

# Engine

Components, Infrastructures and Technology



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First Edition, 2012

ISBN 978-81-323-0876-8

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*Published by:*

**Academic Studio**

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: [info@wtbooks.com](mailto:info@wtbooks.com)

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WORLD TECHNOLOGIES

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## Chapter 1

# Radiator (Engine Cooling)



A typical automobile coolant radiator

**Radiators** are used for cooling internal combustion engines, mainly in automobiles but also in piston-engined aircraft, railway locomotives, motorcycles, stationary generating plant or any similar use of such an engine.

They operate by passing a liquid *coolant* through the engine block, where it is heated, then through the radiator itself where it loses this heat to the atmosphere. This coolant is usually water-based, but may also be oil. It is usual for the coolant flow to be pumped, also for a fan to blow air through the radiator.

## **Automobiles**

In automobiles with a liquid-cooled internal combustion engine a radiator is connected to channels running through the engine and cylinder head, through which a liquid (coolant) is pumped. This liquid may be water (in climates where water is unlikely to freeze), but is more commonly a mixture of water and antifreeze in proportions appropriate to the climate. Antifreeze itself is usually ethylene glycol or propylene glycol (with a small amount of corrosion inhibitor).

The radiator transfers the heat from the fluid inside to the air outside, thereby cooling the engine. Radiators are also often used to cool automatic transmissions, air conditioners, and sometimes to cool engine oil. Radiators are typically mounted in a position where they receive airflow from the forward movement of the vehicle, such as behind a front grill. Where engines are mid- or rear-mounted, it is common to mount the radiator behind a front grill to achieve sufficient airflow, even though this requires long coolant pipes. Alternatively, the radiator may draw air from the flow over the top of the vehicle or from a side-mounted grill. For long vehicles, such as buses, side airflow is most common for engine and transmission cooling and top airflow most common for air conditioner cooling.

## **Radiator construction**

Automobile radiators are constructed of a pair of header tanks, linked by a core with many narrow passageways, thus a high surface area relative to its volume. This core is usually made of stacked layers of metal sheet, pressed to form channels and soldered or brazed together. For many years radiators were made from brass or copper cores soldered to brass headers. Modern radiators save money and weight by using plastic headers and may use aluminium cores. This construction is less easily repaired than traditional materials.

