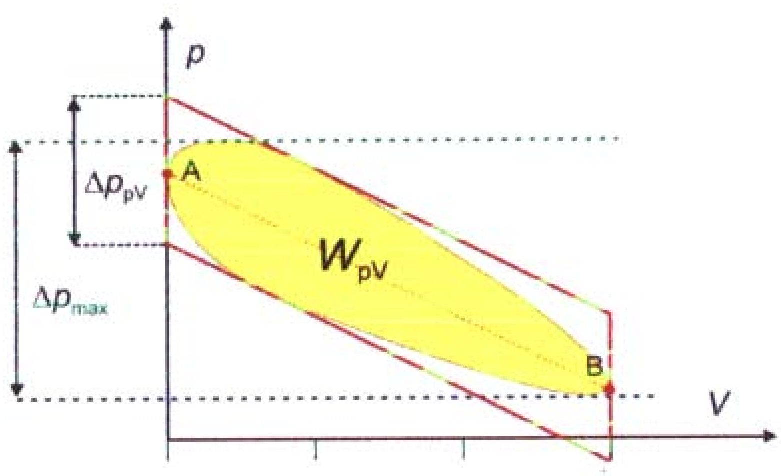
The difference between an idealized cycle and actual performance may be significant. For example, the following images illustrate the differences in work output predicted by an ideal Stirling cycle and the actual performance of a Stirling engine:



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

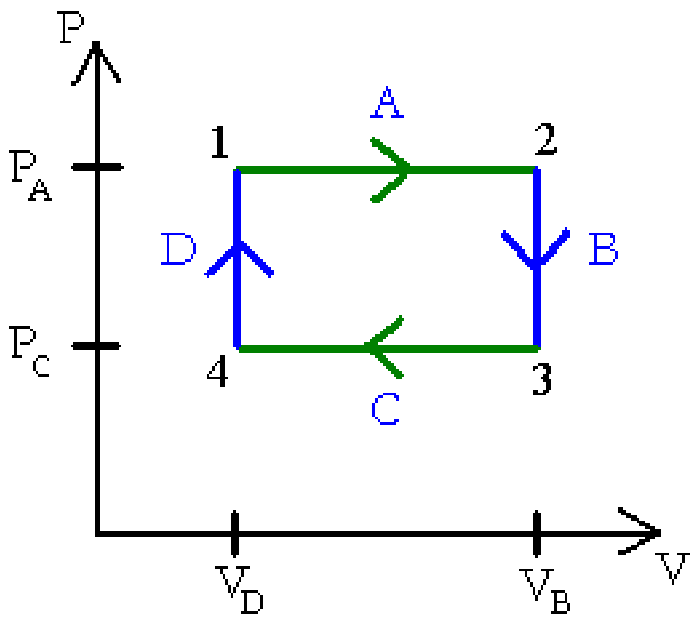
In practice, simple idealized thermodynamic cycles are usually made out of four thermodynamic processes. Any thermodynamic processes may be used. However, when idealized cycles are modeled, often processes where one state variable is kept constant are used, such as an isothermal process (constant temperature), 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

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

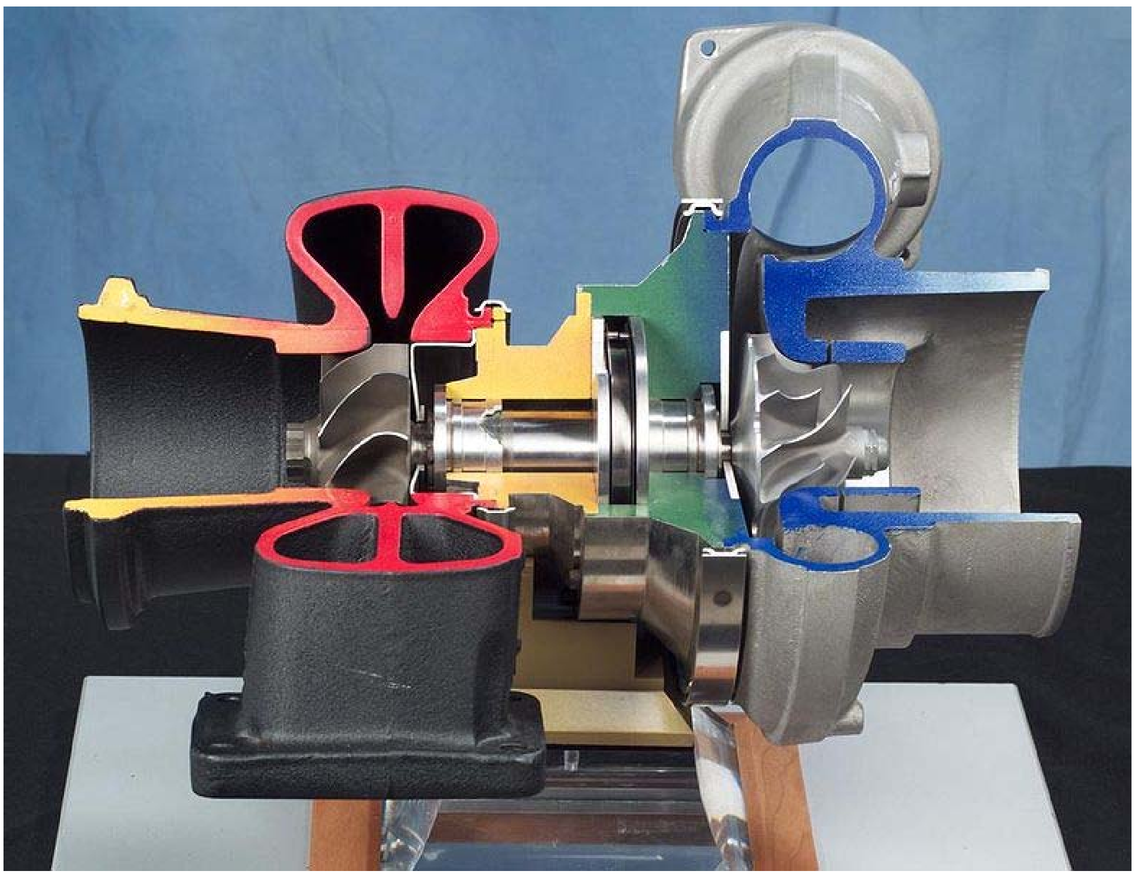
then it is clear that for any cyclic process,

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

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.

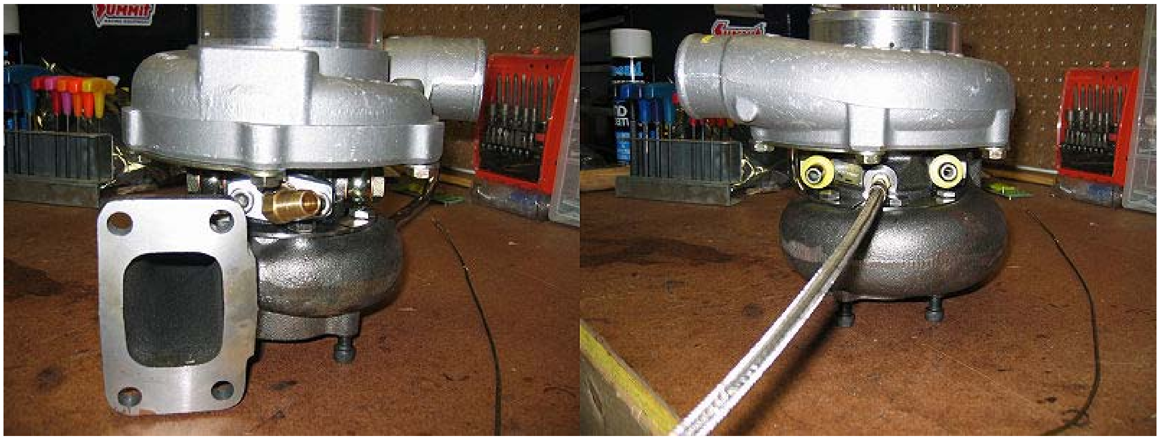
In Formula One, in the so called "Turbo Era" of 1977 until 1989, Renault, Honda, BMW, and Ferrari produced engines with a capacity of 1,500 cc (92 cu in) able to generate 1,000 to 1,500 horsepower (750 to 1,100 kW). Renault was the first manufacturer to apply turbo technology in F1. The project's high 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).

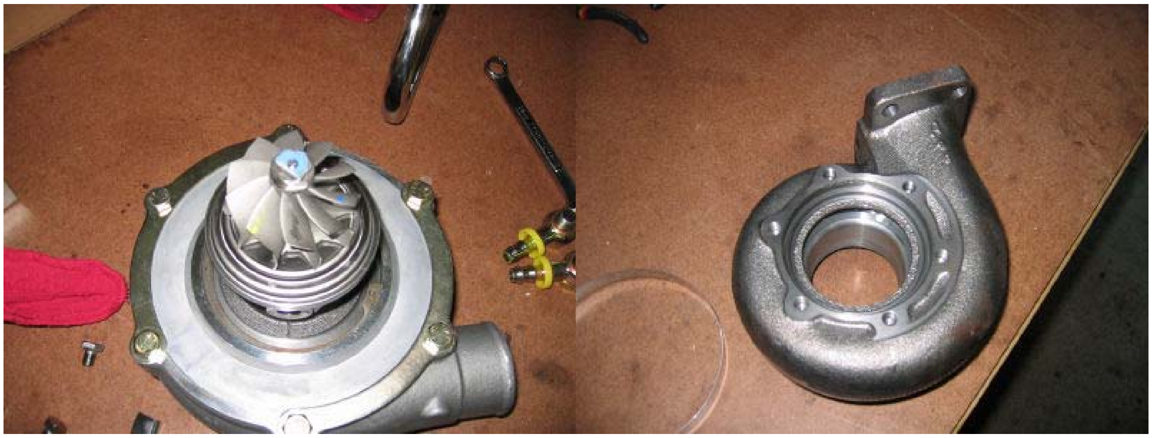
Design and installation

Components

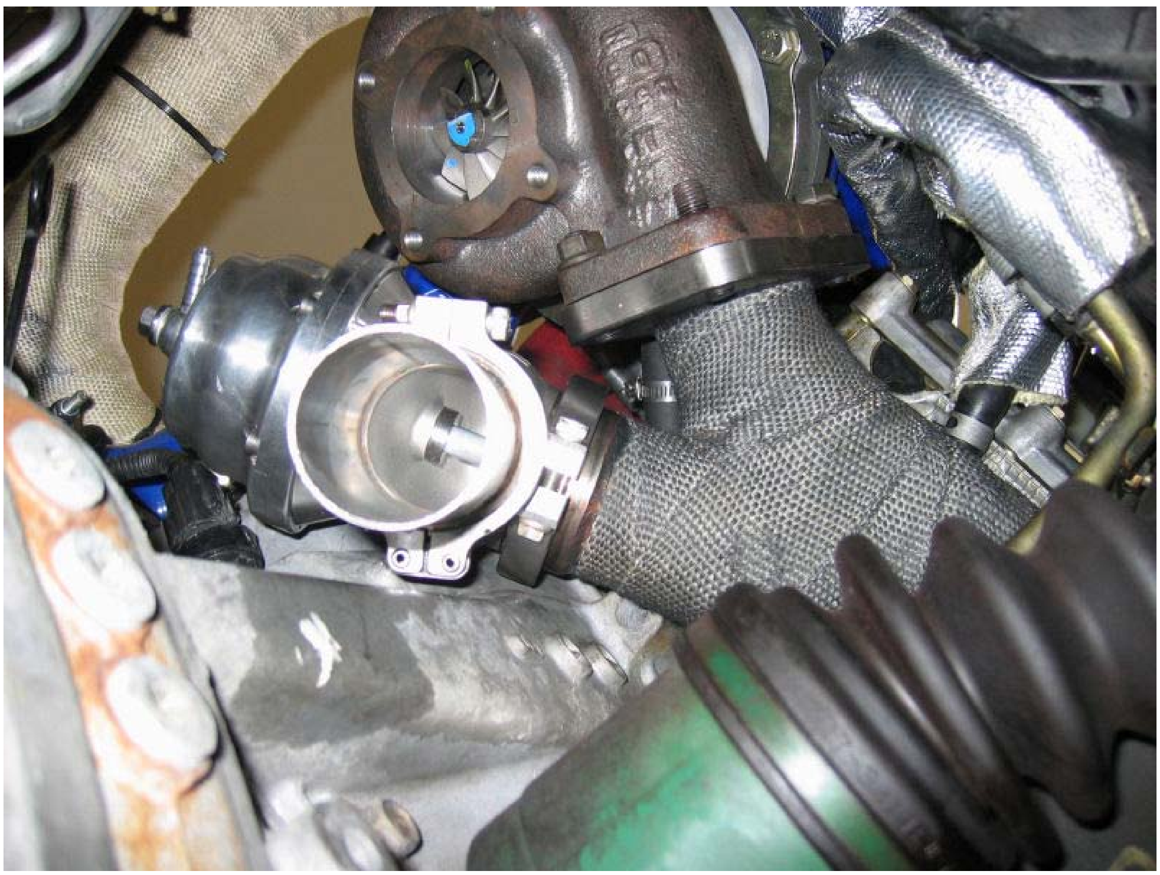


On the left, the brass oil drain connection. On the right are the braided oil supply line and water coolant line connections.

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%.

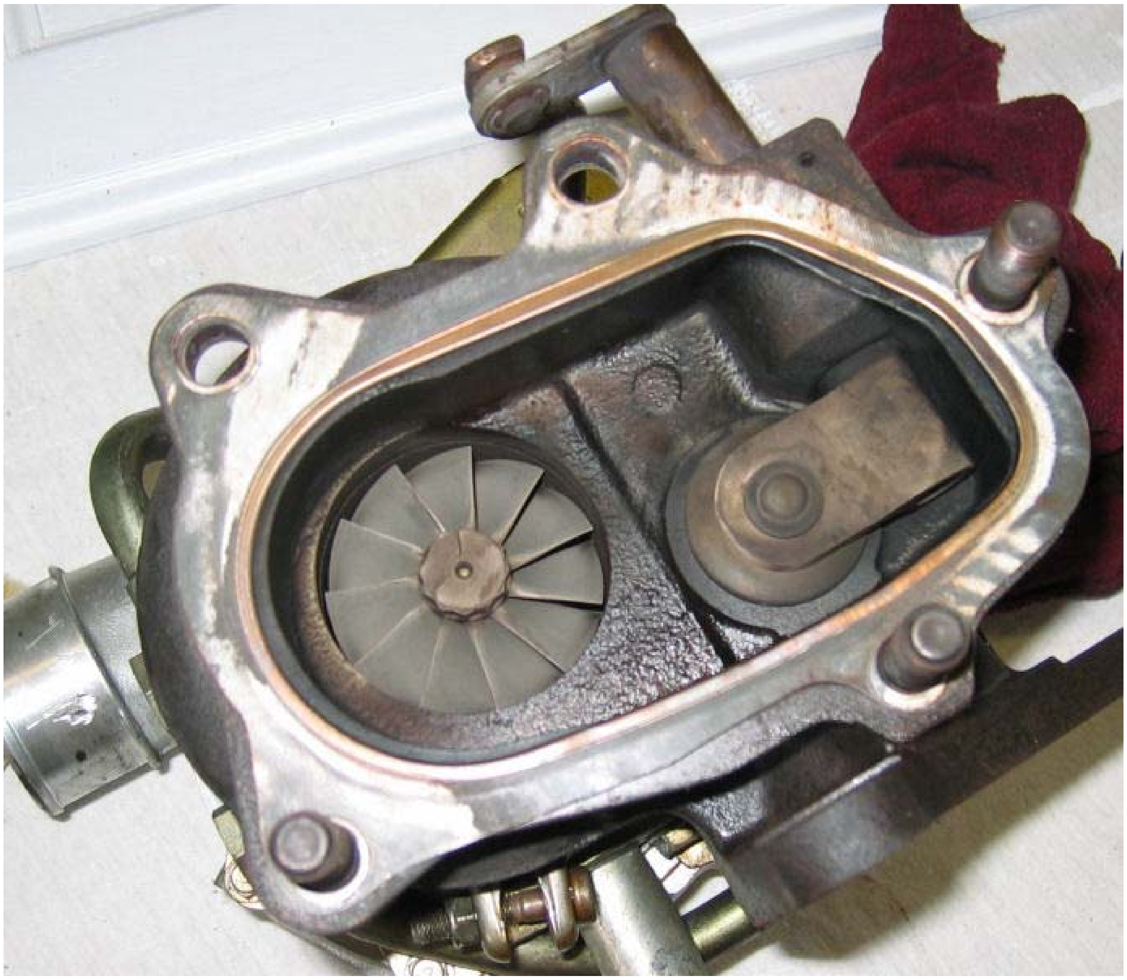
Pressure increase

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

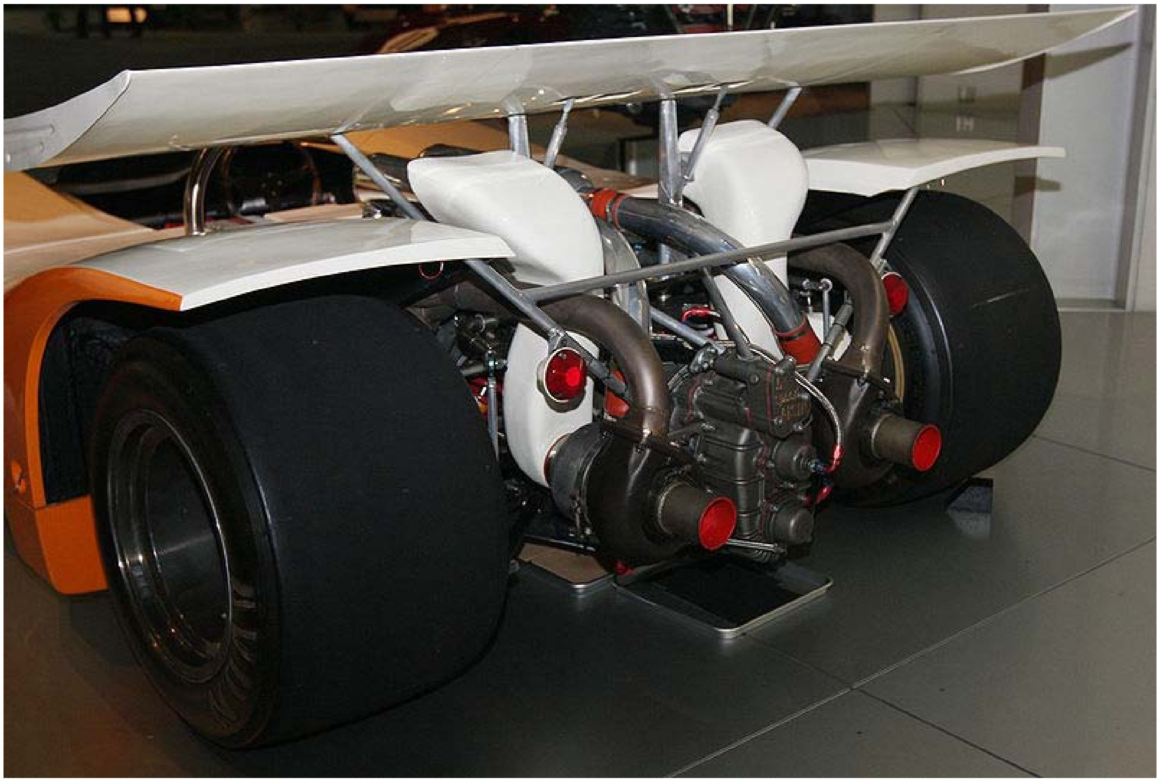
Reliability

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

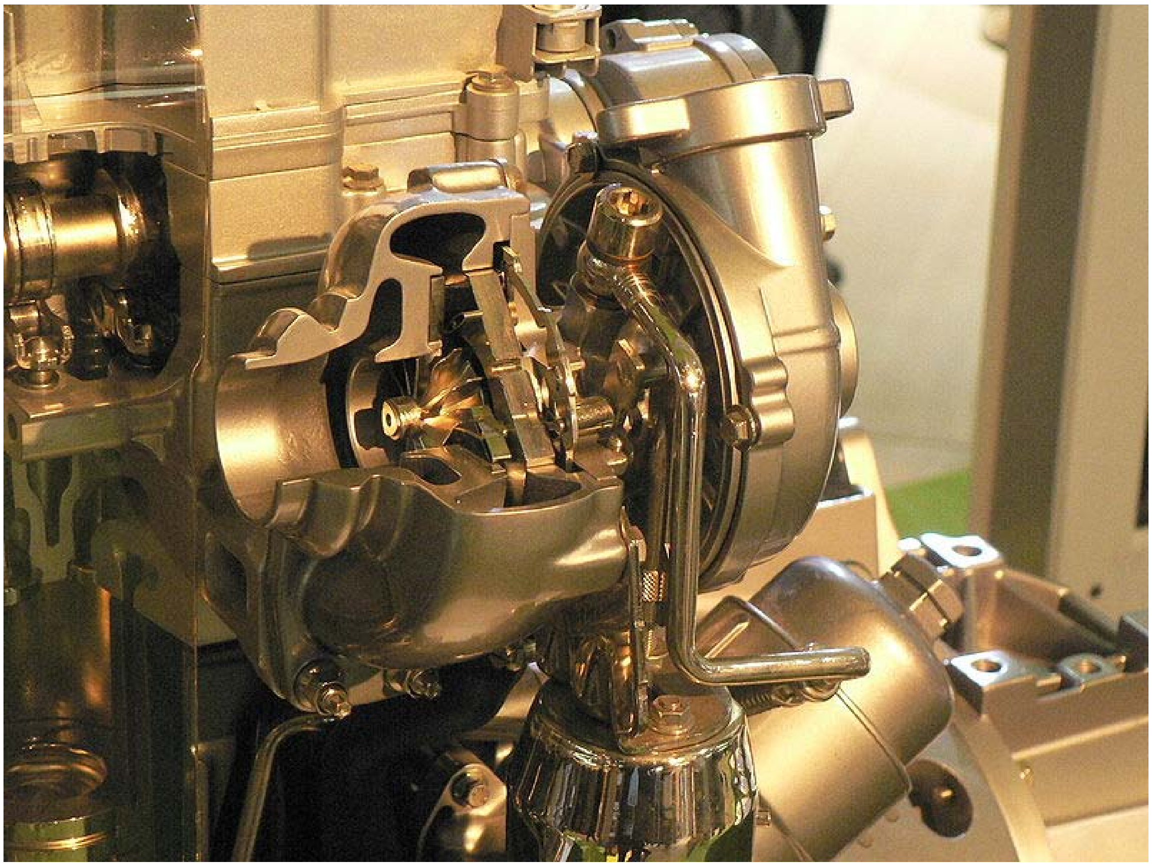


1970 Toyota 7, twin turbo-charged racing car

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.