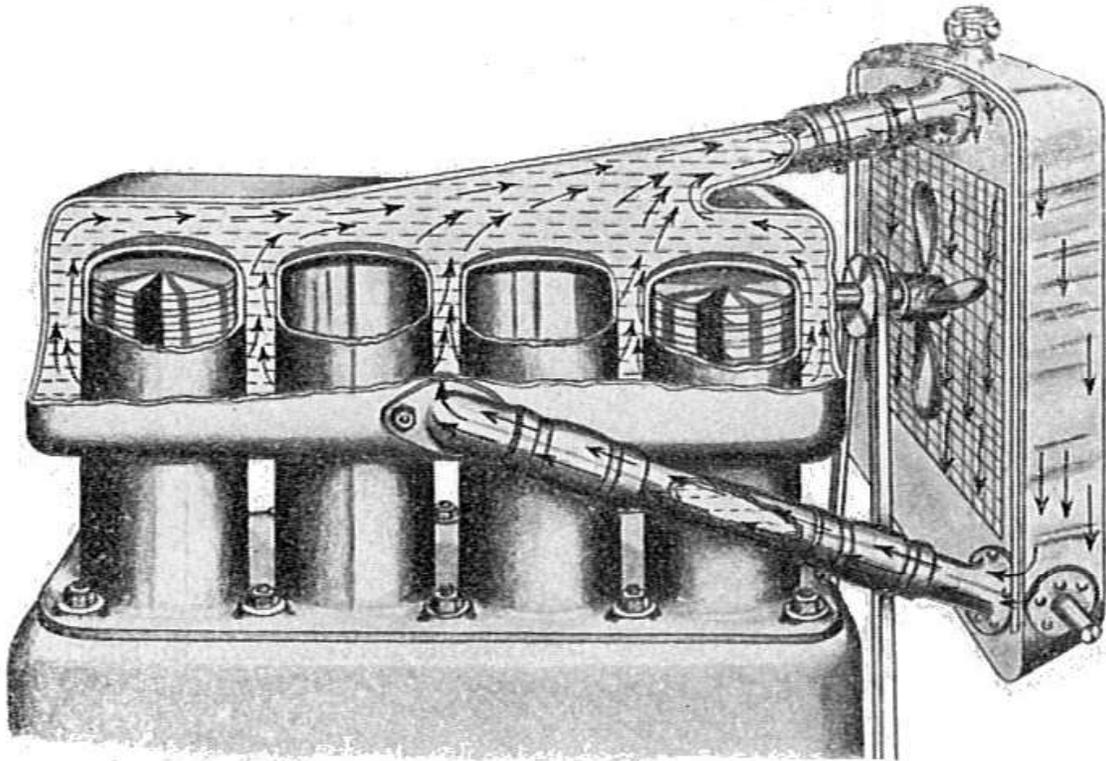


Honeycomb radiator tubes

An earlier construction method was the honeycomb radiator. Round tubes were swaged into hexagons at their ends, then stacked together and soldered. As they only touched at their ends, this formed what became in effect a solid water tank with many air tubes through it.

Vintage cars may also have used radiator cores made from coiled tube, a less-efficient but simpler construction.

## Coolant pumps



Thermosyphon cooling system of 1937, without circulating pump

Radiators first used downward vertical flow, driven solely by a thermosyphon effect. Coolant is heated in the engine, becoming less dense and so rising, cooled, denser coolant in the radiator falling in turn. This effect is sufficient for low-power stationary engines, but inadequate for all but the earliest automobiles. A common fallacy is to assume that a greater vertical separation between engine and radiator can increase the thermosyphon effect. Once the hot and cold headers are separated sufficiently to reach their equilibrium temperatures though, any further separation merely increases pipework length and flow restriction.

All automobiles for many years have used centrifugal pumps to circulate their coolant, driven by geared drives or more commonly by a belt drive. This "fan belt" has a well-established reputation for being slightly unreliable, a failure being rapidly obvious as the engine overheats. Despite the name though, it's the *coolant pump's* failure that causes the overheating, not the fan.

### Heater

A system of valves or baffles, or both, is usually incorporated to simultaneously operate a small radiator inside the car. This small radiator, and the associated blower fan, is called the heater core, and serves to warm the cabin interior. Like the radiator, the heater core

acts by removing heat from the engine. For this reason, automotive technicians often advise operators to turn *on* the heater and set it to high if the engine is overheating.

## Temperature control

### Waterflow control



Car engine thermostat

The engine temperature is primarily controlled by a wax-pellet type of thermostat, a valve which opens once the engine has reached its optimum operating temperature.

When the engine is cold the thermostat is closed, with a small bypass flow so that the thermostat experiences changes to the coolant temperature as the engine warms up. Coolant is directed by the thermostat to the inlet of the circulating pump and is returned directly to the engine, bypassing the radiator. Directing water to circulate only through the engine allows the temperature to reach optimum operating temperature as quickly as possible whilst avoiding localised "hot spots". Once the coolant reaches the thermostat's activation temperature it opens, allowing water to flow through the radiator to prevent the temperature rising higher.

Once at optimum temperature, the thermostat controls the flow of coolant to the radiator so that the engine continues to operate at optimum temperature. Under peak load

conditions, such as labouring slowly up a steep hill whilst heavily laden on a hot day, the thermostat will be approaching fully open because the engine will be producing near to maximum power while the velocity of air flow across the radiator is low. (The velocity of air flow across the radiator has a major effect on its ability to dissipate heat.) Conversely, when cruising fast downhill on a motorway on a cold night on a light throttle, the thermostat will be nearly closed because the engine is producing little power, and the radiator is able to dissipate much more heat than the engine is producing. Allowing too much flow of coolant to the radiator would result in the engine being over cooled and operating at lower than optimum temperature. A side effect of this would be that the passenger compartment heater would not be able to put out enough heat to keep the passengers warm.

The thermostat is therefore constantly moving throughout its range, responding to changes in vehicle operating load, speed and external temperature, to keep the engine at its optimum operating temperature.

## **Airflow control**

Other factors influence the temperature of the engine including radiator size and the type of radiator fan. The size of the radiator (and thus its cooling capacity) is chosen such that it can keep the engine at the design temperature under the most extreme conditions a vehicle is likely to encounter (such as climbing a mountain whilst fully loaded on a hot day).

Airflow speed through a radiator is a major influence on the heat it loses. Vehicle speed affects this, in rough proportion to the engine effort, thus giving crude self-regulatory feedback. Where an additional cooling fan is driven by the engine, this also tracks engine speed similarly.