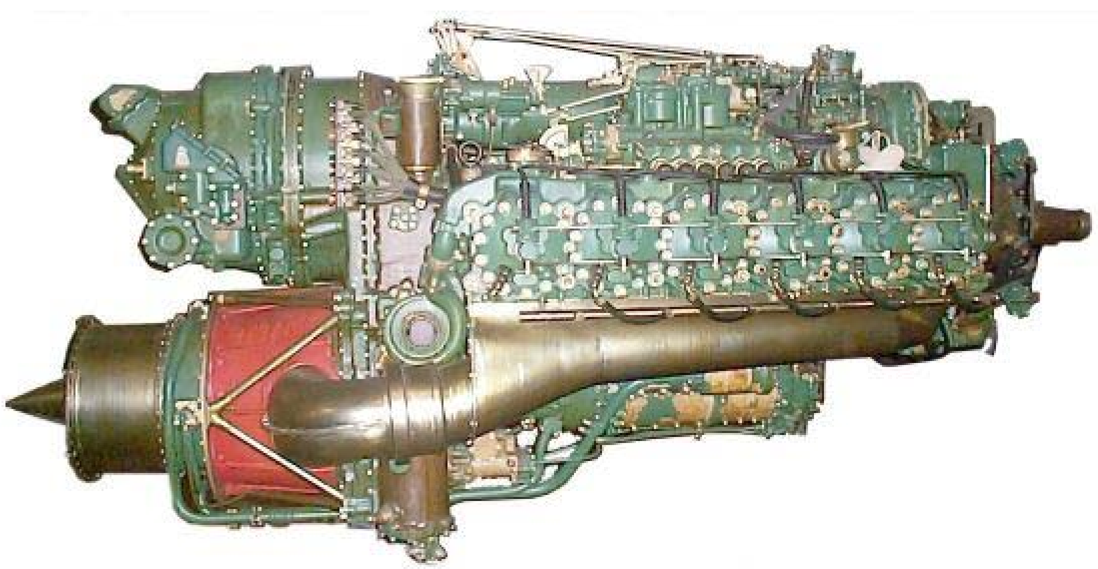
Boost threshold

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

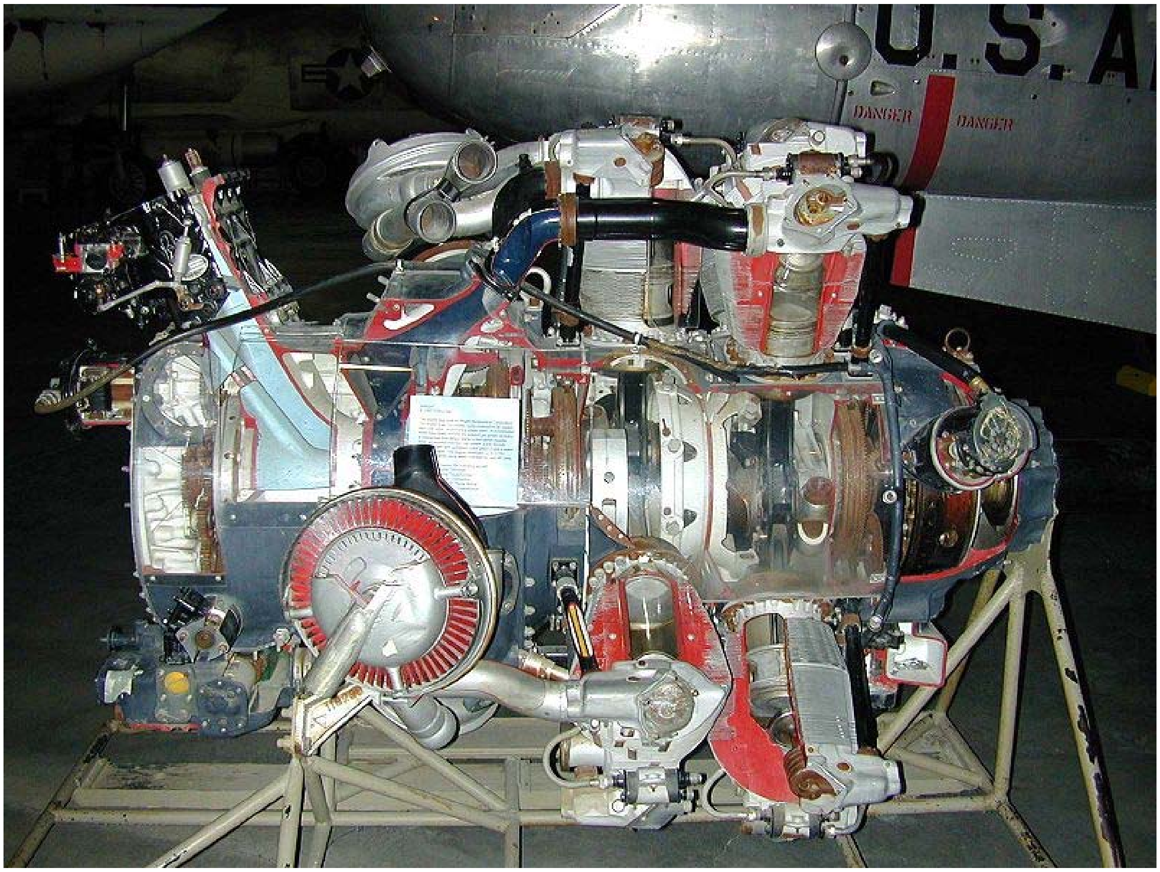
Turbo-Compound Engine & Opposed-Piston Engine

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 maintenance-intensive 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

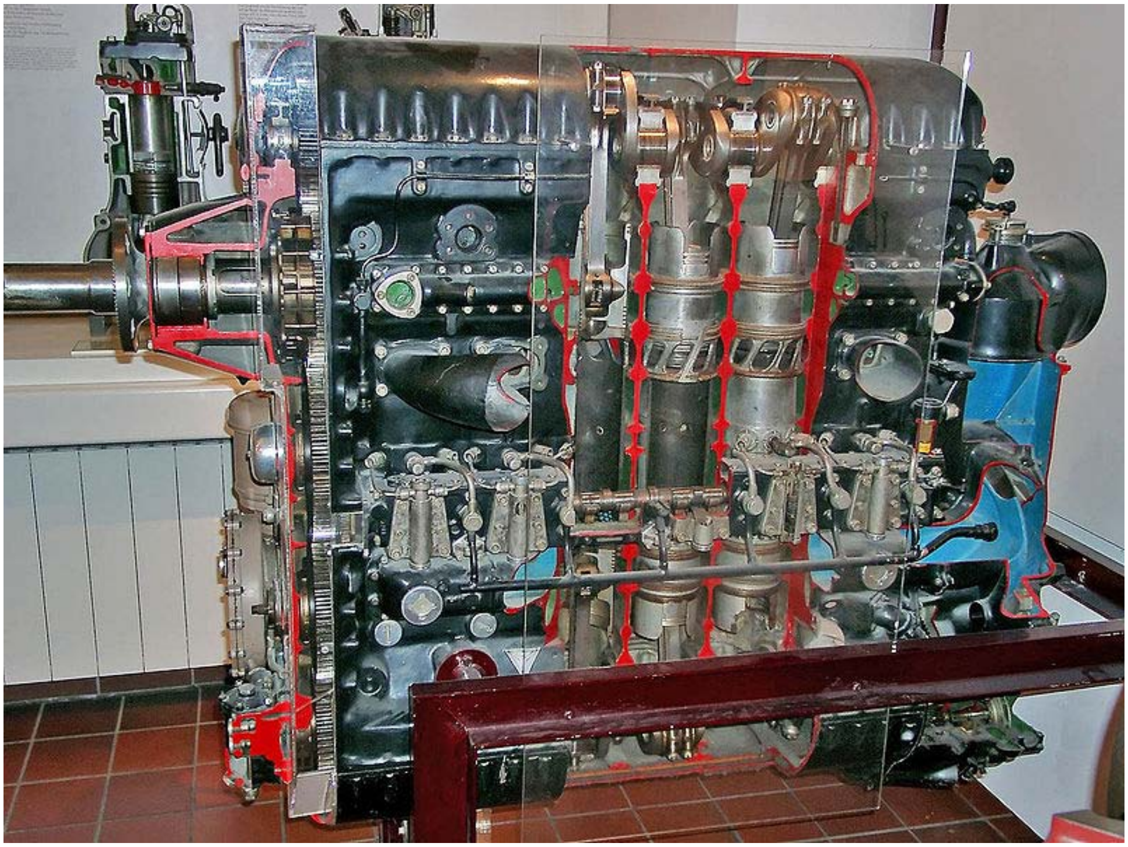
Dobrynin VD-4K

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

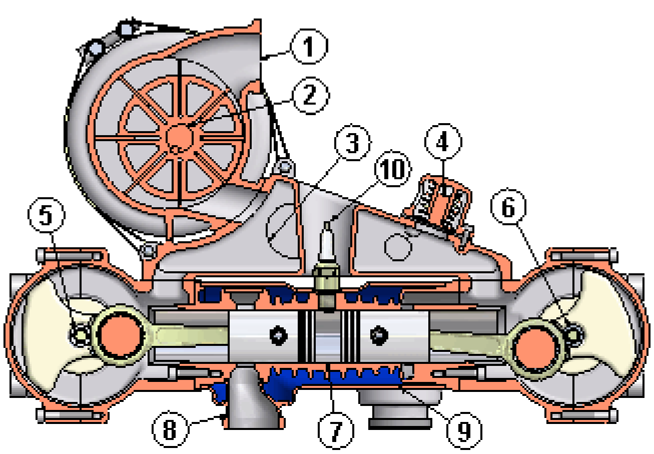
The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently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

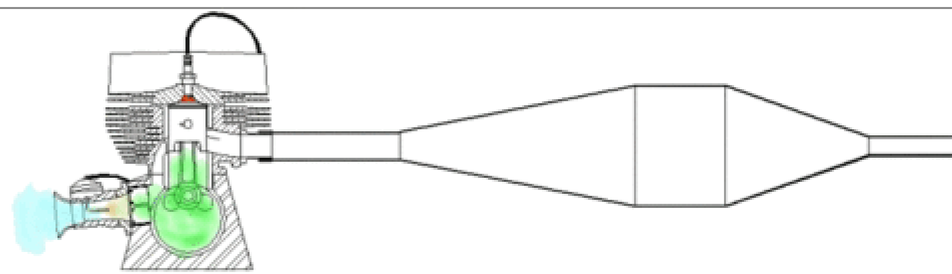
An interesting variation on the opposed-piston engine is the free-piston engine which was patented in 1934 by Raúl Pateras de Pescara. It has no crankshaft and the pistons are returned after each firing stroke by compression and expansion of air in a separate cylinder. Early applications were for use 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

Internal Combustion Engine

The **internal combustion engine** is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine the expansion of the high-temperature and -pressure gases produced by combustion applies direct force to some component of the engine, such as pistons, turbine blades, or a nozzle. This force moves the component over a distance, generating useful mechanical energy.

The term *internal combustion engine* usually refers to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle as previously described.



Two stroke engine in operation

The internal combustion engine (or ICE) is quite different from external combustion engines, such as steam or Stirling engines, in which the energy is delivered to a working fluid not consisting of, mixed with, or contaminated by combustion products. Working fluids can be air, hot water, pressurized water or even liquid sodium, heated in some kind of boiler.

A large number of different designs for ICEs have been developed and built, with a variety of different strengths and weaknesses. Powered by an energy-dense fuel (which is very frequently gasoline, a liquid derived from fossil fuels). While there have been and still are many stationary applications, the real strength of internal combustion engines is in mobile applications and they dominate as a power supply for cars, aircraft, and boats, from the smallest to the largest.

An automobile engine partly opened and colored to show components.

Applications

Internal combustion engines are most commonly used for mobile propulsion in vehicles and portable machinery. In mobile equipment, internal combustion is advantageous since it can provide high power-to-weight ratios together with excellent fuel energy density. Generally using fossil fuel (mainly petroleum), these engines have appeared in transport in almost all vehicles (automobiles, trucks, motorcycles, boats, and in a wide variety of aircraft and locomotives).

Where very high power-to-weight ratios are required, internal combustion engines appear in the form of gas turbines. These applications include jet aircraft, helicopters, large ships and electric generators.

History

Types of internal combustion engine

At one time, the word, "Engine" (from Latin, via Old French, *ingenium*, "ability") meant any piece of machinery—a sense that persists in expressions such as *siege engine*. A "motor" (from Latin *motor*, "mover") is any machine that produces mechanical power. Traditionally, electric motors are not referred to as "Engines"; however, combustion engines are often referred to as "motors." (An *electric engine* refers to a locomotive operated by electricity.)

Engines can be classified in many different ways: By the engine cycle used, the layout of the engine, source of energy, the use of the engine, or by the cooling system employed.

Principles of operation

Reciprocating:

- Two-stroke cycle
- Four-stroke cycle
- Six-stroke engine
- Diesel engine
- Atkinson cycle

Rotary:

- Wankel engine

Continuous combustion:
Brayton cycle:

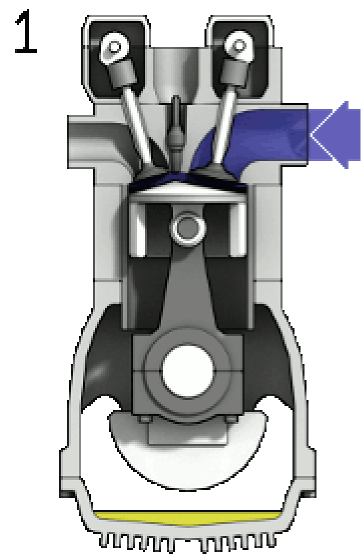
- Gas turbine
- Jet engine (including turbojet, turbofan, ramjet, Rocket etc..

Engine configurations

Internal combustion engines can be classified by their configuration.

Four stroke configuration

Operation



Four-stroke cycle (or Otto cycle)
1. Intake
2. Compression
3. Power
4. Exhaust

As their name implies, operation of four stroke internal combustion engines have four basic steps that repeat with every two revolutions of the engine:

1. **Intake**
   - Combustible mixtures are emplaced in the combustion chamber
2. **Compression**
   - The mixtures are placed under pressure
3. **Combustion (Power)**
   - The mixture is burnt, almost invariably a *deflagration*, although a few systems involve *detonation*. The hot mixture is expanded, pressing on and moving parts of the engine and performing useful work.
4. **Exhaust**
   - The cooled combustion products are exhausted into the atmosphere

Many engines overlap these steps in time; jet engines do all steps simultaneously at different parts of the engines.

Combustion

All **internal combustion engines** depend on the exothermic chemical process of combustion: the reaction of a fuel, typically with oxygen from the air (though it is possible to inject nitrous oxide in order to do more of the same thing and gain a power boost). The combustion process typically results in the production of a great quantity of heat, as well as the production of steam and carbon dioxide and other chemicals at very high temperature; the temperature reached is determined by the chemical make up of the fuel and oxidisers, as well as by the compression and other factors.

The most common modern fuels are made up of hydrocarbons and are derived mostly from fossil fuels (petroleum). Fossil fuels include diesel fuel, gasoline and petroleum gas, and the rarer use of propane. Except for the fuel delivery components, most internal combustion engines that are designed for gasoline use can run on natural gas or liquefied petroleum gases without major modifications. Large diesels can run with air mixed with gases and a pilot diesel fuel ignition injection. Liquid and gaseous biofuels, such as ethanol and biodiesel (a form of diesel fuel that is produced from crops that yield triglycerides such as soybean oil), can also be used. Engines with appropriate modifications can also run on hydrogen gas, wood gas, or charcoal gas, as well as from so-called producer gas made from other convenient biomass.

Internal combustion engines require ignition of the mixture, either by spark ignition (SI) or compression ignition (CI). Before the invention of reliable electrical methods, hot tube and flame methods were used.

Gasoline Ignition Process

Gasoline engine ignition systems generally rely on a combination of a lead-acid battery and an induction coil to provide a high-voltage electric spark to ignite the air-fuel mix in the engine's cylinders. This battery is recharged during operation using an electricity-generating device such as an alternator or generator driven by the engine. Gasoline engines take in a mixture of air and gasoline and compress it to not more than 12.8 bar (1.28 MPa), then use a spark plug to ignite the mixture when it is compressed by the piston head in each cylinder.

Diesel Ignition Process

Diesel engines and HCCI (Homogeneous charge compression ignition) engines, rely solely on heat and pressure created by the engine in its compression process for ignition. The compression level that occurs is usually twice or more than a gasoline engine. Diesel engines will take in air only, and shortly before peak compression, a small quantity of diesel fuel is sprayed into the cylinder via a fuel injector that allows the fuel to instantly ignite. HCCI type engines will take in both air and fuel but continue to rely on an unaided auto-combustion process, due to higher pressures and heat. This is also why diesel and HCCI engines are more susceptible to cold-starting issues, although they will run just as well in cold weather once started. Light duty diesel engines with indirect injection in automobiles and light trucks employ glowplugs that pre-heat the combustion chamber just before starting to reduce no-start conditions in cold weather. Most diesels also have a battery and charging system; nevertheless, this system is secondary and is added by manufacturers as a luxury for the ease of starting, turning fuel on and off (which can also be done via a switch or mechanical apparatus), and for running auxiliary electrical components and accessories. Most new engines rely on electrical and electronic engine control units (ECU) that also adjust the combustion process to increase efficiency and reduce emissions.

Two stroke configuration

Engines based on the two-stroke cycle use two strokes (one up, one down) for every power stroke. Since there are no dedicated intake or exhaust strokes, alternative methods must be used to scavenge the cylinders. The most common method in spark-ignition two-strokes is to use the downward motion of the piston to pressurize fresh charge in the crankcase, which is then blown through the cylinder through ports in the cylinder walls.

Spark-ignition two-strokes are small and light for their power output and mechanically very simple; however, they are also generally less efficient and more polluting than their four-stroke counterparts. In terms of power per cm^3, a two-stroke engine produces comparable power to an equivalent four-stroke engine. The advantage of having one power stroke for every 360° of crankshaft rotation (compared to 720° in a 4 stroke motor) is balanced by the less complete intake and exhaust and the shorter effective compression and power strokes. It may be possible for a two stroke to produce more power than an equivalent four stroke, over a narrow range of engine speeds, at the expense of less power at other speeds.

Small displacement, crankcase-scavenged two-stroke engines have been less fuel-efficient than other types of engines when the fuel is mixed with the air prior to scavenging allowing some of it to escape out of the exhaust port. Modern designs (Sarich and Paggio) use air-assisted fuel injection which avoids this loss, and are more efficient than comparably sized four-stroke engines. Fuel injection is essential for a modern two-stroke engine in order to meet ever more stringent emission standards.

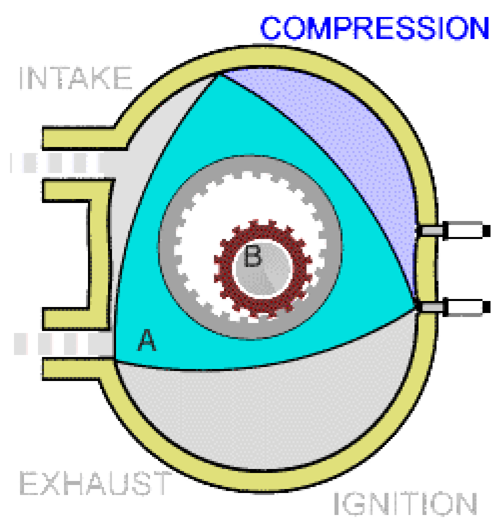
Research continues into improving many aspects of two-stroke motors including direct fuel injection, amongst other things. The initial results have produced motors that are much cleaner burning than their traditional counterparts. Two-stroke engines are widely used in snowmobiles, lawnmowers, string trimmers, chain saws, jet skis, mopeds, outboard motors, and many motorcycles. Two-stroke engines have the advantage of an increased specific power ratio (i.e. *power to volume ratio*), typically around 1.5 times that of a typical four-stroke engine.

The largest internal combustion engines in the world are two-stroke diesels, used in some locomotives and large ships. They use forced induction (similar to super-charging, or turbocharging) to scavenge the cylinders; an example of this type of motor is the Wartsila-Sulzer turbocharged two-stroke diesel as used in large container ships. It is the most efficient and powerful internal combustion engine in the world with over 50% thermal efficiency. For comparison, the most efficient small four-stroke motors are around 43% thermal efficiency (SAE 900648); size is an advantage for efficiency due to the increase in the ratio of volume to surface area.

Common cylinder configurations include the straight or inline configuration, the more compact V configuration, and the wider but smoother flat or boxer configuration. Aircraft engines can also adopt a radial configuration which allows more effective cooling. More unusual configurations such as the H, U, X, and W have also been used.

Multiple crankshaft configurations do not necessarily need a cylinder head at all because they can instead have a piston at each end of the cylinder called an opposed piston design. Because here gas in- and outlets are positioned at opposed ends of the cylinder, one can achieve uniflow scavenging, which is, like in the four stroke engine, efficient over a wide range of revolution numbers. Also the thermal efficiency is improved because of lack of cylinder heads. This design was used in the Junkers Jumo 205 diesel aircraft engine, using at either end of a single bank of cylinders with two crankshafts, and most remarkably in the Napier Deltic diesel engines. These used three crankshafts to serve three banks of double-ended cylinders arranged in an equilateral triangle with the crankshafts at the corners. It was also used in single-bank locomotive engines, and continues to be used for marine engines, both for propulsion and for auxiliary generators.

Wankel



The Wankel cycle. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

The Wankel engine (rotary engine) does not have piston strokes. It operates with the same separation of phases as the four-stroke engine with the phases taking place in separate locations in the engine. In thermodynamic terms it follows the Otto engine cycle, so may be thought of as a "four-phase" engine. While it is true that three power strokes typically occur per rotor revolution due to the 3:1 revolution ratio of the rotor to the eccentric shaft, only one power stroke per shaft revolution actually occurs; this engine provides three power 'strokes' per revolution per rotor giving it a greater power-to-weight ratio than piston engines. This type of engine is most notably used in the current Mazda RX-8, the earlier RX-7, and other models.