Engine-driven fans are often regulated by a viscous-drive clutch from the drivebelt, which slips and reduces the fan speed at low temperatures. This improves fuel efficiency by not wasting power on driving the fan unnecessarily. On modern vehicles, further regulation of cooling rate is provided by either variable speed or cycling radiator fans. Electric fans are controlled by a thermostatic switch or the engine control unit. Electric fans also have the advantage of giving good airflow and cooling at low engine revs or when stationary, such as in slow-moving traffic.

Before the development of viscous-drive and electric fans, engines were fitted with simple fixed fans that drew air through the radiator at all times. Vehicles whose design required the installation of a large radiator to cope with heavy work at high temperatures, such as commercial vehicles and tractors would often run cool in cold weather under light loads, even with the presence of a thermostat, as the large radiator and fixed fan caused a rapid and significant drop in coolant temperature as soon as the thermostat opened. This problem could be solved by fitting a **radiator blind** to the radiator which could be adjusted to partially or fully block the airflow. At its simplest the blind was a roll of material (such as canvas or rubber that was unfurled along the length of the radiator to

cover the desired portion. Some vehicles had a series of shutters that could be adjusted from the driver's seat to provide a very fine degree of control.



These AEC Regent III RT buses are fitted with radiator blinds, seen here covering the lower half of the radiators.

## Coolant pressure

Because the thermal efficiency of internal combustion engines increases with internal temperature the coolant is kept at higher-than-atmospheric pressure to increase its boiling point. A calibrated pressure-relief valve is usually incorporated in the radiator's fill cap. This pressure varies between models, but typically ranges from 9 psi (0.6 bar) to 15 psi (1.0 bar).

As the coolant expands with increasing temperature its pressure in the closed system must increase. Ultimately the pressure relief valve opens and excess fluid is dumped into an overflow container. Fluid overflow ceases when the thermostat modulates the rate of cooling to keep the temperature of the coolant at optimum. When the coolant cools and contracts (as conditions change or when the engine is switched off) the fluid is returned to the radiator through additional valving in the cap.

## Coolant

Before World War II, radiator coolant was usually plain water. Antifreeze was used solely to control freezing, and this was often only done in cold weather.

Development in high-performance aircraft engines required improved coolants with higher boiling points, leading to the adoption of glycol or water-glycol mixtures. These led to the adoption of glycols for their antifreeze properties.

Since the development of aluminium or mixed-metal engines, corrosion inhibition has become even more important than antifreeze, and in all regions and seasons.

## **Boiling or overheating**

On this type system, if the coolant in the overflow container gets too low, fluid transfer to overflow will cause an increased loss by vaporizing the engine coolant.

Severe engine damage can be caused by overheating, by overloading or system defect, when the coolant is evaporated to a level below the water pump. This can happen without warning because, at that point, the sending units are not exposed to the coolant to indicate the excessive temperature.

To protect the unwary the cap often contains a mechanism that attempts to relieve the internal pressure before the cap can be fully opened. Some scalding of one's hands can easily occur in this event. Opening a hot radiator drops the system pressure immediately and may cause a sudden ebullition of super-heated coolant which can cause severe burns.

## **History**

The invention of the automobile water radiator is attributed to Karl Benz. Wilhelm Maybach designed the first honeycomb radiator for the Mercedes 35hp.

## **Supplementary radiators**

It is sometimes necessary for a car to be equipped with a second, or auxiliary, radiator to increase the cooling capacity, when the size of the original radiator cannot be increased. The second radiator is plumbed in series with the main radiator in the circuit. This was the case when the Audi 100 was first turbocharged creating the 200. These are not to be confused with intercoolers.

Some engines have an oil cooler, a separate small radiator to cool the engine oil. Cars with an automatic transmission often have extra connections to the radiator, allowing the transmission fluid to transfer its heat to the coolant in the radiator. These may be either oil-air radiators, as for a smaller version of the main radiator. More simply they may be oil-water coolers, where an oil pipe is inserted inside the water radiator. As water is denser than air, this offers comparable cooling (within limits) from a less complex and thus cheaper oil cooler.

Turbo charged or supercharged engines may have an intercooler, which is an air-to-air or air-to-water radiator used to cool the incoming air charge—not to cool the engine.

## **Aircraft**

Aircraft with liquid-cooled piston engines (usually inline engines rather than radial) also require radiators. As airspeed is higher than for cars, these are efficiently cooled in flight and so do not require large areas or cooling fans. Many high-performance aircraft however suffer extreme overheating problems when idling on the ground - a mere 7 minutes for a Spitfire.

### **Surface radiators**

Reducing drag is a major goal in aircraft design, including the design of cooling systems. An early technique was to take advantage of an aircraft's abundant airflow to replace the honeycomb core (many surfaces, with a high ratio of surface to volume) by a surface mounted radiator. This uses a single surface blended into the fuselage or wing skin, with the coolant flowing through pipes at the back of this surface.

As they are so dependent on airspeed, surface radiators are even more prone to overheating when ground-running. Racing aircraft such as the Supermarine S.6B, a racing seaplane with radiators built into the upper surfaces of its floats, have been described as "being flown on the temperature gauge" as the main limit on their performance.

Surface radiators have also been used by a few high-speed racing cars, such as Malcolm Campbell's Blue Bird of 1928.

### **Radiator thrust**

An aircraft radiator comprises a duct wherein heat is added. As a result, this is effectively a jet engine. High-performance piston aircraft with well-designed low-drag radiators (notably the P-51 Mustang) derived thrust from this effect. The thrust was significant enough to offset the drag of the duct the radiator was enclosed in and allowed the aircraft to achieve zero cooling drag. At one point, there were even plans to equip the Spitfire with a ramjet, by injecting fuel into this duct after the radiator and igniting it. Although ramjets normally require a supersonic airspeed, this light-up speed can be reduced where heat is being added, such as in a radiator duct.

### **Steam cooling**

Pressurized cooling systems operate by adding heat to the coolant fluid, causing it to rise in temperature in inverse proportion to its specific heat capacity. With the need to keep the final temperature below boiling point, this limits the amount of heat that a given mass-flow of coolant can dissipate.

Attempts were made with aero-engines of the 1930s, notably the Rolls-Royce Goshawk, to exceed this limit by *allowing* the coolant to boil. This absorbs an amount of heat equivalent to the specific heat of vaporization, which for water is more than five times the

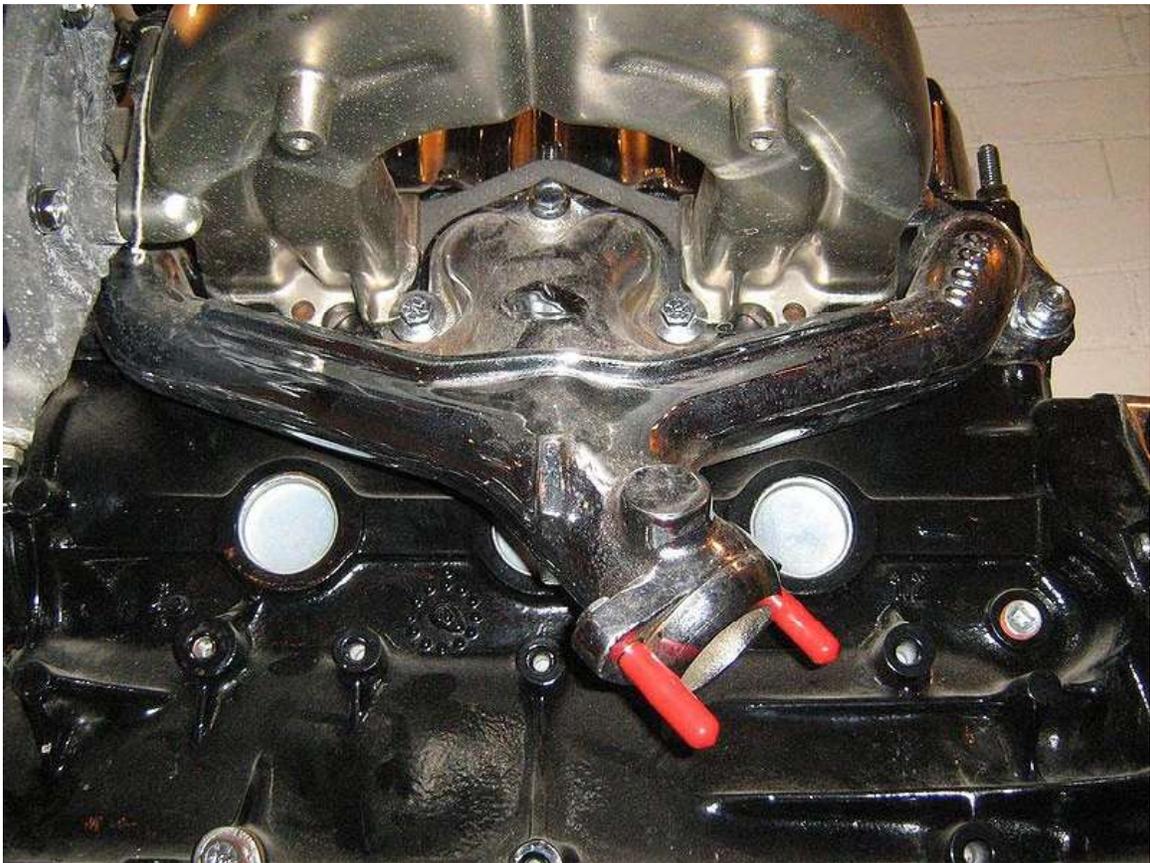
energy required to heat the same quantity of water from 0°C to 100°C. Obviously this allows the necessary cooling effect with far less mass of coolant.