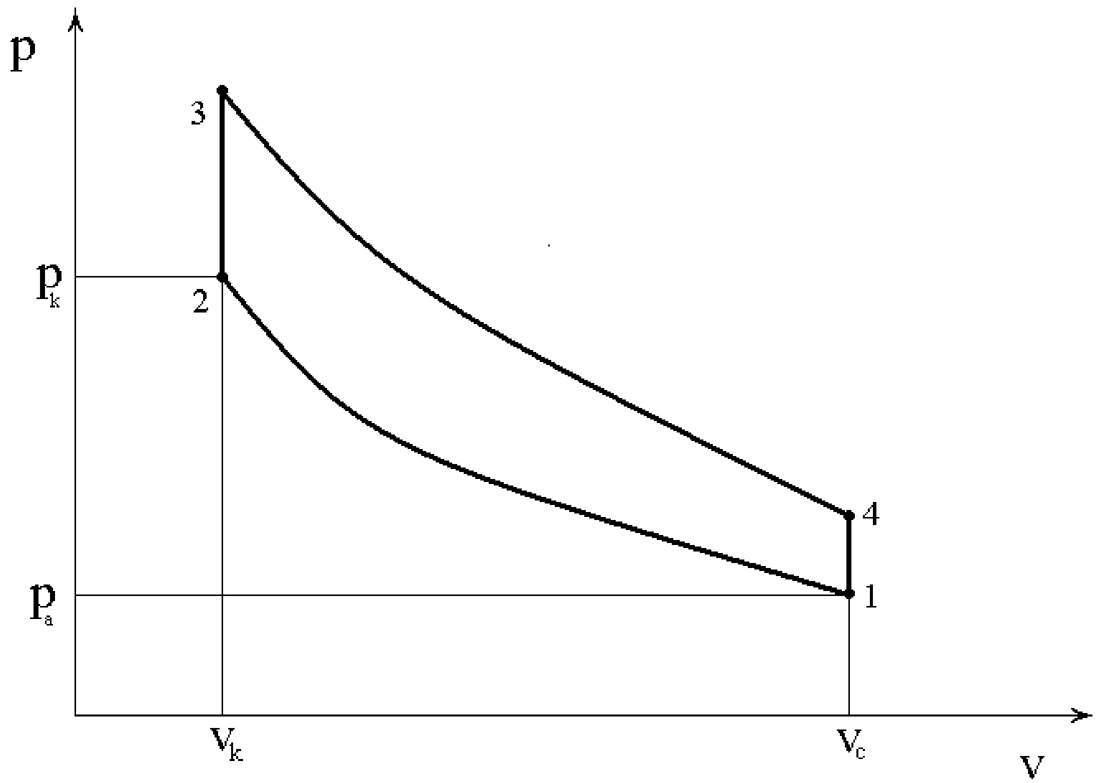
Gas turbines

A gas turbine is a rotary machine similar in principle to a steam turbine and it consists of three main components: a compressor, a combustion chamber, and a turbine. The air after being compressed in the compressor is heated by burning fuel in it. About ⅔ of the heated air combined with the products of combustion is expanded in a turbine resulting in work output which is used to drive the compressor. The rest (about ⅓) is available as useful work output.

Jet engine

Jet engines take a large volume of hot gas from a combustion process (typically a gas turbine, but rocket forms of jet propulsion often use solid or liquid propellants, and ramjet forms also lack the gas turbine) and feed it through a nozzle which accelerates the jet to high speed. As the jet accelerates through the nozzle, this creates thrust and in turn does useful work.

Engine cycle



Idealised P/V diagram for two stroke Otto cycle

Two-stroke

This system manages to pack one power stroke into every two strokes of the piston (up-down). This is achieved by exhausting and re-charging the cylinder simultaneously.

The steps involved here are:

1. Intake and exhaust occur at bottom dead center. Some form of pressure is needed, either crankcase compression or super-charging.
2. Compression stroke: Fuel-air mix compressed and ignited. In case of Diesel: Air compressed, fuel injected and self ignited
3. Power stroke: piston is pushed downwards by the hot exhaust gases.

Two Stroke Spark Ignition (SI) engine:

In a two strokes SI engine a cycle is completed in two stroke of a piston or one complete revolution (360º) of a crankshaft. In this engine the suction stroke and exhaust strokes are eliminated and ports are used instead of valves. Petrol is used in this type of engine.

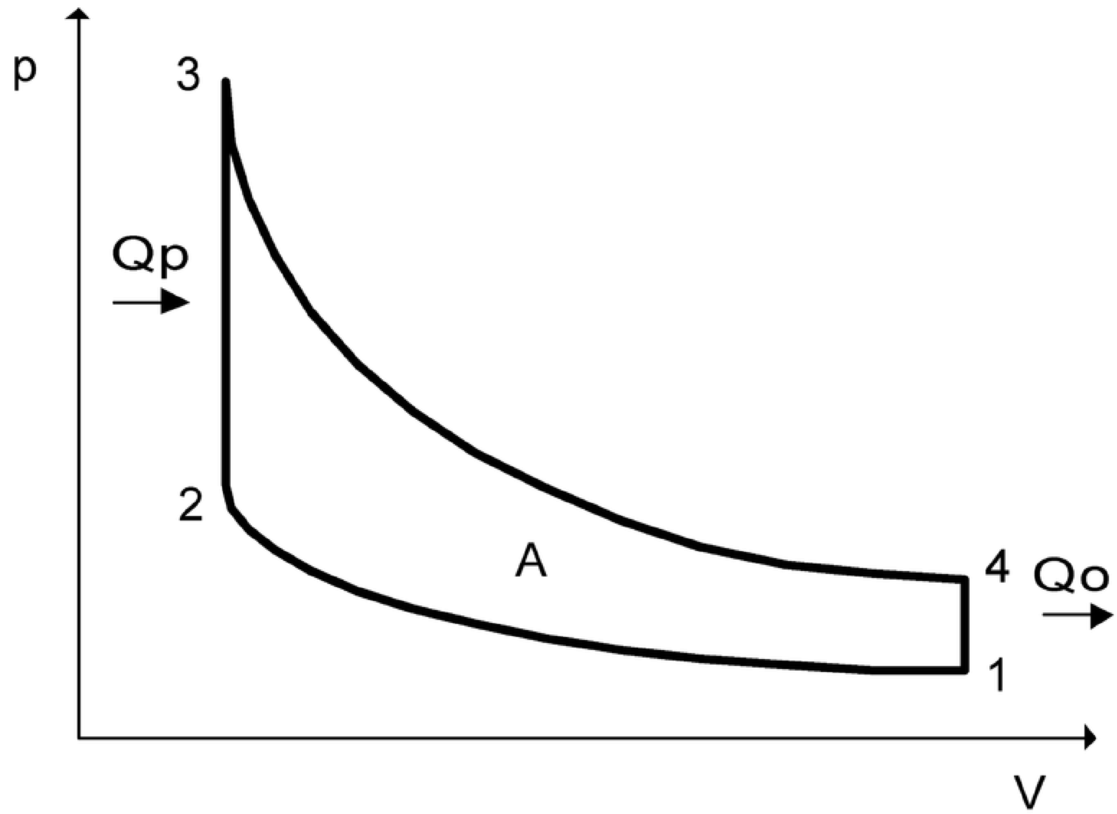
The major components of a two stroke spark Ignition engine are: Cylinder: It is a cylindrical vessel in which a piston makes an up and down motion. Piston: It is a cylindrical component making an up and down movement in the cylinder. Combustion Chamber: It is the portion above the cylinder in which the combustion of the fuel-air mixture takes place. Inlet and exhaust ports: The inlet port allows the fresh fuel-air mixture to enter the combustion chamber and the exhaust port discharges the products of combustion. Crank shaft: a shaft which converts the reciprocating motion of piston into the rotary motion. Connecting rod: connects the piston with the crankshaft. Cam shaft: The cam shaft controls the opening and closing of inlet and Exhaust valves. Spark plug: located at the cylinder head. It is used to initiate the combustion process.

Working: When the piston moves from bottom dead centre to top dead centre, the fresh air and fuel mixture enters the crank chamber through the valve. The mixture enters due to the pressure difference between the crank chamber and outer atmosphere. At the same time the fuel-air mixture above the piston is compressed.

Ignition with the help of spark plug takes place at the end of stroke. Due to the explosion of the gases, the piston moves downward. When the piston moves downwards the valve closes and the fuel-air mixture inside the crank chamber is compressed. When the piston is at the bottom dead centre, the burnt gases escape from the exhaust port.

At the same time the transfer port is uncovered and the compressed charge from the crank chamber enters into the combustion chamber through transfer port. This fresh charge is deflected upwards by a hump provided on the top of the piston. This fresh charge removes the exhaust gases from the combustion chamber. Again the piston moves from bottom dead centre to top dead centre and the fuel-air mixture gets compressed when the both the Exhaust port and Transfer ports are covered. The cycle is repeated.

Four-stroke



Idealised Pressure/volume diagram of the Otto cycle showing combustion heat input Qp and waste exhaust output Qo, the power stroke is the top curved line, the bottom is the compression stroke

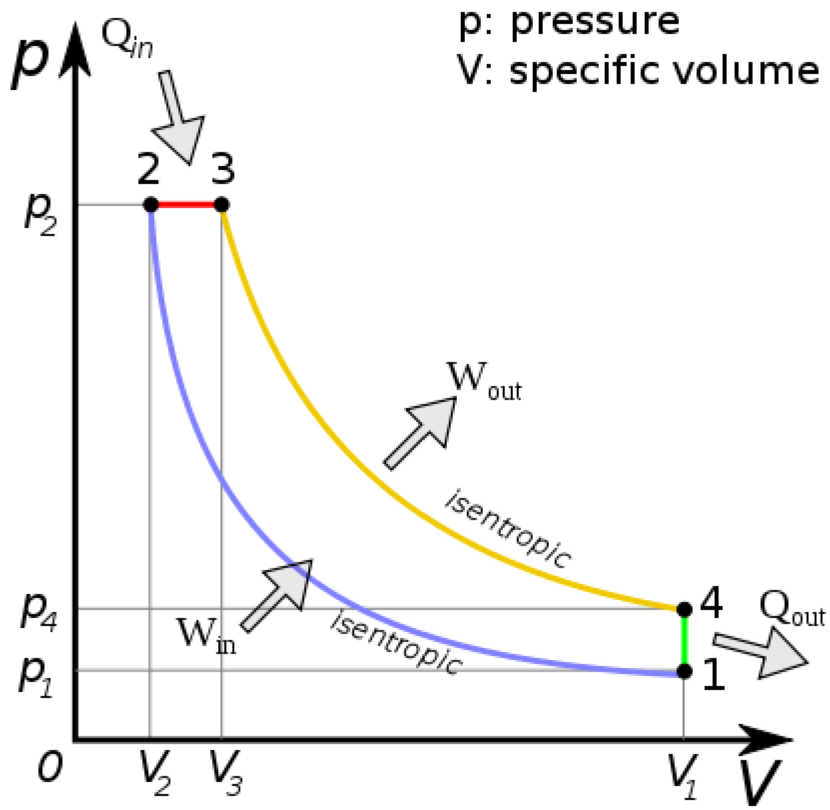
Engines based on the four-stroke ("Otto cycle") have one power stroke for every four strokes (up-down-up-down) and employ spark plug ignition. Combustion occurs rapidly, and during combustion the volume varies little ("constant volume"). They are used in cars, larger boats, some motorcycles, and many light aircraft. They are generally quieter, more efficient, and larger than their two-stroke counterparts.

The steps involved here are:

1. Intake stroke: Air and vaporized fuel are drawn in.
2. Compression stroke: Fuel vapor and air are compressed and ignited.
3. Combustion stroke: Fuel combusts and piston is pushed downwards.
4. Exhaust stroke: Exhaust is driven out. During the 1st, 2nd, and 4th stroke the piston is relying on power and the momentum generated by the other pistons. In that case, a four-cylinder engine would be less powerful than a six or eight cylinder engine.

There are a number of variations of these cycles, most notably the Atkinson and Miller cycles. The diesel cycle is somewhat different.

Diesel cycle



P-v Diagram for the Ideal Diesel cycle. The cycle follows the numbers 1-4 in clockwise direction.

Most truck and automotive diesel engines use a cycle reminiscent of a four-stroke cycle, but with a compression heating ignition system, rather than needing a separate ignition system. This variation is called the diesel cycle. In the diesel cycle, diesel fuel is injected directly into the cylinder so that combustion occurs at constant pressure, as the piston moves.

Five-stroke

The British company ILMOR presented a prototype of 5-Stroke double expansion engine, having two outer cylinders, working as usual, plus a central one, larger in diameter, that performs the double expansion of exhaust gas from the other cylinders, with an increased efficiency in the gas energy use, and an improved SFC. This engine corresponds to a 2003 US patent by Gerhard Schmitz, and was developed apparently also by Honda of Japan for a Quad engine. This engine has a similar precedent in an Spanish 1942 patent (# P0156621), by Francisco Jimeno-Cataneo, and a 1975 patent (# P0433850) by Carlos

Ubierna-Laciana. The concept of double expansion was developed early in the history of ICE by Otto himself, in 1879, and a Connecticut (USA) based company, EHV, built in 1906 some engines and cars with this principle, that didn't give the expected results.

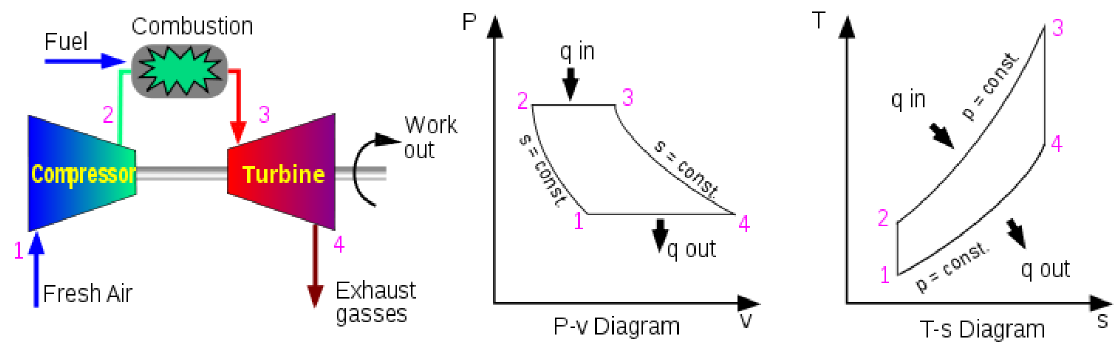
Six-stroke

First invented in 1883, the six-stroke engine has seen renewed interest over the last 20 or so years.

Four kinds of six-stroke use a regular piston in a regular cylinder (Griffin six-stroke, Bajulaz six-stroke, Velozeta six-stroke and Crower six-stroke), firing every three crankshaft revolutions. The systems capture the wasted heat of the four-stroke Otto cycle with an injection of air or water.

The Beare Head and "piston charger" engines operate as opposed-piston engines, two pistons in a single cylinder, firing every two revolutions rather more like a regular four-stroke.

Brayton cycle



Brayton cycle

A gas turbine is a rotary machine somewhat similar in principle to a steam turbine and it consists of three main components: a compressor, a combustion chamber, and a turbine. The air after being compressed in the compressor is heated by burning fuel in it, this heats and expands the air, and this extra energy is tapped by the turbine which in turn powers the compressor closing the cycle and powering the shaft.

Gas turbine cycle engines employ a continuous combustion system where compression, combustion, and expansion occur simultaneously at different places in the engine—giving continuous power. Notably, the combustion takes place at constant pressure, rather than with the Otto cycle, constant volume.

Obsolete

The very first internal combustion engines did not compress the mixture. The first part of the piston downstroke drew in a fuel-air mixture, then the inlet valve closed and, in the remainder of the down-stroke, the fuel-air mixture fired. The exhaust valve opened for the piston upstroke. These attempts at imitating the principle of a steam engine were very inefficient.

Fuels and oxidizers

Engines are often classified by the fuel (or propellant) used.

Fuels

Nowadays, fuels used include:

- Petroleum:
  - Petroleum spirit (North American term: gasoline, British term: petrol)
  - Petroleum diesel.
  - Autogas (liquified petroleum gas).
  - Compressed natural gas.
  - Jet fuel (aviation fuel)
  - Residual fuel
- Coal:
  - Most methanol is made from coal.
  - Gasoline can be made from carbon (coal) using the Fischer-Tropsch process
  - Diesel fuel can be made from carbon using the Fischer-Tropsch process
- Biofuels and vegoils:
  - Peanut oil and other vegoils.
  - Biofuels:
    - Biobutanol (replaces gasoline).
    - Biodiesel (replaces petrodiesel).
    - Bioethanol and Biomethanol (wood alcohol) and other biofuels.
    - Biogas
- Hydrogen (mainly spacecraft rocket engines)

Even fluidized metal powders and explosives have seen some use. Engines that use gases for fuel are called gas engines and those that use liquid hydrocarbons are called oil engines, however gasoline engines are also often colloquially referred to as, "gas engines" ("petrol engines" in the UK).

The main limitations on fuels are that it must be easily transportable through the fuel system to the combustion chamber, and that the fuel releases sufficient energy in the form of heat upon combustion to make practical use of the engine.

Diesel engines are generally heavier, noisier, and more powerful at lower speeds than gasoline engines. They are also more fuel-efficient in most circumstances and are used in heavy road vehicles, some automobiles (increasingly so for their increased fuel efficiency over gasoline engines), ships, railway locomotives, and light aircraft. Gasoline engines are used in most other road vehicles including most cars, motorcycles, and mopeds. Note that in Europe, sophisticated diesel-engined cars have taken over about 40% of the market since the 1990s. There are also engines that run on hydrogen, methanol, ethanol, liquefied petroleum gas (LPG), biodiesel, wood gas, & charcoal gas. Paraffin and tractor vaporizing oil (TVO) engines are no longer seen.

Hydrogen

Hydrogen could eventually replace conventional fossil fuels in traditional internal combustion engines. Alternatively fuel cell technology may come to deliver its promise and the use of the internal combustion engines could even be phased out.

Although there are multiple ways of producing free hydrogen, those methods require converting combustible molecules into hydrogen or consuming electric energy. Unless that electricity is produced from a renewable source—and is not required for other purposes— hydrogen does not solve any energy crisis. In many situations the disadvantage of hydrogen, relative to carbon fuels, is its storage. Liquid hydrogen has extremely low density (14 times lower than water) and requires extensive insulation—whilst gaseous hydrogen requires heavy tankage. Even when liquefied, hydrogen has a higher specific energy but the volumetric energetic storage is still roughly five times lower than petrol. However the energy density of hydrogen is considerably higher than that of electric batteries, making it a serious contender as an energy carrier to replace fossil fuels. The 'Hydrogen on Demand' process creates hydrogen as it is needed, but has other issues such as the high price of the sodium borohydride which is the raw material.

Oxidizers

One-cylinder gasoline engine (ca. 1910)

Since air is plentiful at the surface of the earth, the oxidizer is typically atmospheric oxygen which has the advantage of not being stored within the vehicle, increasing the power-to-weight and power to volume ratios. There are other materials that are used for special purposes, often to increase power output or to allow operation under water or in space.

- Compressed air has been commonly used in torpedoes.
- Compressed oxygen, as well as some compressed air, was used in the Japanese Type 93 torpedo. Some submarines are designed to carry pure oxygen. Rockets very often use liquid oxygen.

- Nitromethane is added to some racing and model fuels to increase power and control combustion.
- Nitrous oxide has been used—with extra gasoline—in tactical aircraft and in specially equipped cars to allow short bursts of added power from engines that otherwise run on gasoline and air. It is also used in the Burt Rutan rocket spacecraft.
- Hydrogen peroxide power was under development for German World War II submarines and may have been used in some non-nuclear submarines and was used on some rocket engines (notably Black Arrow and Me-163 rocket plane)
- Other chemicals such as chlorine or fluorine have been used experimentally, but have not been found to be practical.

Engine starting

An internal combustion engine is not usually self-starting so an auxiliary machine is required to start it. Many different systems have been used in the past but modern engines are usually started by an electric motor in the small and medium sizes or by compressed air in the large sizes.

Measures of engine performance

Engine types vary greatly in a number of different ways:

- energy efficiency
- fuel/propellant consumption (brake specific fuel consumption for shaft engines, thrust specific fuel consumption for jet engines)
- power to weight ratio
- thrust to weight ratio
- Torque curves (for shaft engines) thrust lapse (jet engines)
- Compression ratio for piston engines, Overall pressure ratio for jet engines and gas turbines

Energy efficiency

Once ignited and burnt, the combustion products—hot gases—have more available thermal energy than the original compressed fuel-air mixture (which had higher chemical energy). The available energy is manifested as high temperature and pressure that can be translated into work by the engine. In a reciprocating engine, the high-pressure gases inside the cylinders drive the engine's pistons.

Once the available energy has been removed, the remaining hot gases are vented (often by opening a valve or exposing the exhaust outlet) and this allows the piston to return to its previous position (top dead center, or TDC). The piston can then proceed to the next phase of its cycle, which varies between engines. Any heat that isn't translated into work is normally considered a waste product and is removed from the engine either by an air or liquid cooling system.

Engine efficiency can be discussed in a number of ways but it usually involves a comparison of the total chemical energy in the fuels, and the useful energy extracted from the fuels in the form of kinetic energy. The most fundamental and abstract discussion of engine efficiency is the thermodynamic limit for extracting energy from the fuel defined by a thermodynamic cycle. The most comprehensive is the empirical fuel efficiency of the total engine system for accomplishing a desired task; for example, the miles per gallon accumulated.

Internal combustion engines are primarily heat engines and as such the phenomenon that limits their efficiency is described by thermodynamic cycles. None of these cycles exceed the limit defined by the Carnot cycle which states that the overall efficiency is dictated by the difference between the lower and upper operating temperatures of the engine. A terrestrial engine is usually and fundamentally limited by the upper thermal stability derived from the material used to make up the engine. All metals and alloys eventually melt or decompose and there is significant researching into ceramic materials that can be made with higher thermal stabilities and desirable structural properties. Higher thermal stability allows for greater temperature difference between the lower and upper operating temperatures—thus greater thermodynamic efficiency.

The thermodynamic limits assume that the engine is operating in ideal conditions: a frictionless world, ideal gases, perfect insulators, and operation at infinite time. The real world is substantially more complex and all the complexities reduce the efficiency. In addition, real engines run best at specific loads and rates as described by their power band. For example, a car cruising on a highway is usually operating significantly below its ideal load, because the engine is designed for the higher loads desired for rapid acceleration. The applications of engines are used as contributed drag on the total system reducing overall efficiency, such as wind resistance designs for vehicles. These and many other losses result in an engine's real-world fuel economy that is usually measured in the units of miles per gallon (or fuel consumption in liters per 100 kilometers) for automobiles. The *miles* in miles per gallon represents a meaningful amount of work and the volume of hydrocarbon implies a standard energy content.

Most steel engines have a thermodynamic limit of 37%. Even when aided with turbochargers and stock efficiency aids, most engines retain an *average* efficiency of about 18%-20%. Rocket engine efficiencies are better still, up to 70%, because they combust at very high temperatures and pressures and are able to have very high expansion ratios.