The practical difficulty was the need to provide condensers rather than radiators. Cooling was now needed not just for hot, dense liquid coolant, but for low-density vapor. This required a condenser far larger, and with higher drag, than a radiator. For aircraft, especially high-speed aircraft, it was soon realized this configuration was unworkable and so evaporative cooling was abandoned.

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## Chapter 2

# Exhaust System



Exhaust manifold (chrome plated) on a car engine



Muffler and tail pipe on a car

An **exhaust system** is usually tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine or stove. The entire system conveys burnt gases from the engine and includes one or more **exhaust pipes**. Depending on the overall system design, the exhaust gas may flow through one or more of:

- Cylinder head and exhaust manifold
- A turbocharger to increase engine power.
- A catalytic converter to reduce air pollution.
- A muffler (North America) / silencer (Europe), to reduce noise.

### ***Design criteria***

An exhaust pipe must be carefully designed to carry toxic and/or noxious gases away from the users of the machine. Indoor generators and furnaces can quickly fill an enclosed space with carbon monoxide or other poisonous exhaust gases if they are not properly vented to the outdoors. Also, the gases from most types of machine are very hot; the pipe must be heat-resistant, and it must not pass through or near anything which can

burn or can be damaged by heat. A chimney serves as an exhaust pipe in a stationary structure. For the internal combustion engine it is important to have the Exhaust System "Tuned" (refer to tuned pipe) for optimal efficiency. Also this should meet the regulation norms maintained in each country. In European countries, EURO 5, India BS-4 etc.

## Motorcycles



Ducati muffler

In most motorcycles all or most of the exhaust system is visible and may be chrome plated as a display feature. Aftermarket exhausts may be made from steel, aluminium, titanium, or carbon fiber.

Motorcycle exhausts come in many varieties depending on the type of engine and its intended use. A twin cylinder may flow its exhaust into separate exhaust sections, such as seen in the Kawasaki EX250 (also known as the Ninja 250 in the US, or the GPX 250). Or, they may flow into a single exhaust section known as a two-into-one (2-1). Larger engines that come with 4 cylinders, such as Japanese supersport or superbikes (such the Kawasaki ZX series, Honda's CBR series, Yamaha's YZF series, also known as R6 and R1, and Suzuki's GSX-R series) often come with a twin exhaust system. A "full system" may be bought as an aftermarket accessory, also called a 4-2-1 or 4-1, depending on its layout. In the past, these bikes would come standard with a single exhaust, as seen on the Kawasaki ZX-6R 2000 and 2001 models. However, EU noise and pollution regulations have generally stopped this practice, forcing companies to use other methods to increase performance of the motorcycle. This has often led to a decrease in fuel economy, because of increased weight of the exhaust system and manufacturers forcing more fuel into the engine to gain extra power.

## Trucks

In many trucks / lorries all or most of the exhaust system is visible. Often in such trucks the silencer is surrounded by a perforated metal sheath to avoid people getting burnt

touching the hot silencer. This sheath may be chrome plated as a display feature. Part of the pipe between the engine and the silencer is often flexible metal industrial ducting, as in the image in the section "Terminology". Sometimes a large diesel exhaust pipe is vertical, to blow the hot noxious gas well away from people; in such cases the end of the exhaust pipe often has a hinged metal flap to stop debris and birds and rainwater from falling inside. Sometimes these exhaust pipes have a flex connector attached with it. This helps in minimising the vibration from the engine to be transferred into the exhaust system.

## **Two-stroke engines**

In a two-stroke engine, such as that used on dirt bikes, a bulge in the exhaust pipe known as an expansion chamber uses the pressure of the exhaust to create a pump that squeezes more air and fuel into the cylinder during the intake stroke. This provides greater power and fuel efficiency.