There are many inventions concerned with increasing the efficiency of IC engines. In general, practical engines are always compromised by trade-offs between different properties such as efficiency, weight, power, heat, response, exhaust emissions, or noise. Sometimes economy also plays a role in not only the cost of manufacturing the engine itself, but also manufacturing and distributing the fuel. Increasing the engine's efficiency brings better fuel economy but only if the fuel cost per energy content is the same.

Measures of fuel/propellant efficiency

For stationary and shaft engines including propeller engines, fuel consumption is measured by calculating the brake specific fuel consumption which measures the mass flow rate of fuel consumption divided by the power produced.

For internal combustion engines in the form of jet engines, the power output varies drastically with airspeed and a less variable measure is used: thrust specific fuel consumption (TSFC), which is the number of pounds of propellant that is needed to generate impulses that measure a pound force-hour. In metric units, the number of grams of propellant needed to generate an impulse that measures one kilonewton-second.

For rockets, TSFC can be used, but typically other equivalent measures are traditionally used, such as specific impulse and effective exhaust velocity.

Air and noise pollution

Air pollution

Internal combustion engines such as reciprocating internal combustion engines produce air pollution emissions, due to incomplete combustion of carbonaceous fuel. The main derivatives of the process are carbon dioxide CO_2, water and some soot — also called particulate matter (PM). The effects of inhaling particulate matter have been studied in humans and animals and include asthma, lung cancer, cardiovascular issues, and premature death. There are however some additional products of the combustion process that include nitrogen oxides and sulfur and some uncombusted hydrocarbons, depending on the operating conditions and the fuel-air ratio.

Not all of the fuel will be completely consumed by the combustion process; a small amount of fuel will be present after combustion, some of which can react to form oxygenates, such as formaldehyde or acetaldehyde, or hydrocarbons not initially present in the fuel mixture. The primary causes of this is the need to operate near the stoichiometric ratio for gasoline engines in order to achieve combustion and the resulting "quench" of the flame by the relatively cool cylinder walls, otherwise the fuel would burn more completely in excess air. When running at lower speeds, quenching is commonly observed in diesel (compression ignition) engines that run on natural gas. It reduces the efficiency and increases knocking, sometimes causing the engine to stall. Increasing the amount of air in the engine reduces the amount of the first two pollutants, but tends to encourage the oxygen and nitrogen in the air to combine to produce nitrogen oxides (NO_x) that has been demonstrated to be hazardous to both plant and animal health. Further chemicals released are benzene and 1,3-butadiene that are also particularly harmful; and not all of the fuel burns up completely, so carbon monoxide (CO) is also produced.

Carbon fuels contain sulfur and impurities that eventually lead to producing sulfur monoxides (SO) and sulfur dioxide (SO_2) in the exhaust which promotes acid rain. One final element in exhaust pollution is ozone (O_3). This is not emitted directly but made in the air by the action of sunlight on other pollutants to form "ground level ozone", which, unlike the "ozone layer" in the high atmosphere, is regarded as a bad thing if the levels are too high. Ozone is broken down by nitrogen oxides, so one tends to be lower where the other is higher.

For the pollutants described above (nitrogen oxides, carbon monoxide, sulphur dioxide, and ozone), there are accepted levels that are set by legislation to which no harmful effects are observed — even in sensitive population groups. For the other three: benzene, 1,3-butadiene, and particulates, there is no way of proving they are safe at any level so the experts set standards where the risk to health is, "exceedingly small".

Noise pollution

Significant contributions to noise pollution are made by internal combustion engines. Automobile and truck traffic operating on highways and street systems produce noise, as do aircraft flights due to jet noise, particularly supersonic-capable aircraft. Rocket engines create the most intense noise.

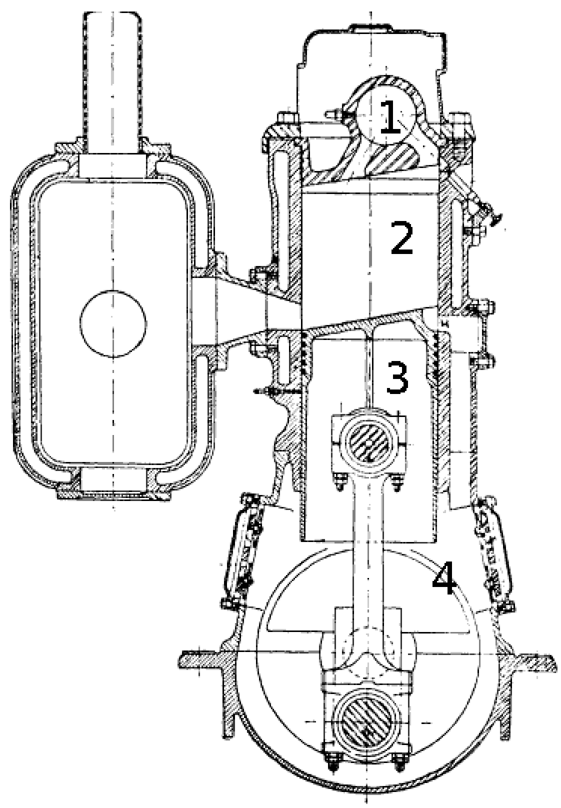
Idling

Internal combustion engines continue to consume fuel and emit pollutants when idling so it is desirable to keep periods of idling to a minimum. Many bus companies now instruct drivers to switch off the engine when the bus is waiting at a terminus.

In the UK (but applying only to England), the Road Traffic (Vehicle Emissions) (Fixed Penalty) Regulations 2002 (Statutory Instrument 2002 No. 1808) introduced the concept of a "*stationary idling offence*". This means that a driver can be ordered "*by an authorised person ... upon production of evidence of his authorisation, require him to stop the running of the engine of that vehicle*" and a "*person who fails to comply ... shall be guilty of an offence and be liable on summary conviction to a fine not exceeding level 3 on the standard scale*". Only a few local authorities have implemented the regulations, one of them being Oxford City Council.

Chapter 9

Hot Bulb Engine



Hot bulb engine (two-stroke).
1. Hot bulb
2. Cylinder
3. Piston
4. Crankcase

The **hot bulb engine**, or **hotbulb** or heavy oil engine is a type of internal combustion engine. It is an engine in which fuel is ignited by being brought into contact with a red hot metal surface inside a bulb. Most hot bulb engines were produced as one-cylinder low-speed two-stroke crankcase scavenging units.

History

The concept of this engine was established by Herbert Akroyd Stuart at the end of the 19th century. The first prototypes were built in 1886 and production started in 1891 by Richard Hornsby & Sons of Grantham, Lincolnshire, England under the title Hornsby Akroyd Patent Oil Engine under licence. It was later developed in the USA by the German emigrants Mietz and Weiss by combining it with the two-stroke engine developed by Joseph Day. Similar engines, for agricultural and marine use, were built by Bolinder and Pythagoras engine factory in Sweden. Bolinder is now part of the Volvo group.

A Hornsby-Akroyd hot bulb engine, built to the original horizontal cylinder, four-stroke design. This particular engine has been adapted to run on lamp oil.

Akroyd-Stuart's heavy oil engine (compared to *spark-ignition*) is distinctly different from Rudolf Diesel's better-known engine where ignition is initiated through the heat of compression. An oil engine will have a compression ratio of about 3:1, where a typical Diesel engine will have a compression ratio ranging between 15:1 and 20:1. Furthermore fuel is injected during the intake stroke and not at the end of the compression stroke as in a diesel.

Operation and working cycle

The hot-bulb engine shares its basic layout with nearly all other internal combustion engines, in that it has a piston, inside a cylinder, connected to a flywheel via a connecting rod and crankshaft. Akroyd-Stuart's original engine operated on the four-stroke cycle (Induction, Compression, Power, Exhaust) and Hornsby continued to build engines to this design, as did several other British manufacturers such as Blackstone and Crossley. Manufacturers in Europe, Scandinavia and in the USA built engines working on the two-stroke cycle with crankcase scavenging. The latter type formed the majority of hot-bulb engine production. The flow of gases through the engine is controlled by valves in four-stroke engines, and by the piston covering and uncovering ports in the cylinder wall in two-strokes.

The type of blow-lamp used to start the Hot Bulb engine.

Blow-lamp being used to heat the Hot Bulb of a Lanz Bulldog tractor.

In the hot-bulb engine combustion takes place in a separated combustion chamber, the "vaporizer" (also called the "hot bulb"), usually mounted on the cylinder head, into which fuel is sprayed. It is connected to the cylinder by a narrow passage and is heated by the combustion while running; an external flame such as a blow-lamp or slow-burning wick is used for starting (on later models sometimes electric heating or pyrotechnics was used).

Another method is the inclusion of a spark plug and vibrator coil ignition. The engine could be started on petrol and switched over to oil after it had warmed to running temperature.

The pre-heating time depends on the engine design, the type of heating used and the ambient temperature, but generally ranges from 2–5 minutes (for most engines in a temperate climate) to as much as half an hour (if operating in extreme cold or the engine is especially large). The engine is then turned over, usually by hand but sometimes by compressed air or an electric motor.

Once the engine is running, the heat of compression and ignition maintains the hot-bulb at the necessary temperature and the blow-lamp or other heat source can be removed. From this point the engine requires no external heat and requires only a supply of air, fuel oil and lubricating oil to run. However, under low power the bulb could cool off too much, and a throttle can cut down the cold fresh air supply. Also, as the engine's load increased, so does the temperature of the bulb, causing the ignition period to advance; to counteract pre-ignition, water is dripped into the air intake. Equally, if the load on the engine is low, combustion temperatures may not be sufficient to maintain the temperature of the hot-bulb. Many hot-bulb engines cannot be run off-load without auxiliary heating for this reason.

The fact that the engine can be left unattended for long periods while running made hot bulb engines a popular choice for applications requiring a steady power output such as farm tractors, generators, pumps and canal boat propulsion.

Four-stroke engines

Air is drawn into the cylinder through the intake valve as the piston descends (the induction stroke). During the same stroke, fuel is sprayed into the vaporizer by a mechanical (jerk-type) fuel pump through a nozzle. The air in the cylinder is then forced through the top of the cylinder as the piston rises (the compression stroke), through the opening into the vaporizer, where it is compressed and its temperature rises. The vaporized fuel mixes with the compressed air and ignites primarily due to the heat of the hot bulb generated while running, or heat applied to the hot-bulb prior to starting. By contracting the bulb to a very narrow neck where it attaches to the cylinder, a high degree of turbulence is set up as the ignited gases flash through the neck into the cylinder, where combustion is completed. The resulting pressure drives the piston down (the power stroke). The piston's action is converted to a rotary motion by the crankshaft-flywheel assembly, to which equipment can be attached for work to be performed. The flywheel stores momentum, some of which is used to turn the engine when power is not being produced. The piston rises, expelling exhaust gases through the exhaust valve (the exhaust stroke). The cycle then starts again.

Two-stroke engines

The cycle starts with the piston at the bottom of its stroke. As it rises, it draws air into the crankcase through the Inlet Port. At the same time fuel is sprayed into the vapouriser. The charge of air *on top* of the piston is compressed into the vapouriser where it is mixed with the atomised fuel and ignites. The piston is driven down the cylinder. As it descends the piston first uncovers the Exhaust Port. The pressurised exhaust gases flow out of the cylinder. A fraction after the Exhaust Port is uncovered, the descending piston uncovers the Transfer Port. The piston is now pressurising the air in the crankcase, which is forced through the Transfer Port and into the space above the piston. Part of the incoming air charge is lost out of the still-open Exhaust Port to ensure all the exhaust gases are cleared from the cylinder (a process known as 'scavenging'). The piston then reaches the bottom of its stroke and begins to rise again, drawing a fresh charge of air into the crankcase and completing the cycle. Induction and Compression are carried out on the upward stroke and Power and Exhaust on the downward stroke.

A supply of lubricating oil must be fed to the crankcase to supply the crankshaft bearings. Since the crankcase is also used to supply air to the engine, the engine's lubricating oil is carried into the cylinder with the air charge, burnt during combustion and carried out of the exhaust. The oil carried from the crankcase to the cylinder is used to lubricate the piston. This means that a two-stroke hot-bulb engine will gradually burn its supply of lubricating oil – a design known as a 'total loss' lubricating system. There were also designs that employed a scavenge pump or similar to remove oil from the crankcase and return it to the lubricating oil reservoir. Lanz hot-bulb tractors and their many imitators had this feature. This reduces oil consumption considerably.

In addition, if excess crankcase oil is present on start up, there is a danger of the engine starting and accelerating uncontrollably to well past the RPM limits of the rotating and reciprocating components. This can result in destruction of the engine. There is normally a bung or stopcock that allows draining of the crankcase before starting.

The lack of valves and the doubled-up working cycle also means that a two-stroke hot bulb engine can run equally well in both directions. A common starting technique for smaller two-stroke engines is to turn the engine over against the normal direction of rotation. The piston will 'bounce' off the compression phase with sufficient force to spin the engine the correct way and start it. This bi-directional running was an advantage in marine applications as the engine could, like the steam engine, drive a vessel forward or backwards without the need for a gearbox. The direction could be reversed either by stopping the engine and starting it again in the other direction or, with sufficient skill and timing on the part of the operator, slowing the engine until it carried just enough momentum to bounce against its own compression and run the other way. This was an undesirable quality in hot-bulb powered tractors equipped with gearboxes. At very low engine speeds the engine could reverse itself almost without any change in sound or running quality and without the driver noticing until the tractor drove in the opposite direction to that intended. Lanz Bulldog tractors featured a dial, mechanically driven by the engine, that showed a spinning arrow. The arrow pointed in the direction of normal engine rotation – if the dial spun the other way the engine had reversed itself.

Advantages

At the time the hot-bulb engine was invented, its great attractions were its economy, simplicity, and ease of operation in comparison to the steam engine, which was then the dominant source of power in industry. Steam engines achieved an average thermal efficiency (the percent of heat generated that is actually turned into useful work) of around 6%. Hot-bulb engines could easily achieve 12% thermal efficiency. During the 1910s–1950s, hot-bulb engines were more economical to manufacture with their low pressure crude fuel injection and lower compression ratio than diesel engines.

The hot-bulb engine is much simpler to construct and operate than the steam engine. Boilers require at least one person to add water and fuel as needed and monitor pressure to prevent overpressure and a resulting explosion. If fitted with automatic lubrication systems and a governor to control engine speed, a hot-bulb engine could be left running, unattended for hours at a time.

Another attraction was their safety. A steam engine, with its exposed fire and hot boiler, steam pipes and working cylinder could not be used in flammable conditions such as munitions factories or fuel refineries. Hot-bulb engines also produced cleaner exhaust fumes. A big danger with the steam engine was that if the boiler pressure grew too high and the safety valve failed, a highly dangerous explosion could occur (although this was a relatively rare occurrence by the time the hot-bulb engine was invented). A more common problem was that if the water level in the boiler of a steam engine dropped too low the lead plug in the crown of the furnace would melt, extinguishing the fire. If a hot bulb engine ran out of fuel, it would simply stop and could be immediately restarted with more fuel. The cooling water was usually a closed circuit, so no water loss would occur unless there was a leak. If the cooling water ran low, the engine would seize through overheating – a major problem, but it carried no danger of explosion.

Compared with steam, gasoline (petrol), and diesel engines, hot-bulb engines are simpler and therefore have fewer potential problems. There is no electrical system as found on a petrol engine, and no external boiler and steam system as on a steam engine.

A big attraction with the hot-bulb engine was its ability to run on a wide range of fuels. Even poor-burning fuels could be used since a combination of vaporiser- and compression-ignition meant that such fuels could be made to combust. The usual fuel used was fuel oil, similar to modern-day diesel, but natural gas, kerosene, paraffin, crude oil, vegetable oil or creosote could also be used. This made the hot-bulb engine very cheap to run, since it could be run on cheaply available fuels. Some operators even ran engines on used engine oil, thus providing almost free power. Recently, this multi-fuel ability has led to an interest in using hot bulb engines in developing nations where they can be run on locally produced biofuel.

Due to the lengthy pre-heating time, hot-bulb engines were nearly always guaranteed to start quickly, even in extremely cold conditions. This made them popular choices in cold regions such as Canada and Scandinavia, where steam engines were not viable and early gasoline and diesel engines could not be relied on to operate.

Uses

1939 Lanz Bulldog, a tractor built around a hot bulb engine.

The reliability of the hot-bulb engine, their ability to run on many fuels and the fact that they can be left running for hours or days at a time made them extremely popular with agricultural, forestry and marine users, where they were used for pumping and for powering milling, sawing and threshing machinery. Hot-bulb engines were also used on road rollers and tractors.

J.V. Svensons Motorfabrik, i Augustendal in Stockholm Sweden used hot bulb engines in their Typ 1 motor plough, produced from 1912 to 1925. Munktells Mekaniska Verkstads AB, in Eskilstuna, Sweden, produced agricultural tractors with hot bulb engines from 1913 onwards. Heinrich Lanz Mannheim AG, in Mannheim, Germany, started to use hot bulb engines in 1921, in the Lanz Bulldog HL. Other well known tractor manufacturers that used bulb engines were Bubba, Gambino, Landini and Orsi in Italy, HSCS in Hungary, SFV in France Ursus in Poland, and Marshall in England.

A 1928 Lanz Bulldog tractor.
The 'hot bulb' is immediately above the front axle, mounted on the front of the cylinder block.

At the start of the 20th century there were several hundreds of European manufacturers of hot bulb engines for marine use. In Sweden alone there were over 70 manufacturers, of which Bolinder is the best known (in the 1920s they had about 80% of the world market). The Norwegian SABB was a very popular hot bulb engine for small fishing boats and many of them are still in working order. In America Standard, Weber, Reid, Stickney, Oil City, and Fairbanks Morse built hotbulb engines.

A vertical twin-cylinder hot bulb engine, developing 70 horsepower. This engine has a top speed of 325 RPM.

A limitation of the design of the engine was that it could only run over quite a narrow (and slow) speed band, typically 50-300 R.P.M.. This made the hot-bulb engine difficult to adapt to automotive uses other than vehicles such as tractors, where speed was not a major requirement. This limitation was of little consequence for stationary applications, where the hot-bulb engine was very popular.

Owing to the lengthy pre-heating time, hot-bulb engines only found favour with users who needed to run engines for long periods of time, where the pre-heating process only represented a small percentage of the overall running period. This included marine use (especially in fishing boats) and pumping/drainage duties.

The hot-bulb engine was invented at the same time that dynamos and electric light systems were perfected, and electricity generation was one of the hot-bulb engines main uses. The engine could achieve higher R.P.M. than a standard reciprocating steam engine (although high-speed steam engines were developed during the 1890s), and its low fuel and maintenance requirements (including the ability to be operated and maintained by only one person) made it ideal for small-scale power supply. Generator sets driven by hot-bulb engines were installed in numerous large houses (especially in rural areas) in Europe, as well as in factories, theatres, lighthouses, radio stations and many other locations where a centralised electricity grid was not available. Usually the dynamo or alternator would be driven off the engine's flywheel by a flat belt, to allow the necessary 'gearing up'- making the generator turn at a faster speed than the engine. Companies such as Armstrong Whitworth and Boulton Paul manufactured and supplied complete generating sets (both the engine and generator) from the 1900s to the late 1920s, when the formation of national grid systems throughout the world and the replacement of the hot-bulb engine by the diesel engine caused a drop in demand.

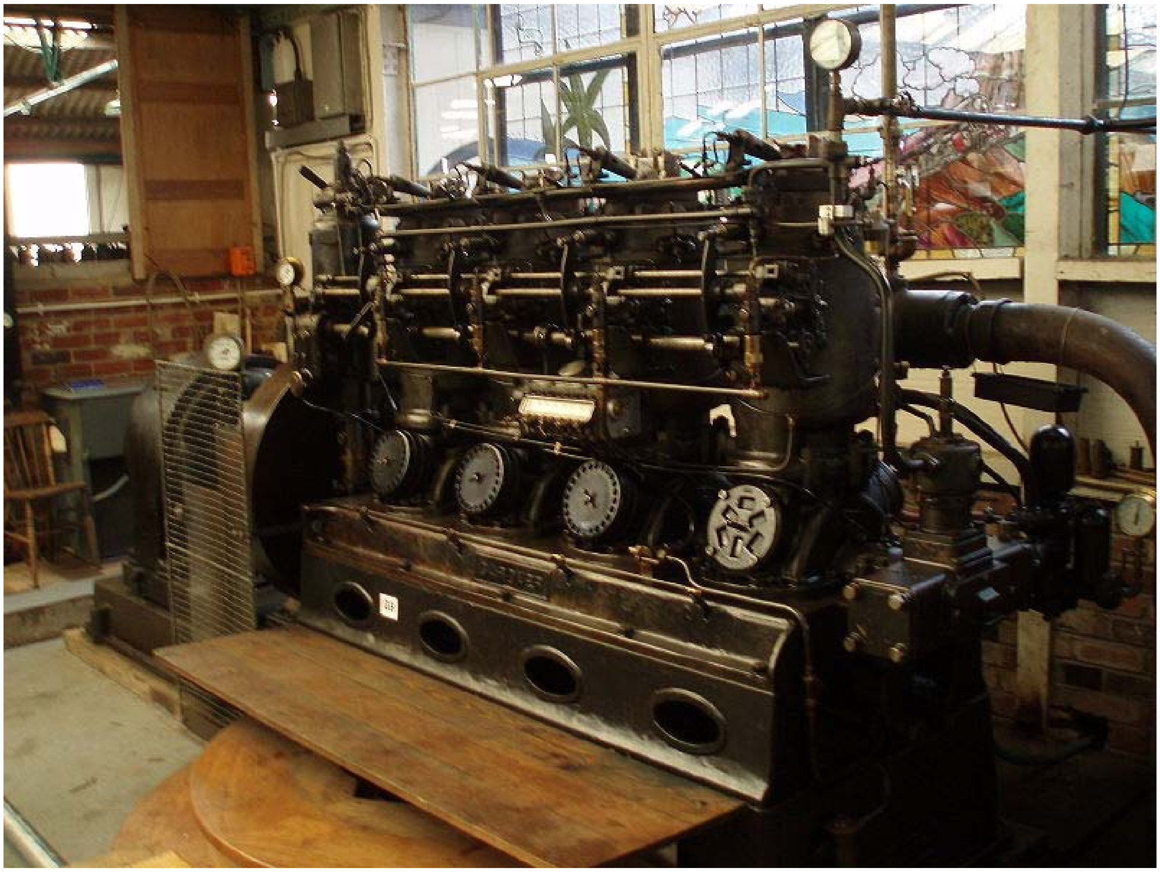
The engines were also used in areas where the fire of a steam engine would be an unacceptable fire risk. Akroyd-Stuart developed the world's first oil-engined locomotive (the 'Lachesis') for the Royal Arsenal, Woolwich, where the use of locomotives had previously been impossible due to the risk. Hot-bulb engines proved very popular for industrial engines in the early 20th century, but lacked the power to be used in anything larger.

Compression ignition

Herbert Akroyd Stuart was always keen to improve the efficiency of his engine. The obvious way to do this was to raise the compression ratio to increase the engine's thermal efficiency. However, above ratios of around 8:1 the fuel oil in the vapouriser would ignite before the piston reached the limit of its travel. This pre-detonation caused rough running, power loss and ultimately engine damage. Working with engineers at Hornsby's, Akroyd Stuart developed a system whereby the compression ratio was increased to as much as 18:1 and fuel oil was delivered to the cylinder only when the piston reached top dead centre, thus preventing pre-ignition.

This system was patented in October 1890 and development continued. In 1892 (5 years before Rudolf Diesel's first prototype), engineers at Hornsby's built an experimental engine. The vapouriser was replaced with a standard cylinder head and used a high-pressure fuel nozzle system. The engine could be started from cold and ran for 6 hours, making it the world's first internal combustion engine to run on purely compression ignition. However, to build a fully practical fuel injection system required using machining techniques and building to tolerances that were not possible to mass produce at the time. Hornsby's was also working at full capacity building and selling hot-bulb engines, so these developments were not pursued.

Replacement



A Gardner 4T5 4-cylinder hot-bulb engine on display at the Anson Engine Museum, Stockport, UK

From around 1910, the diesel engine was improved dramatically, with more power being available at greater efficiencies than the hot-bulb engine could manage (Diesel engines can achieve over 50% efficiency if designed with maximum economy in mind). Diesel engines offered greater power for a given engine size due to the more efficient combustion method (they had no hot-bulb, relying purely on compression-ignition) and greater ease of use as they required no pre-heating.

The hot-bulb engine was limited in its scope in terms of speed and overall power-to-size ratio. To make a hot-bulb engine capable of powering a ship or locomotive, it would have been prohibitively large and heavy. The hot-bulb engines used in Landini tractors were as much as 20 litres in capacity for relatively low power outputs. To create even combustion throughout the multiple hot-bulbs in multi-cylinder engines is difficult. The hot-bulb engine's low compression ratio in comparison to diesel engines limited its efficiency, power output and speed. Most hot-bulb engines could run at a maximum speed of around 100 rpm, while by the 1930s diesel engines capable of 2,000 rpm were being built. Also, due to the design of hot bulb and the limitations of current technology in regards to the injector system, most hot-bulb engines were single-speed engines, running at a fixed speed, or in a very narrow speed range. Diesel engines can be designed to operate over a much wider speed range, making them more versatile. This made these medium-sized diesels a very popular choice for use in generator sets, replacing the hot-bulb engine as the engine of choice for small-scale power generation.

The development of small-capacity, high-speed diesel engines in the 1930s and 1940s, led to hot-bulb engines falling dramatically out of favour. The last large-scale manufacturer of hot-bulb engines stopped producing them in the 1950s and they are now virtually extinct in commercial use, except in very remote areas of the developing world. An exception to this is marine use; hot-bulb engines were widely fitted to inland barges and narrowboats in Europe. The United Kingdom's first two self-powered "motor" narrowboats—Cadbury's *Bournville I* and *Bournville II* in 1911—were powered by 15 horsepower Bolinder single-cylinder hot-bulb engines, and this type became common between the 1920s and the 1950s. With hot-bulb engines being generally long-lived and ideally suited to such a use, it is not uncommon to find vessels still fitted with their original hot-bulb engines today.

Although many people believe that model glow engines are a variation of the hot-bulb engine, this is not the case. Model glow engines are catalytic ignition engines. They take advantage of a reaction between platinum in the glow plug coil and methyl alcohol vapour whereby at certain temperatures and pressures platinum will glow in contact with the vapour.

Hot bulb pseudo diesel development

1890s–1910

The hot-bulb engine is often confused with the diesel engine , and it is true that the two engines are very similar. A hot-bulb engine features a prominent hot-bulb vaporiser; a Diesel engine does not. Other significant differences are:

- The hot-bulb engine mostly reuses the heat retained in the vaporiser to ignite the fuel with, achieving about 12% efficiency.
- The Diesel engine uses only compression to ignite the fuel. It operates at pressures many times higher than the hot-bulb engine, resulting in over 50% efficiency with large diesels.
- The hot bulb engine required preheating of the hot bulb with a torch for about 15 minutes before starting.

There is also a crucial difference in the timing of the fuel injection process:

- In the hot-bulb engine, before 1910 fuel was injected earlier into the vapouriser (during the intake stroke). This caused the start of combustion to be out of synchronization with the crank angle, meaning that the engine would only run smoothly at one low-speed or load. If the engine's load increased, so would the temperature of the bulb, causing the ignition period to advance, causing pre-

ignition. To counteract pre-ignition, water would be dripped into the air intake, providing some flexibility.
- In the diesel engine, fuel is injected into the cylinder, with an adjusted timing relative to the engine speed and load, shortly before the top dead center of the Compression Stroke is reached.

There is another, detailed difference in the method of fuel injection:

- The hot-bulb engine uses a medium-pressure pump to deliver fuel to the cylinder, through a simple nozzle.
- In the original Diesel engine, fuel was sprayed into the cylinder by high pressure compressed air, through an injector. The camshaft lifted a spring-loaded pin to initiate fuel delivery though the nozzle.

During this period technology had not advanced to the point that oil engines could run faster than 150 rpm. The structure of these engines were basically the same as steam engines and without pressured lubrication. In hot-bulb engines, fuel is injected at low pressure, using a more economical and more reliable, and simpler configuration. However, by not using compressed air injection it is less efficient. In this period diesel and hot bulb engines were four stroke. In 1902 F. Rundlof invented the two-stroke crankcase scavenged engine that went on to become the prevalent hot bulb type engine.

1910–1950s

Direct injected small diesel engines still were not practical. and the prechambered indirect injected engine was invented, along with the requirement of glowplugs to be used for starting. With technology developed by Robert Bosch GmbH pump and injector systems could be built to run at a much higher pressure. Combined with high precision injectors, high speed diesels were produced from 1927.

The hot bulbs started to develop cracks and breakups and were gradually replaced by water cooled cylinder heads with a flat hot spot. Over time the compression ratios were increased from $^1\!/_3$ to $^1\!/_{14}$.Fuel injection started from 135 degrees before top dead center, with low compression to 20 degrees before top dead center with later higher compression engines increasing the hot air factor for ignition and increasing the fuel efficiency. Glowplugs finally replaced the preheating with a blowtorch methods and engine speeds were increased, resulting in what is now classified as an indirect injection diesel. Hot bulb or prechambered engines are always easier to produce. more reliable and could handle smaller amounts of fuel in smaller engines, than the direct injected "pure" diesels could.

Production

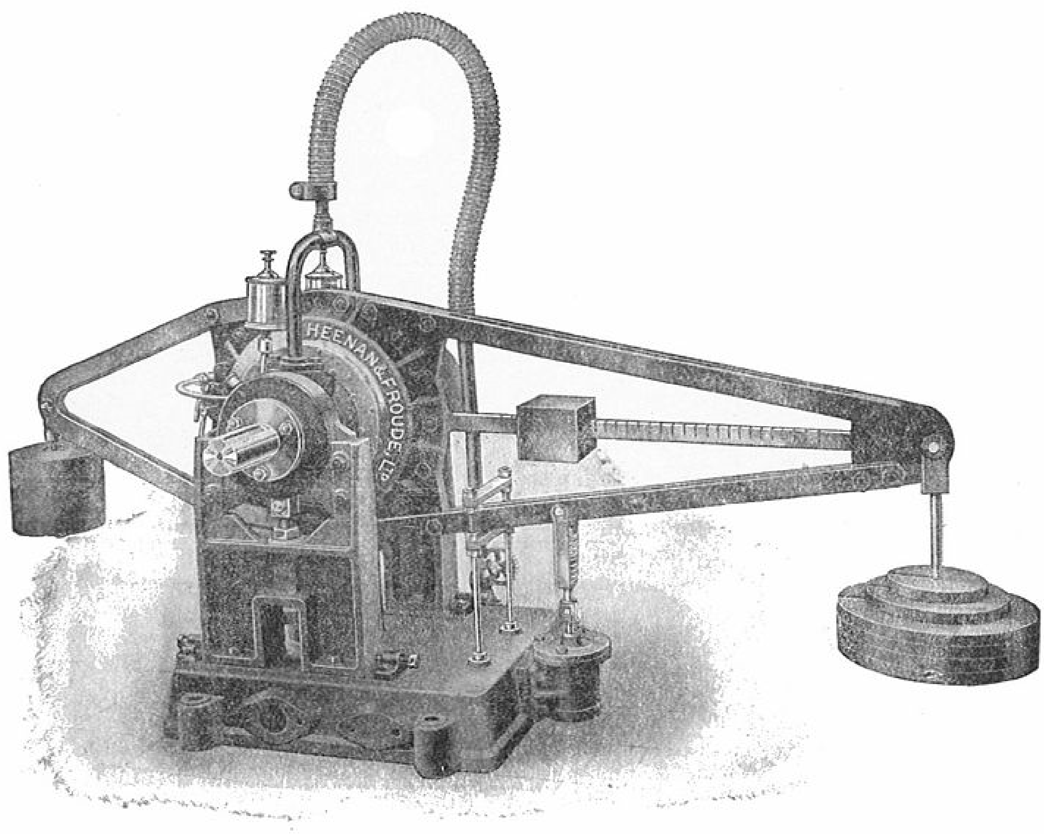
A *Drott* hot bulb engine, manufactured at the Pythagoras Mechanical Workshop Museum in Norrtälje, Sweden, after original drawings from the Pythagoras Engine Factory

Hot bulb engines were built by a large number of manufacturers, usually in modest series.These engines were slow running (300-400 RPM) and mostly with cast iron parts including pistons. The fuel pump was usually made with a brass housing and steel plunger operating with a variable stroke length. This resulted in a simple, rugged heavy engine. Therefore they could be machined in an average machine shop without special tools.

The Pythagoras Engine Factory in Norrtälje in Sweden is kept as a museum (the Pythagoras Mechanical Workshop Museum), and has a functioning production line and extensive factory archives.

Chapter 10

Dynamometer



Early hydraulic dynamometer, with dead-weight torque measurement.

A **dynamometer** or **"dyno"** for short, is a device for measuring force, moment of force (torque), or power. For example, the power produced by an engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed (RPM).

A dynamometer can also be used to determine the torque and power required to operate a driven machine such as a pump. In that case, a *motoring* or *driving* dynamometer is used. A dynamometer that is designed to be driven is called an *absorption* or *passive* dynamometer. A dynamometer that can either drive or absorb is called a *universal* or *active* dynamometer.

In addition to being used to determine the torque or power characteristics of a machine under test (MUT), dynamometers are employed in a number of other roles. In standard emissions testing cycles such as those defined by the US Environmental Protection Agency (US EPA), dynamometers are used to provide simulated road loading of either the engine (using an engine dynamometer) or full powertrain (using a chassis dynamometer). In fact, beyond simple power and torque measurements, dynamometers can be used as part of a testbed for a variety of engine development activities such as the calibration of engine management controllers, detailed investigations into combustion behavior and tribology.

In the medical terminology, hand dynamometers are used for routine screening of grip strength and initial and ongoing evaluation of patients with hand trauma and dysfunction. They are also used to measure grip strength in patients where compromise of the cervical nerve roots or peripheral nerves is suspected.

In the rehabilitation, kinesiology, and ergonomics realms, force dynamometers are used for measuring the back, grip, arm, and/or leg strength of athletes, patients, and workers to evaluate physical status, performance, and task demands. Typically the force applied to a lever or through a cable are measured and then converted to a moment of force by multiplying by the perpendicular distance from the force to the axis of the level.

Principles of operation of torque power (absorbing) dynamometers

An absorbing dynamometer acts as a load that is driven by the prime mover that is under test (e.g. Pelton wheel). The dynamometer must be able to operate at any speed and load to any level of torque that the test requires.

Absorbing dynamometers are not to be confused with "inertia" dynamometers, which calculate power solely by measuring power required to accelerate a known mass drive roller and provide no variable load to the prime mover.

An Absorption dynamometer is usually equipped with some means of measuring the operating torque and speed.

The dynamometer's Power Absorption Unit absorbs the power developed by the prime mover. The power absorbed by the dynamometer is converted into heat and the heat generally dissipates into the ambient air or transfers to cooling water that dissipates into the air. Regenerative dynamometers, in which the prime mover drives a DC motor as a generator to create load, make excess DC power and potentially, using a DC/AC inverter, can feed AC power back into the commercial electrical power grid - where the power produced is eventually converted back into heat (as in an oven or light bulb, etc.).

Absorption dynamometers can be equipped with two types of control systems to provide different main test types.

Constant Force

The dynamometer has a "braking" torque regulator, the PAU (Power Absorption Unit) is configured to provide a set braking force torque load while the prime mover is configured to operate at whatever throttle opening, fuel delivery rate or any other variable it is desired to test. The prime mover is then allowed to accelerate the engine through the desired speed or RPM range. Constant Force test routines require the PAU to be set slightly torque deficient as referenced to prime mover output to allow some rate of acceleration. Power is calculated based on torque x RPM / 5252 + calculated power required for the acceleration rate that occurred.

Constant Speed

If the dynamometer has a speed regulator (human or computer), the PAU provides a variable mount of braking force (torque) that is necessary to cause the prime mover to operate at the desired single test speed or RPM. The PAU braking load applied to the prime mover to can be manually controlled or determined by a computer. Most systems employ eddy current, oil hydraulic or DC motor produced loads because of their linear and quick load change ability.

Power is calculated based on torque x RPM / 5252.

A motoring dynamometer acts as a motor that drives the equipment under test. It must be able to drive the equipment at any speed and develop any level of torque that the test requires. In common usage, AC or DC motors are used to drive the equipment or "load" device.

In most dynamometers power (P) is not measured directly; it must be calculated from torque (τ) and angular velocity (ω) values or force (F) and linear velocity (v):

$$P = \tau \cdot \omega$$

or

$$P = F \cdot v$$

where

P is the power in watts

τ is the torque in newton metres

ω is the angular velocity in radians per second

F is the force in newtons

v is the linear velocity in metres per second

Division by a conversion constant may be required depending on the units of measure used.

For imperial units,

$$P_{\mathrm{hp}} = \frac{\tau_{\mathrm{lb \cdot ft}} \cdot \omega_{\mathrm{rpm}}}{5252}$$

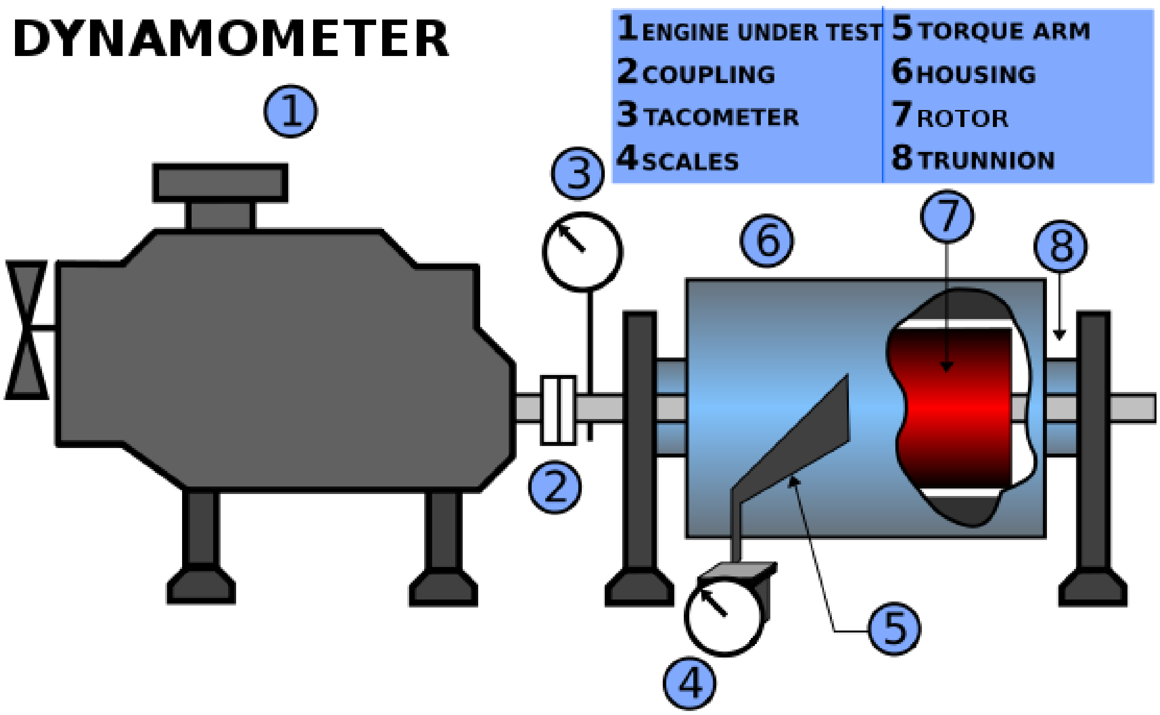
where
P_{hp} is the power in horsepower
$\tau_{\mathrm{lb \cdot ft}}$ is the torque in pound-feet
ω_{RPM} is the rotational velocity in revolutions per minute

For metric units,

$$P_{\mathrm{kW}} = \frac{\tau_{\mathrm{N \cdot m}} \cdot \omega_{\mathrm{rpm}}}{9549}$$

where
P_{kW} is the power in kilowatts
$\tau_{\mathrm{N \cdot m}}$ is the torque in newton metres
ω_{rpm} is the rotational velocity in revolutions per minute

Detailed dynamometer description



Electrical dynamometer setup showing engine, torque measurement arrangement and tachometer

A dynamometer consists of an absorption (or absorber/driver) unit, and usually includes a means for measuring torque and rotational speed. An absorption unit consists of some type of rotor in a housing. The rotor is coupled to the engine or other equipment under test and is free to rotate at whatever speed is required for the test. Some means is provided to develop a braking torque between dynamometer's rotor and housing. The means for developing torque can be frictional, hydraulic, electromagnetic etc. according to the type of absorption/driver unit.

One means for measuring torque is to mount the dynamometer housing so that it is free to turn except that it is restrained by a torque arm. The housing can be made free to rotate by using trunnions connected to each end of the housing to support the dyno in pedestal mounted trunnion bearings. The torque arm is connected to the dyno housing and a weighing scale is positioned so that it measures the force exerted by the dyno housing in attempting to rotate. The torque is the force indicated by the scales multiplied by the length of the torque arm measured from the center of the dynamometer. A load cell transducer can be substituted for the scales in order to provide an electrical signal that is proportional to torque.

Another means for measuring torque is to connect the engine to the dynamometer through a torque sensing coupling or torque transducer. A torque transducer provides an electrical signal that is proportional to torque.

With electrical absorption units, it is possible to determine torque by measuring the current drawn (or generated) by the absorber/driver. This is generally a less accurate method and not much practiced in modern times, but it may be adequate for some purposes.

When torque and speed signals are available, test data can be transmitted to a data acquisition system rather than being recorded manually. Speed and torque signals can also be recorded by a chart recorder or plotter.

Types of dynamometers

In addition to classification as *Absorption*, *Motoring* or *Universal* as described above, dynamometers can be classified in other ways.

A dyno that is coupled directly to an engine is known as an *engine dyno*.

A dyno that can measure torque and power delivered by the power train of a vehicle directly from the drive wheel or wheels (without removing the engine from the frame of the vehicle), is known as a *chassis dyno*.

Dynamometers can also be classified by the type of absorption unit or absorber/driver that they use. Some units that are capable of absorption only can be combined with a motor to construct an absorber/driver or universal dynamometer. The following types of absorption/driver units have been used:

Types of absorption/driver units

- Eddy current or electromagnetic brake (absorption only)

- Magnetic Powder brake (absorption only)
- Hysteresis Brake (absorption only)
- Electric motor/generator (absorb or drive)
- Fan brake (absorption only)
- Hydraulic brake (absorption only)
- Mechanical friction brake or Prony brake (absorption only)
- Water brake (absorption only)
- Compound dyno (usually an absorption dyno in tandem with an electric/motoring dyno)

Eddy current type absorber

EC dynamometers are currently the most common absorbers used in modern chassis dynos. The EC absorbers provide the quick load change rate for rapid load settling. Most are air cooled, but some are designed to require external water cooling systems.

Eddy current dynamometers require an electrically conductive core, shaft or disc, moving across a magnetic field to produce resistance to movement. Iron is a common material, but copper, aluminum and other conductive materials are usable.

In current (2009) applications, most EC brakes use cast iron discs, similar to vehicle disc brake rotors, and use variable electromagnets to change the magnetic field strength to control the amount of braking.

The electromagnet voltage is usually controlled by a computer, using changes in the magnetic field to match the power output being applied.

Sophisticated EC systems allow steady state and controlled acceleration rate operation.

Powder dynamometer

A powder dynamometer is similar to an eddy current dynamometer, but a fine magnetic powder is placed in the air gap between the rotor and the coil. The resulting flux lines create "chains" of metal particulate that are constantly built and broken apart during rotation creating great torque. Powder dynamometers are typically limited to lower RPM due to heat dissipation issues.

Hysteresis dynamometers

Hysteresis dynamometers, use a steel rotor that is moved through flux lines generated between magnetic pole pieces. This design, as in the usual "disc type" eddy current absorbers, allows for full torque to be produced at zero speed, as well as at full speed. Heat dissipation is assisted by forced air. Hysteresis and "disc type" EC dynamometers are one of the most efficient technologies in small (200 hp (150 kW) and less) dynamometers. A hysteresis brake is an eddy current absorber that, unlike most "disc type" eddy current absorbers, puts the electromagnet coils inside a vented and ribbed cylinder and rotates the cylinder, instead of rotating a disc between electromagnets. The potential benefit for the hysteresis absorber is that the diameter can be decreased and operating RPM of the absorber may be increased.

Electric motor/generator dynamometer

Electric motor/generator dynamometers are a specialized type of adjustable-speed drives. The absorption/driver unit can be either an alternating current (AC) motor or a direct current (DC) motor. Either an AC motor or a DC motor can operate as a generator that is driven by the unit under test or a motor that drives the unit under test. When equipped with appropriate control units, electric motor/generator dynamometers can be configured as universal dynamometers. The control unit for an AC motor is a variable-frequency drive and the control unit for a DC motor is a DC drive. In both cases, regenerative control units can transfer power from the unit under test to the electric utility. Where permitted, the operator of the dynamometer can receive payment (or credit) from the utility for the returned power.

In engine testing, universal dynamometers can not only absorb the power of the engine but also, drive the engine for measuring friction, pumping losses and other factors.