## **Marine engines**

With an onboard diesel engine below-decks on marine vessels:-

- Lagging the exhaust pipe stops it from overheating the engine room where people must work to service the engine.
- Feeding water into the exhaust pipe cools the exhaust gas and thus lessens the back-pressure at the engine's cylinders' exhaust ports and thus helps the cylinders to empty quicker.

## **Outboard motors**

In outboard motors the exhaust system is usually a vertical passage through the engine structure and to reduce out-of-water noise blows out underwater, sometimes through the middle of the propeller.

## Terminology

### Manifold or header



Aftermarket exhaust manifold

In most production engines, the **manifold** is an assembly designed to collect the exhaust gas from two or more cylinders into one pipe. Manifolds are often made of cast iron in stock production cars, and may have material-saving design features such as to use the least metal, to occupy the least space necessary, or have the lowest production cost. These design restrictions often result in a design that is cost effective but that does not do the most efficient job of venting the gases from the engine. Inefficiencies generally occur due to the nature of the combustion engine and its cylinders. Since cylinders fire at different times, exhaust leaves them at different times, and pressure waves from gas emerging from one cylinder might not be completely vacated through the exhaust system when another comes. This creates a back pressure and restriction in the engine's exhaust system that can restrict the engine's true performance possibilities.

A **header** (sometimes called **extractor** in Australia) is a manifold specifically designed for performance. During design, engineers create a manifold without regard to weight or cost but instead for optimal flow of the exhaust gases. This design results in a header that is more efficient at **scavenging** the exhaust from the cylinders. Headers are generally circular steel tubing with bends and folds calculated to make the paths from each cylinder's exhaust port to the common outlet all equal length, and joined at narrow angles to encourage pressure waves to flow through the outlet, and not back towards other

cylinders. In a set of **tuned headers** the pipe lengths are carefully calculated to enhance exhaust flow in a particular engine revolutions per minute range.

Headers are generally made by aftermarket automotive companies, but sometimes can be bought from the high-performance parts department at car dealerships. Generally, most car performance enthusiasts buy aftermarket headers made by companies solely focused on producing reliable, cost-effective well-designed headers specifically for their car. Headers can also be custom designed by a custom shop. Due to the advanced materials that some aftermarket headers are made of, this can be expensive. Luckily, an exhaust system can be custom built for any car, and generally is not specific to the car's motor or design except for needing to properly connect solidly to the engine. This is usually accomplished by correct sizing in the design stage, and selecting a proper gasket type and size for the engine.

## **Header-back**

The **Header-back** (or **header back**) is the part of the exhaust system from the outlet of the header to the final vent to open air — everything from the header back. Header-back systems are generally produced as aftermarket performance systems for cars without turbochargers.

## **Turbo-back**

The **Turbo-back** (or **turbo back**) is the part of the exhaust system from the outlet of a turbocharger to the final vent to open air. Turbo-back systems are generally produced as aftermarket performance systems for cars with turbochargers. Some turbo-back (and header-back) systems replace stock catalytic converters with others having less flow restriction.

## **With or without catalytic converter**

Some systems (including in former time all systems) (sometimes nowadays called **catless**) eliminate the catalytic converter. This is illegal in some places if the vehicle is driven on public roads.

## **Cat-back**

**Cat-back** (also **cat back** and **catback**) refers to the portion of the exhaust system from the outlet of the catalytic converter to the final vent to open air. This generally includes the pipe from the converter to the muffler, the muffler, and the final length of pipe to open air.

Cat-back exhaust systems generally use larger diameter pipe than the stock system. Good systems will have mandrel-bent turns that allow the exhaust gas to exit with as little back pressure as possible. The mufflers included in these kits are often glasspacks, to reduce back pressure. If the system is engineered more for show than functionality, it may be

tuned to enhance the lower sounds that are lacking from high-RPM low-displacement engines.

## **Tailpipe and tip**

With trucks, sometimes the silencer is crossways under the front of the cab and its tailpipe blows sideways to the offside (right side if driving on the left, left side if driving on the right). The side of a passenger car on which the exhaust exits beneath the rear bumper usually indicates the market for which the vehicle was designed, i.e. Japanese (and some older British) vehicles have exhausts on the right so they are furthest from the curb in countries which drive on the left, while European vehicles have exhausts on the left.