Electric motor/generator dynamometers are generally more costly and complex than other types of dynamometers.

Fan brake

A fan is used to blow air to provide engine load. Changing gearing or fan or simply measuring the max RPM attained.

Hydraulic brake

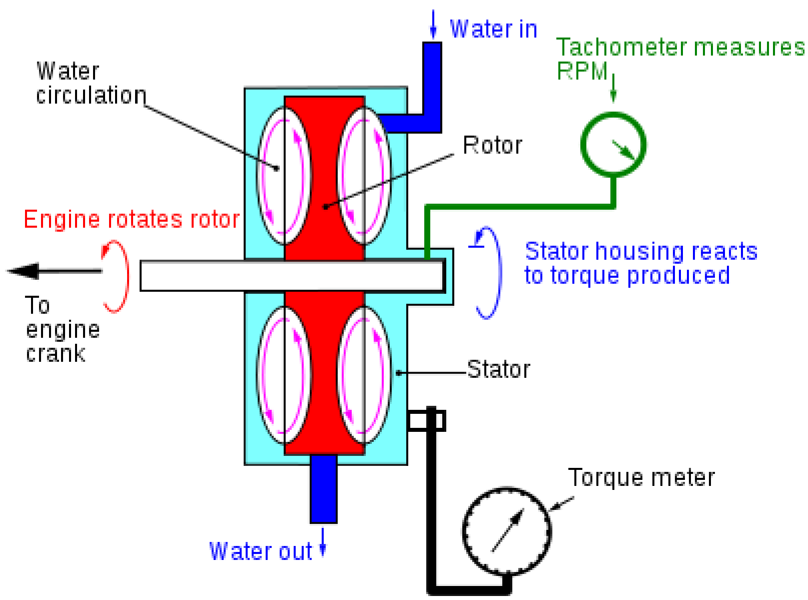
The hydraulic brake system consists of a hydraulic pump (usually a gear type pump), a fluid reservoir and piping between the two parts. Inserted in the piping is an adjustable valve and between the pump and the valve is a gauge or other means of measuring hydraulic pressure. Usually, the fluid used was hydraulic oil, but recent synthetic multi-grade oils may be a better choice. In simplest terms, the engine is brought up to the desired RPM and the valve is incrementally closed and as the pumps outlet is restricted, the load increases and the throttle is simply opened until at the desired throttle opening. Unlike most other systems, power is calculated by factoring flow volume (calculated from pump design specs), hydraulic pressure and RPM. Brake HP, whether figured with pressure, volume and RPM or with a different load cell type brake dyno, should produce essentially identical power figures. Hydraulic dynos are renowned for having the absolute quickest load change ability, just slightly surpassing the eddy current absorbers. The downside is that they require large quantities of hot oil under high pressure and the requirement for an oil reservoir.

Water brake type absorber

The water brake absorber is sometimes mistakenly called a "hydraulic dynamometer." Water brake absorbers are relatively common, having been manufactured for many years and noted for their high power capability, small package, light weight, and relatively low manufacturing cost as compared to other, quicker reacting "power absorber" types.

Their drawbacks are that they can take a relatively long period of time to "stabilize" their load amount and the fact that they require a constant supply of water to the "water brake housing" for cooling. In many parts of the country, environmental regulations now prohibit "flow through" water and large water tanks must be installed to prevent contaminated water from entering the environment.

The schematic shows the most common type of water brake, the variable level type. Water is added until the engine is held at a steady RPM against the load. Water is then kept at that level and replaced by constant draining and refilling, which is needed to carry away the heat created by absorbing the horsepower. The housing attempts to rotate in response to the torque produced but is restrained by the scale or torque metering cell that measures the torque.



This schematic shows a water brake, which is actually a fluid coupling with a housing restrained from rotating—similar to a water pump with no outlet.

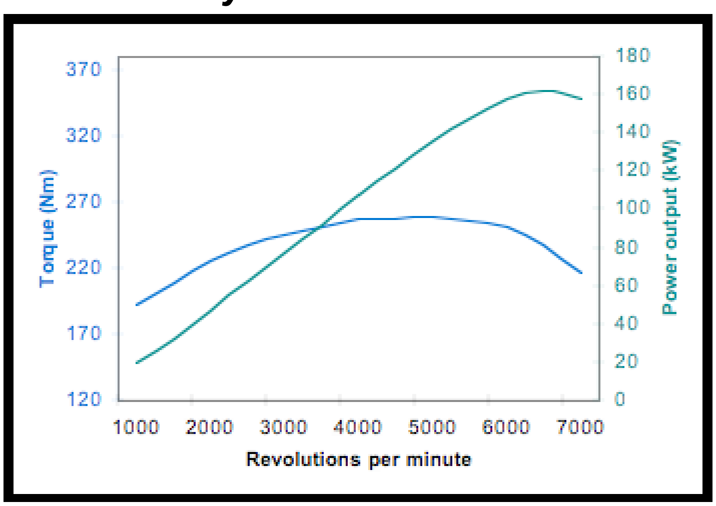
Compound Dynamometers

In most cases, motoring dynamometers are symmetrical; a 300 kW AC dynamometer can absorb 300 kW as well as motor at 300 kW. This is an uncommon requirement in engine testing and development. Sometimes, a more cost-effective solution is to attach a larger absorption dynamometer with a smaller motoring dynamometer; alternatively, a larger absorption dynamometer and a simple AC or DC motor may be used in a similar manner with the electric motor only providing motoring power when required and no absorption. The (cheaper) absorption dynamometer is sized for the maximum required absorption, whereas the motoring dynamometer is sized for motoring. A typical size ratio for common emission test cycles and most engine development is approximately 3:1. Torque measurement is somewhat complicated since there are two machines in tandem; an inline torque transducer is the preferred method of torque measurement in this case. An eddy-current or waterbrake dynamometer with electronic control combined with a variable frequency drive and AC induction motor is a commonly used configuration of this type. Disadvantages include requiring a second set of test cell services (electrical power and cooling), and a slightly more complicated control system. Attention must be paid to the transition between motoring and braking in terms of control stability.

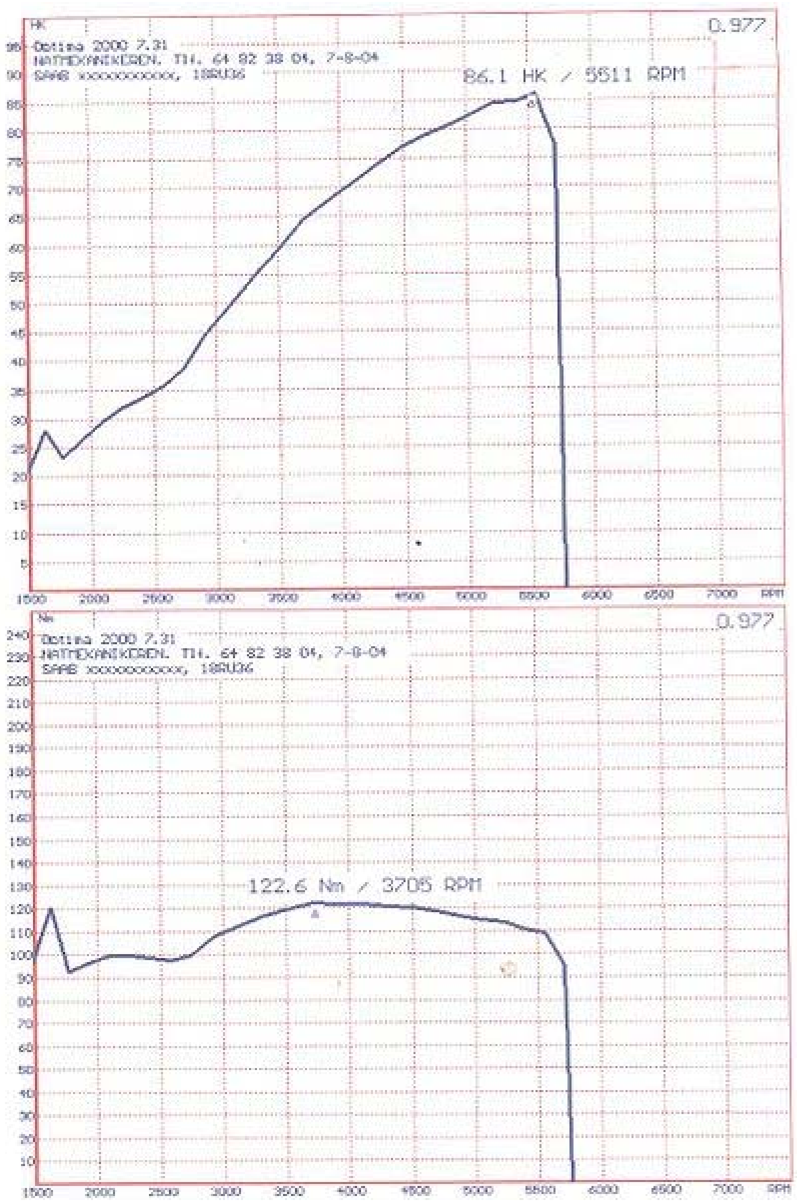
How dynamometers are used for engine testing

Dynamometers are useful in the development and refinement of modern day engine technology. The concept is to use a dyno to measure and compare power transfer at different points on a vehicle, thus allowing the engine or drivetrain to be modified to get more efficient power transfer. For example, if an engine dyno shows that a particular engine achieves 400 N·m (300 lbf·ft) of torque, and a chassis dynamo shows only 350 N·m (260 lbf·ft), one would know to look to the drivetrain for the major improvements. Dynamometers are typically very expensive pieces of equipment, reserved for certain fields that rely on them for a particular purpose.

Types of dynamometer systems



Dyno graph 1



Dyno graph 2

A **brake** dynamometer applies variable load on the Prime Mover (PM) and measures the PM's ability to move or hold the RPM as related to the "braking force" applied. It is usually connected to a computer that records applied braking torque and calculates engine power output based on information from a "load cell" or "strain gauge" and RPM (speed sensor).

An **inertia** dynamometer provides a fixed inertial mass load and calculates the power required to accelerate that fixed, known mass and uses a computer to record RPM and acc. rate to calculate torque. The engine is generally tested from somewhat above idle to its maximum RPM and the output is measured and plotted on a graph.

A **motoring** dynamometer provides the features of a brake dyne system, but in addition, can "power" (usually with an AC or DC motor) the Prime Mover (PM) and allow testing of very small power small outputs. Example, duplicating speeds and loads that are experienced when operating a vehicle traveling downhill or on/off throttle operations.

There are essentially 3 types of dynamometer test procedures

1. Steady state (only on brake dynamometers), where the engine is held at a specified RPM (or series of usually sequential RPMs) for a desired amount of time by the variable brake loading as provided by the PAU (power absorber unit)
2. Sweep test (on inertia or brake dynamometers), where the engine is tested under a load (inertia or brake loading), but allowed to "sweep" up in RPM in a continuous fashion, from a specified lower "starting" RPM to a specified "end" RPM
3. Transient test (usually on AC or DC dynamometers), where the engine power and speed are varied throughout the test cycle. Different test cycles are used in different jurisdictions. Chassis test cycles include the US light-duty UDDS, HWFET, US06, SC03, ECE, EUDC, and CD34. Engine test cycles include ETC, HDDTC, HDGTC, WHTC, WHSC, and ED12.

Types of Sweep Tests:

1. **Inertia sweep**: An inertia dyno system provides a fixed inertial mass flywheel and computes the power required to accelerate the flywheel (load) from the starting to the ending RPM. The actual rotational mass of the engine or engine and vehicle in the case of a chassis dyno is not known and the variability of even tire mass will skew power results. The inertia value of the flywheel is "fixed," so low power engines are under load for a much longer time and internal engine temperatures are usually too high by the end of the test, skewing optimal "dyno" tuning settings away from the outside world's optimal tuning settings. Conversely, high powered engines, commonly complete a common "4th gear sweep" test in less than 10 seconds, which is not a reliable load condition as compared to operation in the outside world. By not providing enough time under load, internal combustion chamber temps are unrealistically low and power readings, especially past the power peak, are skewed low.

1. **Loaded Sweep Tests** (brake dyno type) consist of 2 types:
    1. **Simple fixed Load Sweep Test**: A fixed load, of somewhat less than the engine's output, is applied during the test. The engine is allowed to accelerate from its starting RPM to its ending RPM, varying in its own acceleration rate, depending on power output at any particular RPM point Power is calculated using torque * RPM / 5252 + the power required to accelerate the dyno and engine's / vehicle's rotating mass.
    2. **Controlled Acceleration Sweep Test**: Similar in basic usage as the above Simple fixed Load Sweep Test, but with the addition of active load control that targets a specific rate of acceleration. Commonly, 20fps/ps is used.

Controlled Acceleration Rate test is that the acc. rate used is controlled from low power to high power engines and over extension and contraction of "test duration" is avoided, providing more repeatable tests and tuning results.

In every Sweep Test, there is still the remaining issue of potential power reading error due to the variable engine / dyno / vehicle total rotating mass. Many modern computer controlled brake dyno systems are capable of deriving that "inertial mass" value to eliminate the error.

Interestingly, A "sweep test" will always be suspect, as many "sweep" users ignore the rotating mass factor and prefer to use a blanket "factor" on every test, on every engine or vehicle. Simple inertia dyne systems aren't capable of deriving "inertial mass" and are forced to use the same assumed inertial mass on every vehicle.

Using Steady State testing eliminates a Sweep Test rotating inertial mass error , as there is no acceleration during a Steady State test.

Transient Test Characteristics: Aggressive throttle movements, engine speed changes, and engine motoring are characteristics of most transient engine tests. The usual purpose of these tests are for vehicle emissions development and homologation. In some cases, the lower-cost eddy-current dynamometer is used to test one of the transient test cycles for early development and calibration. An eddy current dyne system offers fast load response, which allows rapid tracking of speed and load, but does not allow motoring. Since most required transient tests contain a significant amount of motoring operation, a transient test cycle with an eddy-current dyno will generate different emissions test results. Final adjustments are required to be done on a motoring-capable dyno.

Engine dynamometer

HORIBA engine dynamometer TITAN

An engine dynamometer measures power and torque directly from the engine's crankshaft (or flywheel), when the engine is removed from the vehicle. These dynos do not account for power losses in the drivetrain, such as the gearbox, transmission or differential etc.

Chassis dynamometer

Saab 96 on chassis dynamometer

AVL ROADSIM Light and medium duty vehicle chassis dynamometer for exhaust emission testing (Homologation) and other applications

A chassis dynamometer measures power delivered to the surface of the "drive roller" by the drive wheels. The vehicle is often parked on the roller or rollers, which the car then turns and the output is measured.

Modern roller type chassis dyne systems use the Salvisberg roller, which improved traction and repeatability over smooth or knurled drive rollers.

On a motorcycle, typical power loss at higher power levels, mostly through tire flex, is about 10% and gearbox chain and other power transferring parts are another 2% to 5%.

Other types of chassis dynamometers are available that eliminate the potential wheel slippage on old style drive rollers and attach directly to the vehicle's hubs for direct torque measurement from the axle. Hub mounted dynos include units made by Dynapack and Rototest.

Chassis dynos can be fixed or portable.

Modern chassis dynamometers can do much more than display RPM, horsepower, and torque. With modern electronics and quick reacting, low inertia dyne systems, it is now possible to tune to best power and the smoothest runs, in realtime.

In retail settings it is also common to "tune the air fuel ratio" , using a wideband oxygen sensor that is graphed along with RPM.

Some, dyne systems can also add vehicle diagnostic information to the dyno graph as well. This is done by gathering data directly from the vehicle using on-board diagnostics communication.

Emissions development and homologation dynamometer test systems often integrate emissions sampling, measurement, engine speed and load control, data acquisition, and safety monitoring into a complete test cell system. These test systems usually include complex emissions sampling equipment (such as constant volume samplers or raw exhaust gas sample preparation systems), and exhaust emissions analyzers. These analyzers are much more sensitive and much faster than a typical portable exhaust gas analyzer. Response times of well under one second are common and required by many transient test cycles.

Integration of the dynamometer control system along with automatic calibration tools for engine system calibration is often found in development test cell systems. In these test cell systems, the dynamometer load and engine speed are varied to many engine operating points, and selected engine management parameters are varied and the results recorded automatically. Later analysis of this data may then be used to generate engine calibration data used by the engine management software.

Because of frictional and mechanical losses in the various drivetrain components, the measured rear wheel brake horsepower is generally 15-20 percent less than the brake horsepower measured at the crankshaft or flywheel on an engine dynamometer. Other sources, after researching several different "engine" dyno software packages, found that the engine dyno user can integrally add "frictional loss" channel factors of +10% to +15% to the flywheel power, raising the claim that 20% to 25% or even more power is actually lost between the crankshaft at high power outputs.

Common misconceptions about dynos

Drag racing: 1/4 mile prediction based on dynamometer measured power

Horsepower figures are a strong predictor but do not guarantee a specific 0-60 mph, 1/4 mile elapsed time (ET) or 1/4 mile speed. An engine accelerating in a vehicle experiences different conditions than on a dyno. G forces and different temperatures as well as different modes of vibration in a vehicle can cause significant differences in power output.

Inexpensive "inertia dynamometers" commonly provide insufficient loading, and complete their "test" in less time than the real world 1/4 mile takes, causing inherent power value errors, due to unrealistic internal engine temperatures.

More sophisticated dyne systems are capable of "loaded testing," which can potentially recreate the same temperatures as on the drag strip.

In engineering units, the power figures used should be "True" or "Effective" horsepower scale.

Engine damage: Can dyno testing damage engines?

A brake dyno, in steady state mode only provides a load that is equal the amount of power that the engine is making at any specifically selected RPM point. If the engine makes 200 brake HP at 5000 RPM, the dynamometer's brake or power absorber will provide exactly 200 hp (150 kW) of load against it, keeping the RPM at 5000 RPM.

That's a realistic load that simulates a vehicle pulling a large trailer up a hill. It should be no problem on the dyno if there's no problem on the road.

Apprehension over dyno testing and engine damage has solid roots in fact. Old style dynamometers commonly used an inexpensive water brake type of power absorber. Load was increased or decreased by filling and draining water in the housing to change the amount of internal water volume to change the load, all the while draining and refilling the water to keep the water from boiling. It would sometimes take some time for the operator or computer to stabilize inflow and outflow rates. That extra time could pose a risk to engines.

Water brakes are still commonly used in applications where their small size and light weight are important and engine torque curves are relatively straight, as in large automotive and boats.

Engine testing may damage engines primarily due to insufficient instrumentation, insufficient safety monitoring systems, and insufficient cooling. An engine on a dyno does not receive air cooling due to engine speeds. Automotive engines are not typically designed for wide-open throttle operation for extended periods of time; internal components may overheat and fail.

History

Gaspard de Prony invented the de Prony brake in 1821. The de Prony brake (or Prony brake) is considered to be one of the earliest dynamometers.

Froude Hofmann of Worcester, UK, manufactures engine and vehicle dynamometers. They credit William Froude with the invention of the hydraulic dynamometer in 1877 and say that the first commercial dynamometers were produced in 1881 by their predecessor company, Heenan & Froude.

In 1928, the German company "*Carl Schenck Eisengießerei & Waagenfabrik*" built the first vehicle dynamometers for brake tests with the basic design of the today's vehicle test stands.

The eddy current dynamometer was invented by Martin and Anthony Winther in about 1931. At that time, DC Motor/generator dynamometers had been in use for many years. A company founded by the Winthers, Dynamatic Corporation, manufactured dynamometers in Kenosha, Wisconsin until 2002. Dynamatic was part of Eaton Corporation from 1946 to 1995. In 2002, Dyne Systems of Jackson, Wisconsin acquired the Dynamatic dynamometer product line. Starting in 1938, Heenan & Froude manufactured eddy current dynamometers for many years under license from Dynamatic and Eaton.

Chapter 11

Air-Fuel Ratio Meter & Air Flow Bench

Air-Fuel Ratio Meter

An **air-fuel ratio meter** monitors the air-fuel ratio of an internal combustion engine. Also called **air-fuel ratio gauge**, **air-fuel meter**, or **air-fuel gauge**. It reads the voltage output of an oxygen sensor, sometimes also called lambda sensor, whether it be from a *narrow band* or *wide band* oxygen sensor.

The original narrow band oxygen sensors became factory installed standard in the late 70's and early 80's. In recent years, a newer and much more accurate 'wide band' sensor, though more expensive, has become available.

Most stand-alone narrow band meters have 10 LEDs and some have more. Also common, narrow band meters in round housings with the standard mounting 2 1/16" and 2 5/8" diameters, as other types of car 'gauges'. These usually have 10 or 20 LEDs. Analogue 'needle' style gauges are also available.

As stated above, there are wide band meters that stand alone or are mounted in housings. Nearly all of these show the air-fuel ratio on a numeric display, since the wide band sensors provide a much more accurate reading. And since they use more accurate electronics, these meters are more expensive.

Benefits of air-fuel ratio metering

- Determining the condition of the oxygen sensor: A malfunctioning oxygen sensor will result in air-fuel ratios which respond more slowly to changing engine conditions. A damaged or defective sensor may lead to increased fuel consumption and increased pollutant emissions as well as decreased power, and throttle response.
- Reducing emissions: Keeping the air-fuel mixture near the stoichiometric ratio of 14.7:1 (for gasoline engines) allows the catalytic converter to operate at maximum efficiency.

- Fuel economy: An air-fuel mixture leaner than the stoichiometric ratio will result in near optimum fuel mileage, costing less per mile traveled and producing the least amount of CO_2 emissions. However, from the factory, cars are designed to operate at the stoichiometric ratio (rather than as lean as possible while remaining driveable) in order to maximize the efficiency and life of the catalytic converter. While it may be possible to run smoothly at mixtures leaner than the stoichiometric ratio, manufacturers must focus on emissions and especially catalytic converter life (which must now be 100,000 miles on new vehicles) as a higher priority due to U.S. EPA regulations.
- Engine performance: Carefully mapping out air-fuel ratios throughout the range of rpm and manifold pressure will maximize power output in addition to reducing the risk of detonation.

Lean mixtures improve the fuel economy but also cause sharp rises in the amount of nitrogen oxides (NOX). If the mixture becomes too lean, the engine may fail to ignite, causing misfire and a large increase in unburned hydrocarbon (HC) emissions. Lean mixtures burn hotter and may cause rough idle, hard starting and stalling, and can even damage the catalytic converter, or burn valves in the engine. The risk of spark knock/engine knocking (detonation) is also increased when the engine is under load.

Mixtures that are richer than stoichiometric allow for greater peak engine power when using vapourized liquid fuels, due to the cooling effect of the evaporating fuel. This increases the intake oxygen density, allowing for more fuel to be combusted and more power developed. The ideal mixture in this type of operation depends on the individual engine. For example, engines with forced induction such as turbochargers and superchargers typically require a richer mixture under wide open throttle than naturally aspirated engines. Forced induction engines can be catastrophically damaged by burning too lean for too long. The leaner the air/fuel mixture, the higher the combustion temperature is inside the cylinder. Too high a temperature will destroy an engine - melting the pistons and valves. This can happen if you port the head and/or manifolds or increase boost without compensating by installing larger or more injectors, and/or increasing the fuel pressure to a sufficient level. Conversely, engine performance can be lessened by increasing fuelling without increasing air flow into the engine.

Cold engines also typically require more fuel and a richer mixture when first started (see: cold start injector), because fuel does not vaporize as well when cold and therefore requires more fuel to properly "saturate" the air. Rich mixtures also burn slower and decrease the risk of spark knock/engine knocking (detonation) when the engine is under load. However, rich mixtures sharply increase carbon monoxide (CO) emissions.

Oxygen sensor types

Oxygen sensors are installed in the exhaust system of the vehicle, attached to the engine's exhaust manifold, the sensor measures the ratio of the air-fuel mixture.

As mentioned above, there are two types of sensors available; narrow band and wide band. Narrow band sensors were the first to be introduced. The wide band sensor was introduced much later.

A narrow band sensor has a non-linear output, and switches between the thresholds of lean (ca 100-200 mV) and rich (ca 650-800 mV) areas very steeply.

Also, narrow band sensors are temperature-dependent. If the exhaust gases become warmer, the output voltage in the lean area will rise, and in the rich area it will be lowered. Consequently, a sensor, without pre-heating has a lower lean-output and a higher rich-output, possibly even exceeding 1 Volt. The influence of temperature to voltage is smaller in the lean mode than in the rich mode.

A "cold" engine makes the sensor switch the output voltage between ca 100 and 850/900 mV and after a while the sensor may output a switch voltage between ca 200 and 700/750mV, for turbocharged cars even less.

The Engine Control Unit (ECU) tries to maintain a stoichiometric balance, wherein the air-fuel mixture is approximately 14.7 times the mass of air to fuel for gasoline. This ratio is selected in order to maintain a neutral engine performance (lower fuel consumption yet decent engine power and minimal pollution).

The average level of the sensor is defined as 450 mV. Since narrow band sensors cannot output a fixed voltage level between the lean and the rich areas, the ECU tries to control the engine by controlling the mixture between lean and rich in such a sufficiently fast manner, that the average level becomes ca 450 mV.

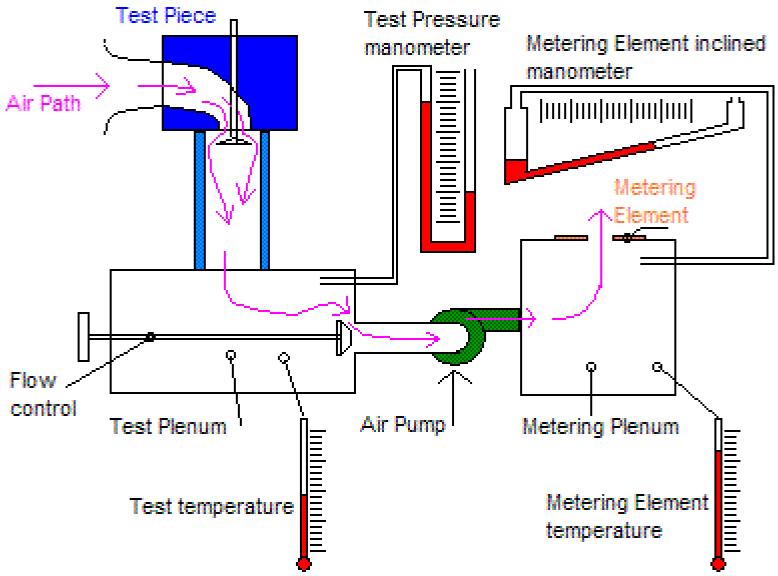
A wide band sensor, on the other hand, has a very linear output, 0 - 5 V, and is not temperature dependent.

Which type of air-fuel ratio meter to be used

If the purpose of the air-fuel ratio meter is to diagnose an existing or possible problem with the sensor and/or to check the general mixture and performance, a narrow band air-fuel ratio meter is sufficient.

In high-performance tuning applications the wide-band system is desirable.

Air Flow Bench



Typical Flow Bench schematic

An **air flow bench** is a device used for testing the internal aerodynamic qualities of an engine component and is related to the more familiar wind tunnel.

Used primarily for testing the intake and exhaust ports of cylinder heads of internal combustion engines. It is also used to test the flow capabilities of any component such as air filters, carburetors, manifolds or any other part that is required to flow gas. It is one of the primary tools of high performance engine builders and porting cylinder heads would be strictly hit or miss without it.

A flow bench consists of an air pump of some sort, a metering element, pressure and temperature measuring instruments such as manometers, and various controls. The test piece is attached in series with the pump and measuring element and air is pumped through the whole system. Therefore all the air passing through the metering element also passes through the test piece. Because the flow through the metering element is known and the flow through the test piece is the same, it is also known.

Air pump

The air pump used must be able to deliver the volume required at the pressure required. Most flow testing is done at 10 and 28 inches of water pressure (2.5 to 7 kilopascals). Although other test pressures will work, the results would have to be converted for comparison to the work of others. The pressure developed must account for the test pressure plus the loss across the metering element plus all other system losses. The greater the accuracy of the metering element the greater is the loss. Flow volume of between 100 and 600 cubic feet per minute (0.05 to 0.28 m^3/s) would serve almost all applications depending on the size of the engine under test.

Any type of pump that can deliver the required pressure difference and flow volume can be used. Most often used is the centrifugal dynamic type, which is familiar to most as a vacuum cleaner. Multistaged axial-flow fan types and positive displacement types (piston and rotary) could also be used with suitable provisions for damping the pulsations. The pressure ratio of a single fan blade is too low and cannot be used.

Metering element

There are several possible types of metering element in use. Flow benches ordinarily use three types: orifice plate, venturi meter and pitot/static tube, all of which deliver similar accuracy. Most commercial machines use orifice plates due to their simple construction. Although the venturi offers substantial improvements in efficiency, its cost is higher

Instrumentation

Air flow conditions must be measured at two locations, across the test piece and across the metering element. The pressure difference across the test piece allows the standardization of tests from one to another. The pressure across the metering element allows calculation of the actual flow through the whole system.

The pressure across the test piece is typically measured with a U tune manometer while, for increased sensitivity and accuracy, the pressure difference across the metering element is measured with an inclined manometer. One end of each manometer is connected to its respective plenum chamber while the other is open to the atmosphere.

Ordinarily all flow bench manometers measure in inches of water although the inclined manometer's scale is usually replaced with a logarithmic scale reading in percentage of total flow of the selected metering element which makes flow calculation simpler.

Temperature must also be accounted for because the air pump will heat the air passing through it making the air down stream of it less dense and more viscous. This difference must be corrected for. Temperature is measured at the test piece plenum and at the metering element plenum. Correction factors are then applied during flow calculations. Some flow bench designs place the air pump after the metering element so that heating by the air pump is not as large a concern.

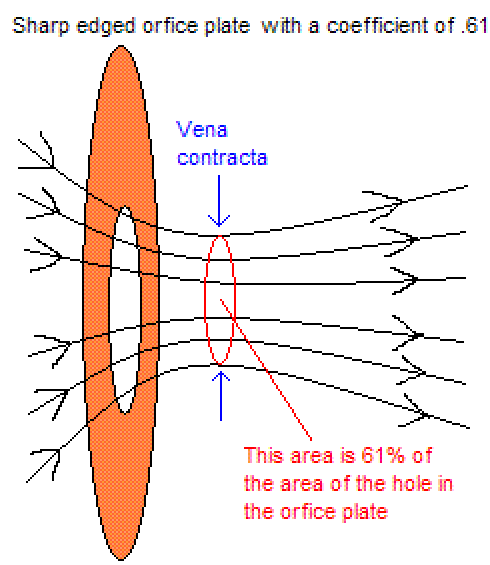
Additional manometers can be installed for use with hand held probes, which are used to explore local flow conditions in the port.

Flow bench data

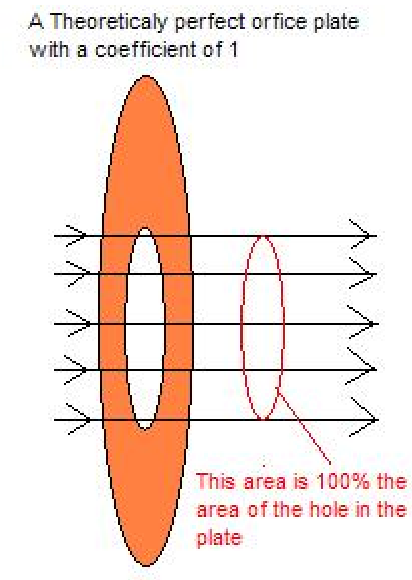
The air flow bench can give a wealth of data about the characteristics of a cylinder head or whatever part is tested. The result of main interest is bulk flow. It is the volume of air that flows through the port in a given time. Expressed in cubic feet per minute or cubic meters per second/minute.

Valve lift can be expressed as an actual dimension in decimal inches or mm. It can also be specified as a ratio between a characteristic diameter and the lift *L*/*D*. Most often used is the valve head diameter. Normally engines have an *L*/*D* ratio from 0 up to a maximum of .35. For example, a 1-inch-diameter (25 mm) valve would be lifted a maximum of 0.350 inch. During flow testing the valve would be set at *L*/*D* .05 .1 .15 .2 .25 .3 and readings taken successively. This allows the comparison of efficiencies of ports with other valve sizes, as the valve lift is proportional rather than absolute. For comparison with tests by others the characteristic diameter used to determine lift must be the same.

Flow coefficients are determined by comparing the actual flow of a test piece to the theoretical flow of a perfect orifice of equal area. Thus the flow coefficient should be a close measure of efficiency. It cannot be exact because the *L*/*D* does not indicate the actual minimum size of the duct.



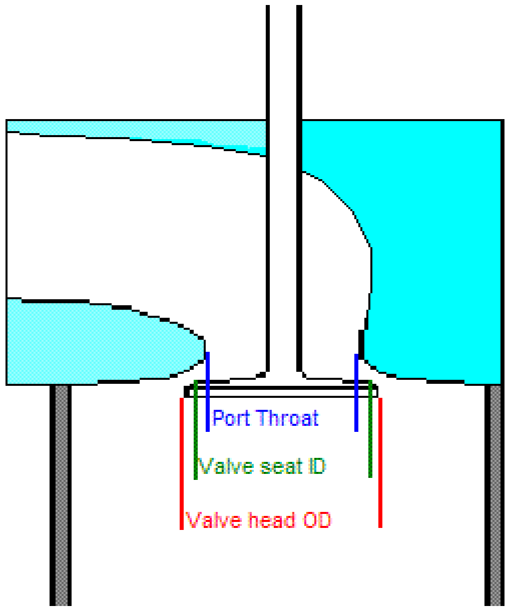
A real orifice plate showing how the fluid would actually flow



A theoretical orifice plate showing perfect flow which is used as a standard for comparing the efficiencies of real flows

An orifice with a flow coefficient of .59 would flow the same amount of fluid as a perfect orifice with 59% of its area or 59% of the flow of a perfect orifice with the same area (orifice plates of the type shown would have a coefficient of between .58 and .62 depending on the precise details of construction and the surrounding installation).

Valve/port coefficient is non dimensional and is derived by multiplying a characteristic physical area of the port and by the bulk flow figures and comparing the result to an ideal orifice of the same area. It is here that air flow bench norms differ from fluid dynamics or aerodynamics at large. The coefficient may be based on the inner valve seat diameter, the outer valve head diameter, the port throat area or the valve open curtain area. Each of these methods are valid for some purpose but none of them represents the true minimum area for the valve/port in question and each results in a different flow coefficient. The great difficulty of measuring the actual minimum area at all the various valve lifts precludes using this as a characteristic measurement. This is due to the minimum area changing shape and location throughout the lift cycle. Because of this non standardization, port flow coefficients are not "true" flow coefficients, which would be based on the actual minimum area in the flow path. Which method to choose depends on what use is intended for the data. Engine simulation applications each require their own specification. If the result is to be compared to the work of others then the same method would have to be selected.



Various characteristic measurements used to determine flow coefficients

Using extra instrumentation (manometers and probes) the detailed flow through the port can be mapped by measuring multiple points within the port with probes. Using these tools, the velocity profile throughout the port can be mapped which gives insight into what the port is doing and what might be done to improve it.

Of less interest is mass flow per minute or second since the test is not of a running engine which would be affected by it. It is the weight of air that flows through the port in a given time. Expressed in pounds per minute/hour or kilograms per second/minute. Mass flow is derived from the volume flow result to which a density correction is applied.

With the information gathered on the flow bench, engine power curve and system dynamics can be roughly estimated by applying various formulae. With the advent of accurate engine simulation software, however, it is much more useful to use flow data to create an engine model for a simulator.

Determining air velocity is a useful part of flow testing. It is calculated as follows:

For one set of English units

$$V = 1096.7\sqrt{H/d}$$

Where:

V = Velocity in feet per minute
H = Pressure drop across test piece in inches of water measured by the test pressure manometer

d = density of air in pounds per cubic foot (*0.075 pound per cubic foot at standard conditions*)

For SI units

$$V = \sqrt{H/d}$$

Where:

V = Velocity in meters per second
H = Pressure drop across test piece in pascals measured by the test pressure manometer
d = density of air in kilograms per cubic meter (*1.20 kilograms per cubic meter at standard conditions*)

This represents the highest speed of the air in the flow path, at or near the section of minimum area (*through the valve seat at low values of L/D for instance*).

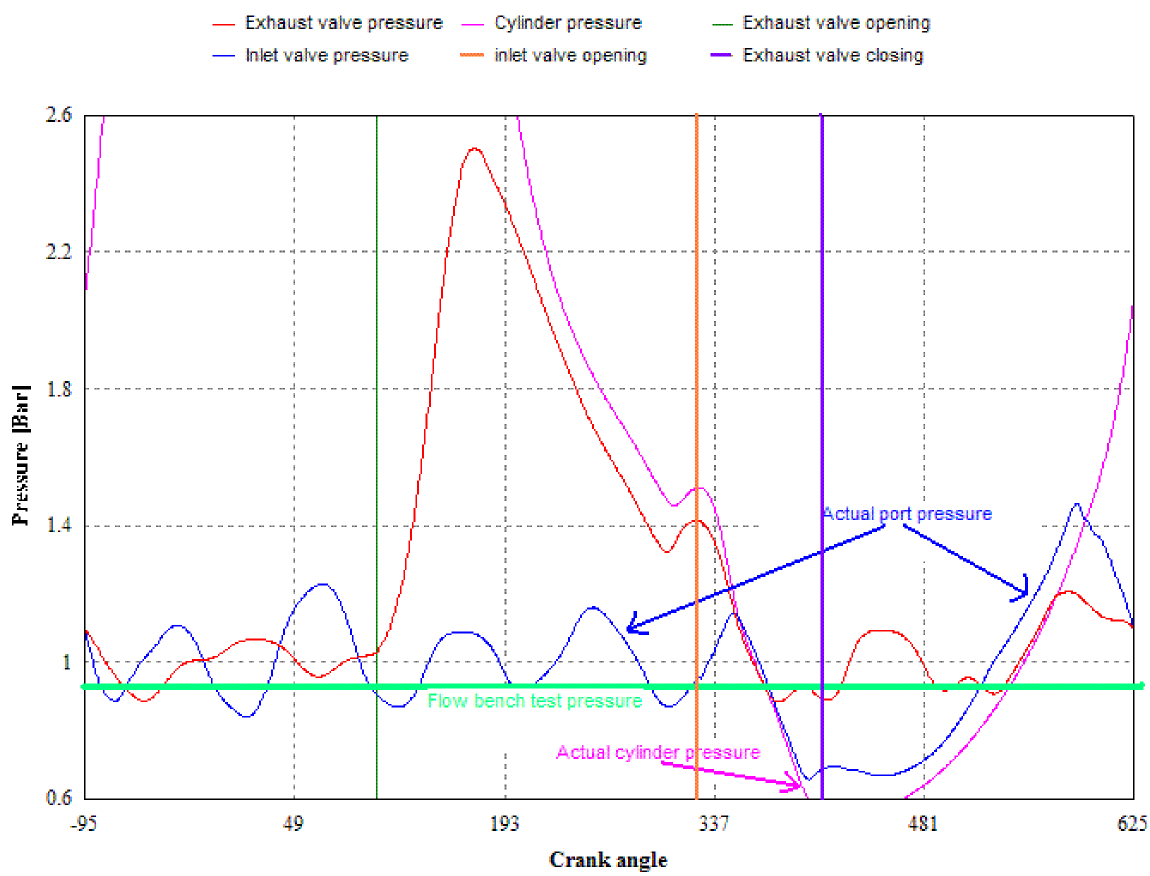
Once velocity has been calculated, the volume can be calculated by multiplying the velocity by the orifice area times its flow coefficient.

Limitations

A flow bench is capable of giving flow data which is closely but not perfectly related to actual engine performance. There are a number of limiting factors which contribute to the discrepancy.

Steady state flow vs dynamic flow

A flow bench tests ports under a steady pressure difference while in the actual engine the pressure difference varies widely during the whole cycle. The exact flow conditions existing in the flow bench test exist only fleetingly if at all in an actual running engine. Running engines cause the air to flow in strong waves rather than the steady stream of the flow bench. This acceleration/deceleration of the fuel/air column causes effects not accounted for in flow bench tests.



Comparison of flow bench test pressure to actual engine pressures predicted by an engine simulation program

This graph, generated with an engine simulation program, shows how widely the pressures vary in a running engine vs. the steady test pressure of the flow bench.

(**Note**, on the graph, that, in this case, when the intake valve opens, the cylinder pressure is above atmospheric (nearly 50% above or 1.5 bar or 150 kPa). This will cause ***reverse*** flow into the intake port until pressure in the cylinder falls below the ports pressure).

Pressure differential

The coefficient of the port ***may*** change somewhat at different pressure differentials due to changes in Reynolds number regime leading to a possible loss of dynamic similitude. Flow bench test pressure are typically conducted at 10 to 28 inches of water (2.5 to 7 kPa) while a real engine may see 190 inches of water (47 kPa) pressure difference.

Air only vs mixed gas/fuel mist flow

The flow bench tests using only air while a real engine usually uses air mixed with fuel droplets and fuel vapor, which is significantly different. Evaporating fuel passing through the port-runner has the effect of adding gas to and lowering the temperature of the air stream along the runner and giving the outlet flow rate slightly higher than the flow rate entering the port-runner. A port which flows dry air well might cause fuel droplets to fall out of suspension causing a loss of power not indicated by flow figures alone.

Bulk flow vs flow velocity

Large ports and valves can show high flow rates on a flow bench but the velocity can be lowered to the point that the gas dynamics of a real engine are ruined. Overly large ports also contribute to fuel fall out.

Even room temperature vs. uneven high temperature

A running engine is much hotter than room temperature and the temperature in various parts of the system vary widely. This affects the actual flow, fuel effects as well as the dynamic wave effects in the engine which do not exist on the flow bench.

Physical and mechanical differences

The proximity, shape and movement of the piston as well as the movement of the valve itself significantly alters the flow conditions in a real engine that do not exist in flow bench tests.

Exhaust port conditions

The flow simulated on a flow bench bears almost no similarity to the flow in a real exhaust port. Here even the coefficients measured on flow benches are inaccurate. This is due to the very high and wide ranging pressures and temperatures. From the graph above it can be seen that the pressure in the port reaches 2.5 bar (250 kPa) and the cylinder pressure at opening is 6 bar (600 kPa) and more. This is many times more than the capabilities of a typical flow bench of 0.06 bar (6 kPa).

The flow in a real exhaust port can easily be sonic with choked flow occurring and even supersonic flow in areas. The very high temperature causes the viscosity of the gas to increase, all of which alters the Reynolds number drastically.

Added to the above is the profound effect that downstream elements have on the flow of the exhaust port. Far more than upstream elements found on the intake side.

Exhaust port size and flow information might be considered as vague, but there are certain guidelines which are used when creating a base-line to optimum performance. This base line, of course, is further tuned and qualified through a dynometer.

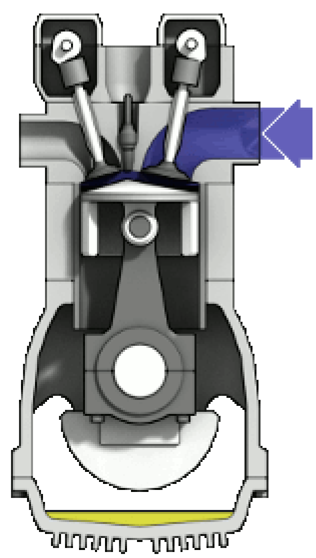
In a given 2-Valve push-rod engine, it's common to see exhaust port sizes roughly 60% the size of the intake. 2-Valve push-rod engines, regardless of how well tuned, don't flow well nor are capable of 100% volumetric efficiency with out extreme amounts of work done, which would make them unsuitable for daily driven applications. Due to the poor flowing characteristics, these styles of engines typically make more torque than horsepower. In that regard, it's often held that complimenting the engine's strengths will offer the best gains. Thusly, exhaust ports and valves are sized much smaller as to facilitate the production of torque.

In a given 4-valve Dual Over Head Cam (DOHC), the head is capable of both far greater flow and velocity characteristics, and is thusly tuned for this. The standard practice for a naturally aspirated 4-valve DOHC engine is to match both the exhaust valves and flow to roughly 85% of the intake size, which compliments horsepower rather than torque. Because DOHC engines flow better than conventional 2-valve engines, the entire combustion process operates at a lower temperature and a higher quality of oxygen concentration is realized with in the cylinder. These two factors contribute largely to the volumetric efficiency of this head design, which typically boasts better fuel economy and performance than 2-valve pushrod engines.

Lastly, in forced-induction applications, an exhaust valve and flow can be as-large-as the intake side – or larger. The notion is that an engine running 1 bar of boost is taking in twice as much as it could on its own, thus there will be roughly twice the exhaust to expunge. To encourage the best flow of exhaust, and quality of oxygen concentration in the cylinder, it's common for turbo/supercharged camshaft profiles to have a little overlap so that both the intake and exhaust valves are open at the same time so that the intake air assists in expunging the cylinder.

Chapter 12

Four-Stroke Engine



Four-stroke cycle used in gasoline/petrol engines. The right blue side is the intake and the left yellow side is the exhaust. The cylinder wall is a thin sleeve surrounded by cooling water.