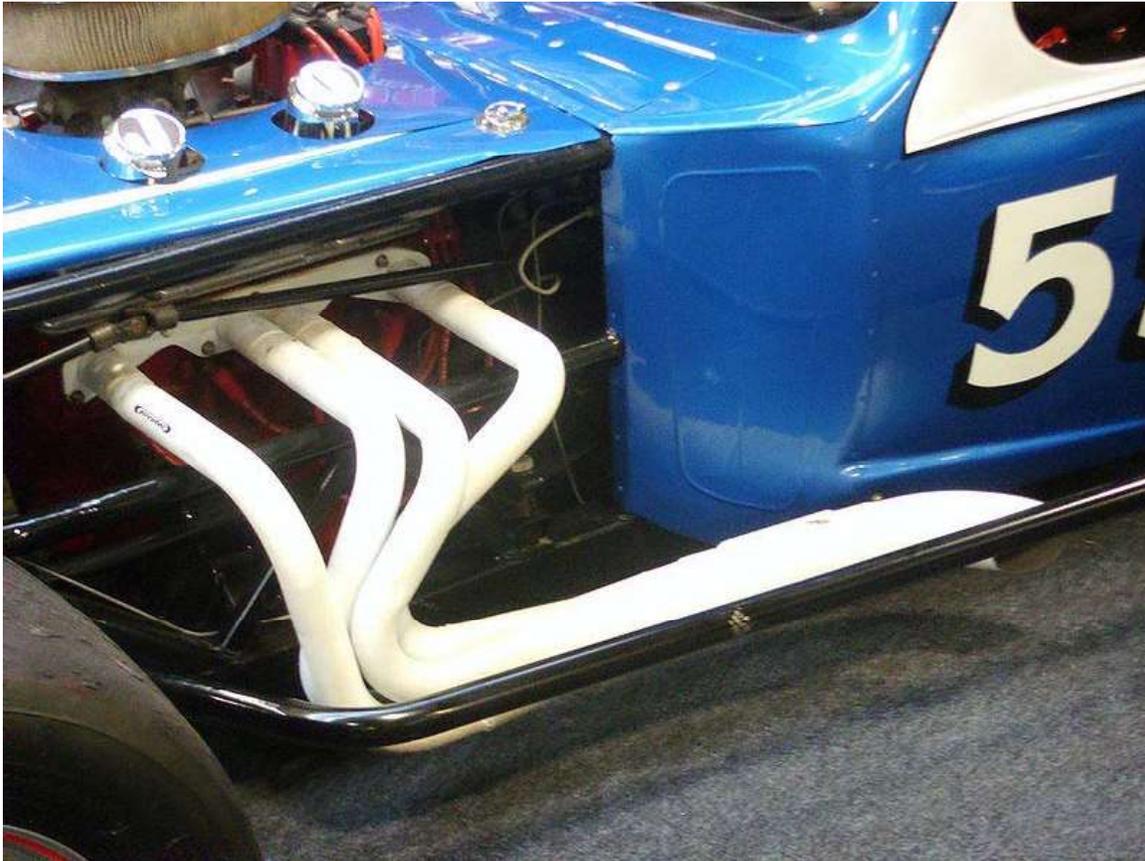
The end of the final length of exhaust pipe where it vents to open air, generally the only visible part of the exhaust system part on a vehicle, often ends with just a straight or angled cut, but may include a fancy tip. The tip is sometimes chromed. It is often of larger pipe than the rest of the exhaust system. This produces a final reduction in pressure, and sometimes used to enhance the appearance of the car.

In the late 1950s in the United States manufacturers had a fashion in car styling to form the rear bumper with a hole at each end through which the exhaust would pass. Two outlets symbolized V-8 power, and only the most expensive cars (Cadillac, Lincoln, Imperial, Packard) were fitted with this design. One justification for this was that luxury cars in those days had such a long rear overhang that the exhaust pipe scraped the ground when the car traversed ramps. The fashion disappeared after customers noted that the rear end of the car, being a low-pressure area, collected soot from the exhaust and its acidic content ate into the chrome-plated rear bumper.

When a bus, truck or tractor or excavator has a vertical exhaust pipe (called stacks or pipes behind the cab), sometimes the end is curved, or has a hinged cover flap which the gas flow blows out of the way, to try to prevent foreign objects (including droppings from a bird perching on the exhaust pipe when the vehicle is not being used) getting inside the exhaust pipe.

In some trucks, when the silencer is front-to-back under the chassis, the end of the tailpipe turns 90° and blows downwards. That protects anyone near a stationary truck from getting a direct blast of the exhaust gas, but often raises dust when the truck is driving on a dry dusty unmade surface such as on a building site.