Today, internal combustion engines in cars, trucks, motorcycles, aircraft, construction machinery and many others, most commonly use a **four-stroke cycle**. The four strokes refer to intake, compression, combustion (power), and exhaust strokes that occur during two crankshaft rotations per working cycle of the gasoline engine and diesel engine.

The cycle begins at *Top Dead Center* (TDC), when the piston is farthest away from the axis of the crankshaft. A stroke refers to the full travel of the piston from Top Dead Center (TDC) to Bottom Dead Center (BDC).

1. INTAKE stroke: On the *intake* or *induction* stroke of the piston , the piston descends from the top of the cylinder to the bottom of the cylinder, reducing the pressure inside the cylinder. A mixture of fuel and air is forced by atmospheric (or greater) pressure into the cylinder through the intake port. The intake valve(s) then close.

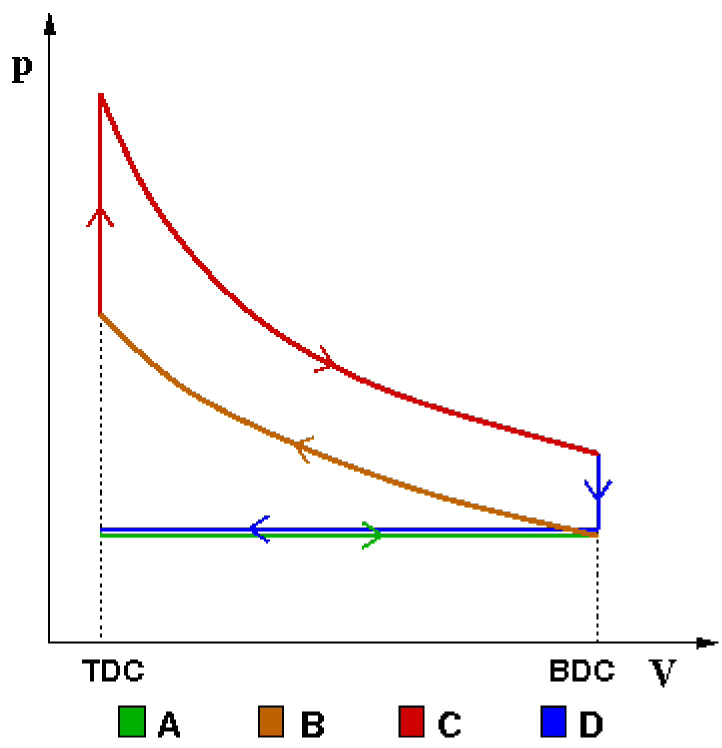
2. COMPRESSION stroke: With both intake and exhaust valves closed, the piston returns to the top of the cylinder compressing the fuel-air mixture. This is known as the *compression* stroke.

3. POWER stroke.: While the piston is close to Top Dead Center, the compressed air–fuel mixture is ignited, usually by a spark plug (for a gasoline or Otto cycle engine) or by the heat and pressure of compression (for a diesel cycle or compression ignition engine). The resulting massive pressure from the combustion of the compressed fuel-air mixture drives the piston back down toward bottom dead center with tremendous force. This is known as the *power* stroke, which is the main source of the engine's torque and power.

4. EXHAUST stroke.: During the *exhaust* stroke, the piston once again returns to top dead center while the exhaust valve is open. This action evacuates the products of combustion from the cylinder by pushing the spent fuel-air mixture through the exhaust valve(s).

History

The Otto cycle



The idealized four-stroke Otto cycle p-V diagram: the intake (A) stroke is performed by an isobaric expansion, followed by the compression (B) stroke, performed by an adiabatic compression. Through the combustion of fuel an isochoric process is produced, followed by an adiabatic expansion, characterizing the power (C) stroke. The cycle is closed by an isochoric process and an isobaric compression, characterizing the exhaust (D) stroke.

The four-stroke engine was first patented by Alphonse Beau de Rochas in 1861. Before, in about 1854–57, two Italians (Eugenio Barsanti and Felice Matteucci) invented an engine that was rumored to be very similar, but the patent was lost.

"The request bears the no. 700 of Volume VII of the Patent Office of the Reign of Piedmont. We do not have the text of the patent request, only a photo of the table which contains a drawing of the engine. We do not even know if it was a new patent or an extension of the patent granted three days earlier, on December 30, 1857, at Turin."

The first person to actually build a car with this engine was German engineer Nikolaus Otto. That is why the four-stroke principle today is commonly known as the Otto cycle and four-stroke engines using spark plugs often are called Otto engines. The Otto cycle consists of adiabatic compression, heat addition at constant volume, adiabatic expansion and rejection of heat at constant volume. In the case of a four-stroke Otto cycle, there are also an isobaric compression and an isobaric expansion, usually ignored since in an idealized process those do not play any role in the heat intake or work output.

Otto engines running at the Western Minnesota Steam Threshers Reunion (WMSTR), in Rollag, Minnesota. (2 min 16 sec, 320×240, 340 kbit/s)

Design and engineering principles

Fuel octane rating

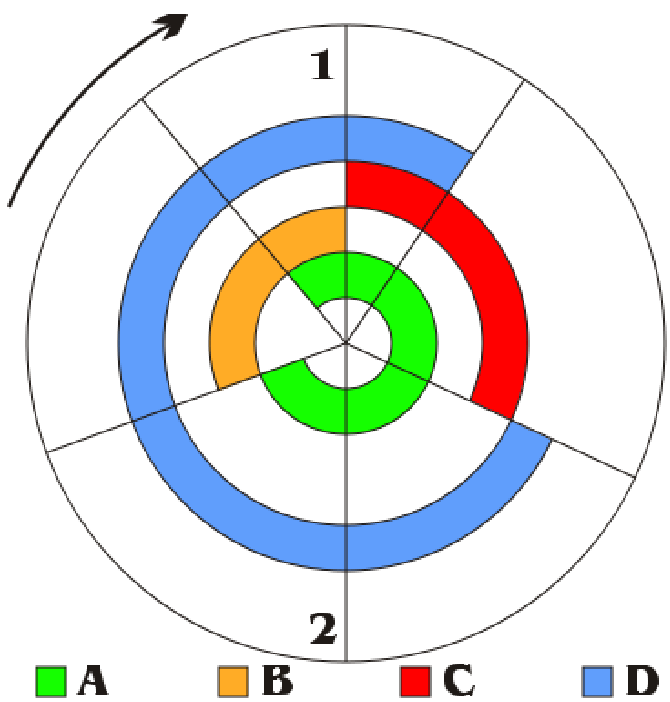
Internal combustion engine power primarily originates from the expansion of gases in the power stroke. Compressing the fuel and air into a very small space increases the efficiency of the power stroke, but increasing the cylinder compression ratio also increases the heating of the fuel as the mixture is compressed (following Charles's law).

A highly flammable fuel with a low self-ignition temperature can combust before the piston reaches top-dead-center (TDC), potentially forcing the piston backwards against rotation. Alternately, a fuel which self-ignites at TDC but before the piston has started downwards can damage the piston and cylinder due to the extreme thermal energy concentrated into a very small space with no relief. This damage is often referred to as engine knocking and can lead to permanent engine damage if it occurs frequently.

The octane rating is a measure of the fuel's resistance to self-ignition, by increasing the temperature at which it will self-ignite. A fuel with a greater octane rating allows for a much higher compression ratio, virtually eliminating the risk of damage due to self-ignition.

Diesel engines rely on self-ignition for the engine to function. The premature ignition problem is solved by separately injecting high-pressure fuel into the cylinder shortly before the piston has reached TDC. Air without fuel can be compressed to a very high degree without concern for self-ignition, and the highly pressurized fuel in the fuel injection system cannot ignite without the presence of air.

Power output limit



The four-stroke cycle
1=TDC
2=BDC

A: Intake
B: Compression
C: Power
D: Exhaust

The maximum amount of power generated by an engine is determined by the maximum amount of air ingested. The amount of power generated by a piston engine is related to its size (cylinder volume), whether it is a two-stroke or four-stroke design, volumetric efficiency, losses, air-to-fuel ratio, the calorific value of the fuel, oxygen content of the air and speed (RPM). The speed is ultimately limited by material strength and lubrication. Valves, pistons and connecting rods suffer severe acceleration forces. At high engine speed, physical breakage and piston ring flutter can occur, resulting in power loss or even engine destruction. Piston ring flutter occurs when the rings oscillate vertically within the piston grooves they reside in. Ring flutter compromises the seal between the ring and the cylinder wall which results in a loss of cylinder pressure and power. If an engine spins too quickly, valve springs cannot act quickly enough to close the valves. This is commonly referred to as 'valve float', and it can result in piston to valve contact, severely damaging the engine. At high speeds the lubrication of piston cylinder wall interface tends to break down. This limits the piston speed for industrial engines to about 10 m/s.

Intake/exhaust port flow

The output power of an engine is dependent on the ability of intake (air–fuel mixture) and exhaust matter to move quickly through valve ports, typically located in the cylinder head. To increase an engine's output power, irregularities in the intake and exhaust paths, such as casting flaws, can be removed, and, with the aid of an air flow bench, the radii of valve port turns and valve seat configuration can be modified to reduce resistance. This process is called porting, and it can be done by hand or with a CNC machine.

Supercharging

One way to increase engine power is to force more air into the cylinder so that more power can be produced from each power stroke. This can be done using some type of air compression device known as a supercharger, which can be powered by the engine crankshaft.

Supercharging increases the power output limits of an internal combustion engine relative to its displacement. Most commonly, the supercharger is always running, but there have been designs that allow it to be cut out or run at varying speeds (relative to engine speed). Mechanically driven supercharging has the disadvantage that some of the output power is used to drive the supercharger, while power is wasted in the high pressure exhaust, as the air has been compressed twice and then gains more potential volume in the combustion but it is only expanded in one stage.

Turbocharging

A turbocharger is a supercharger that is driven by the engine's exhaust gases, by means of a turbine. It consists of a two piece, high-speed turbine assembly with one side that compresses the intake air, and the other side that is powered by the exhaust gas outflow.

When idling, and at low-to-moderate speeds, the turbine produces little power from the small exhaust volume, the turbocharger has little effect and the engine operates nearly in a naturally-aspirated manner. When much more power output is required, the engine speed and throttle opening are increased until the exhaust gases are sufficient to 'spin up' the turbocharger's turbine to start compressing much more air than normal into the intake manifold.

Turbocharging allows for more efficient engine operation because it is driven by exhaust pressure that would otherwise be (mostly) wasted, but there is a design limitation known as turbo lag. The increased engine power is not immediately available, due to the need to sharply increase engine RPM, to build up pressure and to spin up the turbo, before the turbo starts to do any useful air compression. The increased intake volume causes increased exhaust and spins the turbo faster, and so forth until steady high power operation is reached. Another difficulty is that the higher exhaust pressure causes the exhaust gas to transfer more of its heat to the mechanical parts of the engine.

Rod and piston-to-stroke ratio

The rod-to-stroke ratio is the ratio of the length of the connecting rod to the length of the piston stroke. A longer rod will reduce the sidewise pressure of the piston on the cylinder wall and the stress forces, hence increasing engine life. It also increases the cost and engine height and weight.

A "square engine" is an engine with a bore diameter equal to its stroke length. An engine where the bore diameter is larger than its stroke length is an oversquare engine, conversely, an engine with a bore diameter that is smaller than its stroke length is an undersquare engine.

Valvetrain

The valves are typically operated by a camshaft rotating at half the speed of the crankshaft. It has a series of cams along its length, each designed to open a valve during the appropriate part of an intake or exhaust stroke. A tappet between valve and cam is a contact surface on which the cam slides to open the valve. Many engines use one or more camshafts “above” a row (or each row) of cylinders, as in the illustration, in which each cam directly actuates a valve through a flat tappet. In other engine designs the camshaft is in the crankcase, in which case each cam contacts a push rod, which contacts a rocker arm which opens a valve. The overhead cam design typically allows higher engine speeds because it provides the most direct path between cam and valve.

Valve clearance

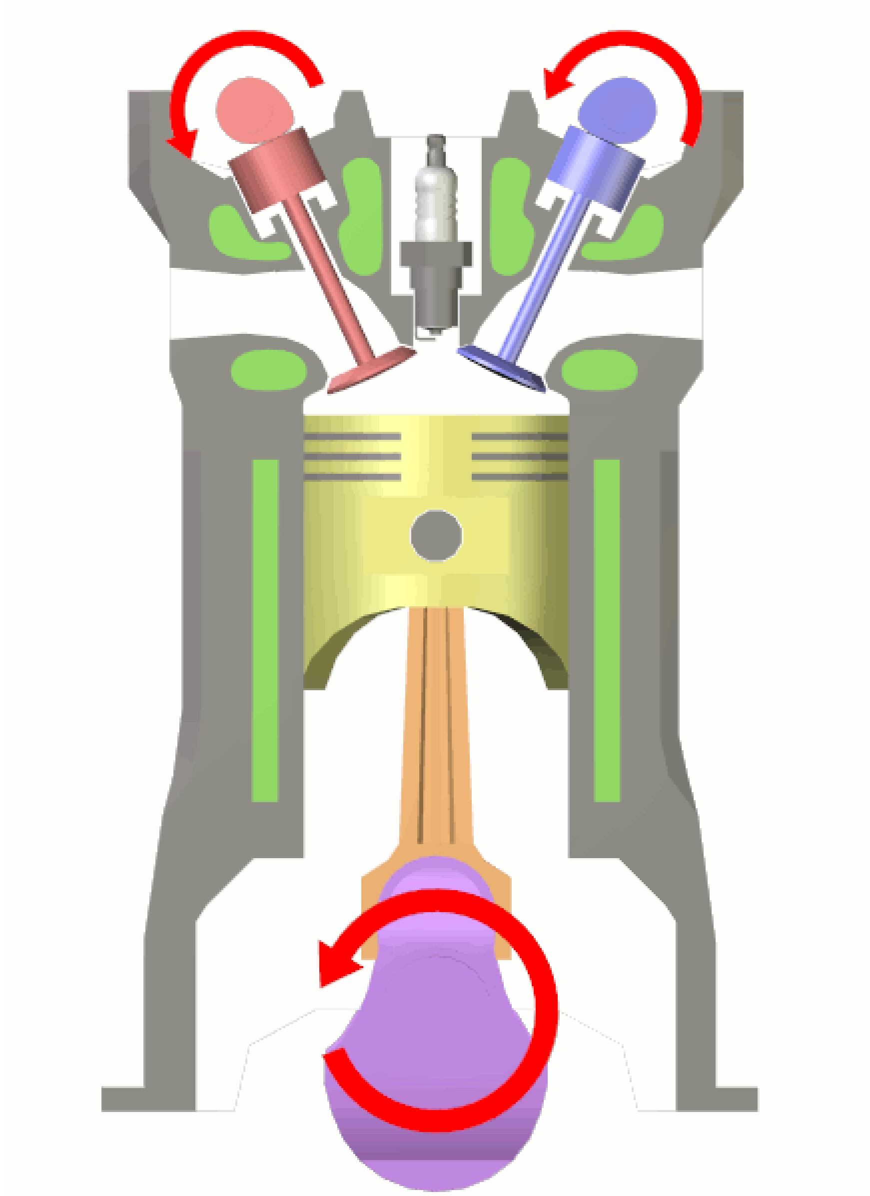
Valve clearance refers to the small gap between a valve lifter and a valve stem that ensures that the valve completely closes. On engines with mechanical valve adjustment excessive clearance will cause noise from the valve train. Typically the clearance has to be readjusted each 20,000 miles (32,000 km) with a feeler gauge.

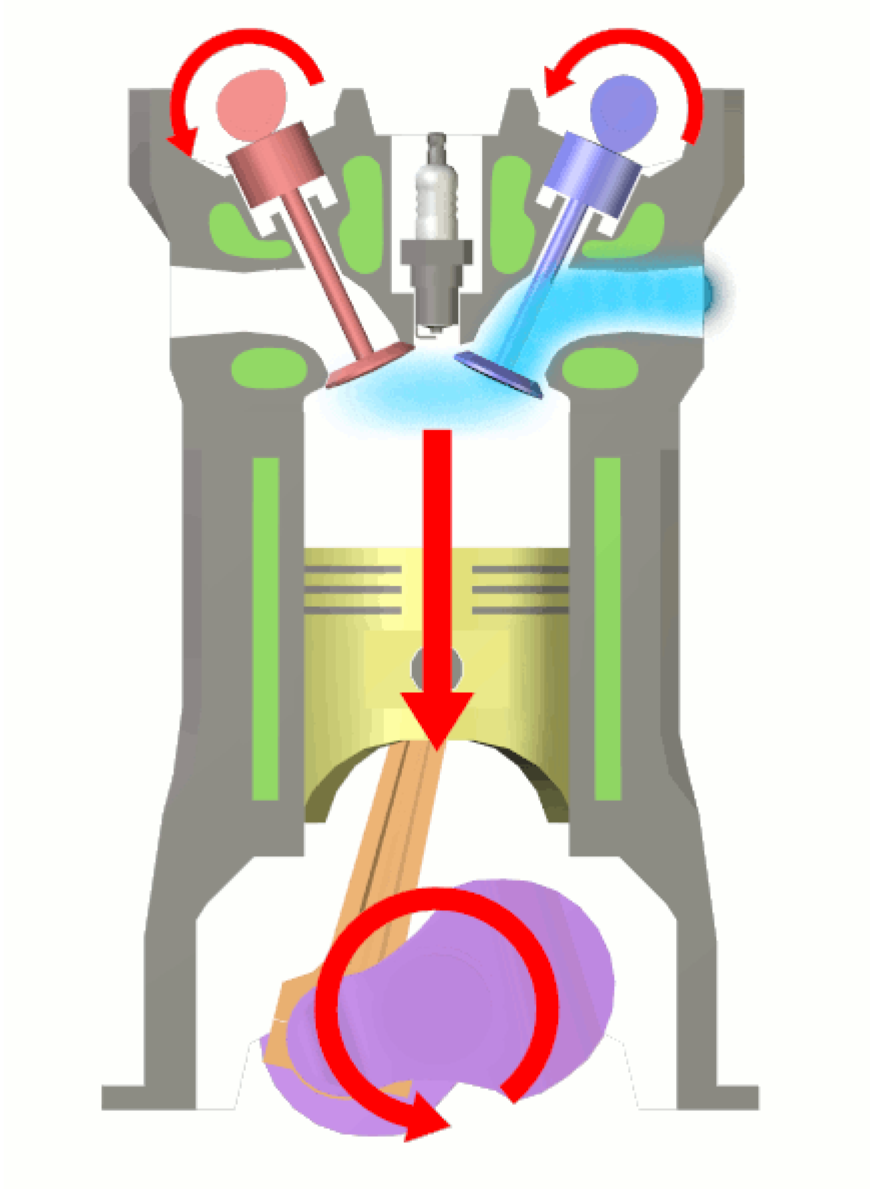
Most modern production engines use hydraulic lifters to automatically compensate for valve train component wear. Dirty engine oil may cause lifter failure.

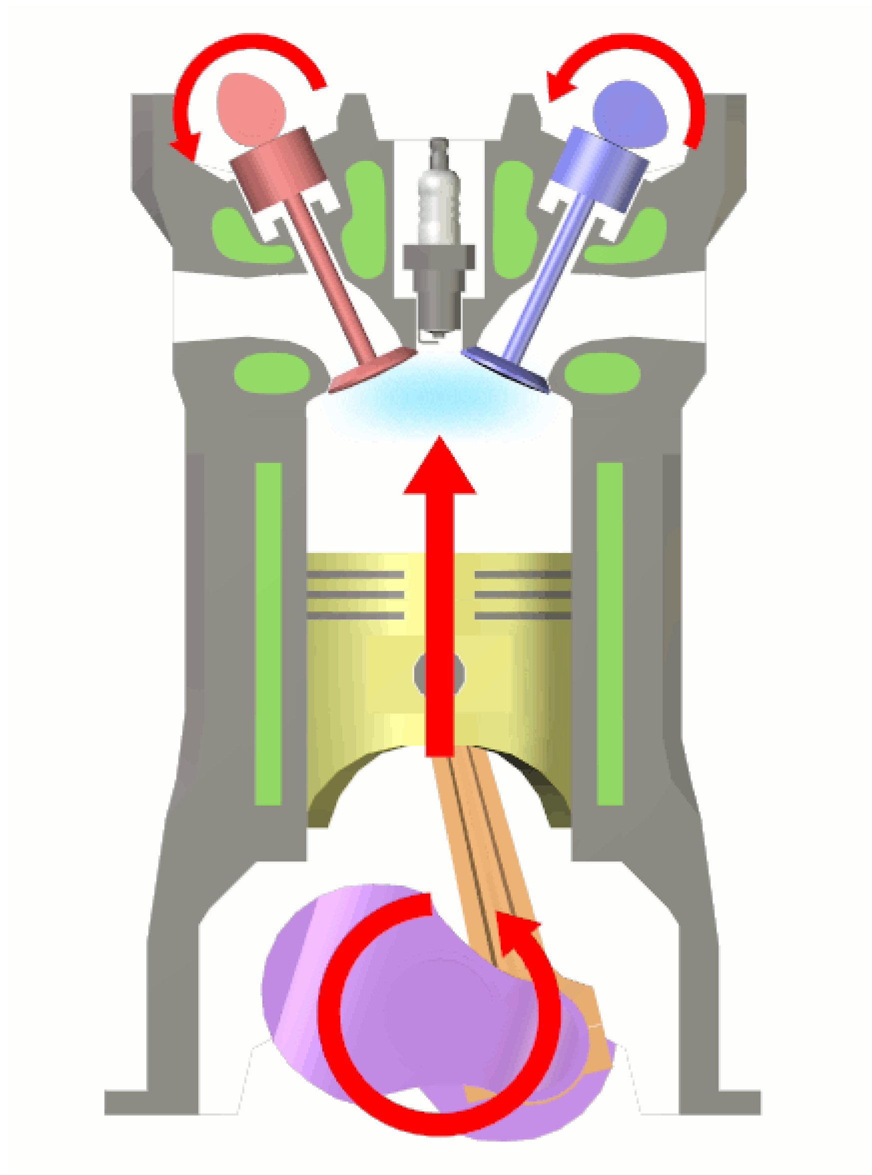
Energy balance

Otto engines are about 35% efficient – in other words, 35% of the energy generated by combustion is converted into useful rotational energy at the output shaft of the engine, while the remainder appears as waste heat.By contrast, a six-stroke engine may convert more than 50% of the energy of combustion into useful rotational energy.

Modern engines are often intentionally built to be slightly less efficient than they could otherwise be. This is necessary for emission controls such as exhaust gas recirculation and catalytic converters that reduce smog and other atmospheric pollutants. Reductions in efficiency may be counteracted with an engine control unit using lean burn techniques.







Starting position, intake stroke, and compression stroke.