## **Exhaust System Tuning**



Aftermarket exhaust system including headers and a white plasma-sprayed ceramic coating

Many automotive companies offer aftermarket exhaust system upgrades as a subcategory of engine tuning. This is often fairly expensive as it usually includes replacing the entire exhaust manifold or other large components. These upgrades however can significantly improve engine performance and do this through means of two main principles:

- By reducing the exhaust back pressure, engine power is increased in four-stroke engines
- By reducing the amount of heat from the exhaust being lost into the underbonnet area. This reduces the underbonnet temperature and consequently lowers the intake manifold temperature, increasing power. This also has positive side effect of preventing heat-sensitive components from being damaged. Furthermore, keeping the heat in the exhaust gases speeds these up, therefore reducing back pressure as well.

Back pressure is most commonly reduced by replacing exhaust manifolds with headers, which have smoother bends and normally wider pipe diameters.

Exhaust Heat Management is the term that describes reducing the amount of exhaust heat loss. One dominant solution to aftermarket upgraders is the use of a ceramic coating applied via thermal spraying. This not only reduces heat loss and lessens back pressure, but provides an effective way to protect the exhaust system from wear and tear, thermal degradation and corrosion.



Large truck's diesel exhaust pipe



Waste collection vehicle's diesel exhaust pipe



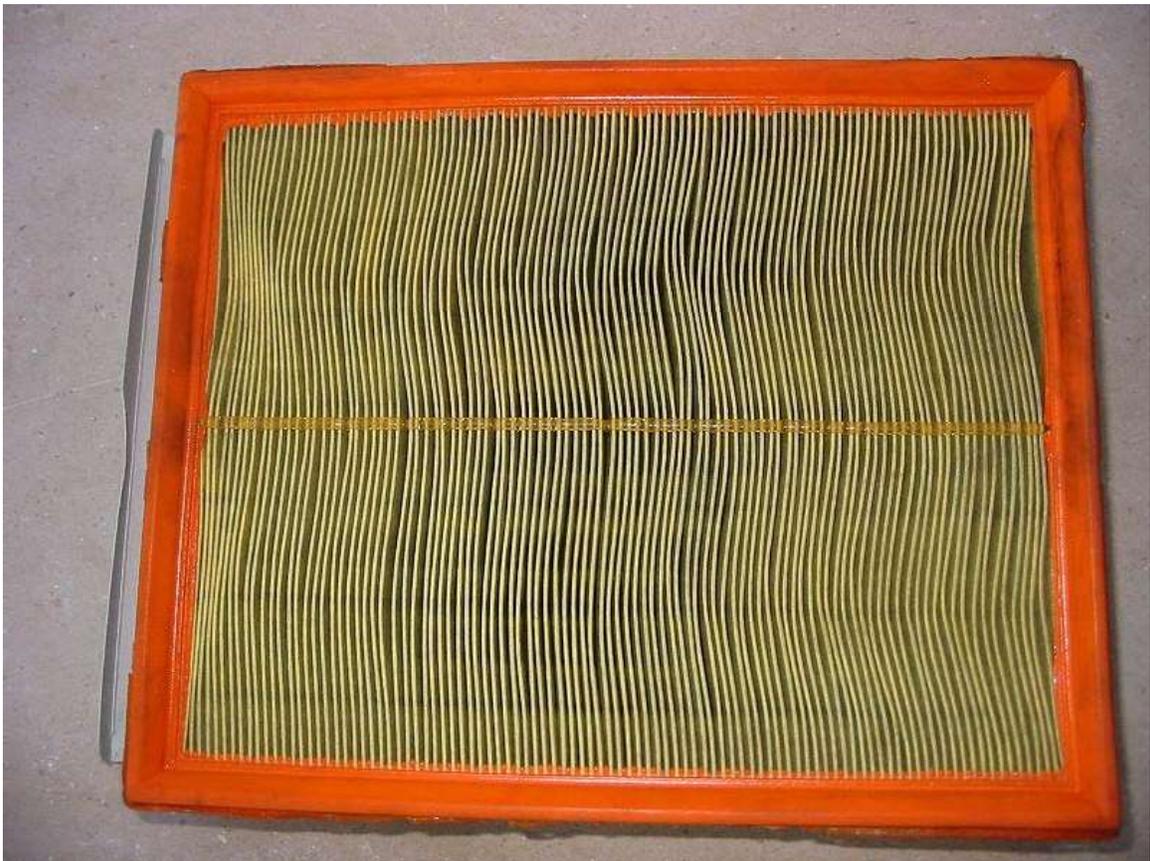
Dual exhaust pipes attached to a car's muffler



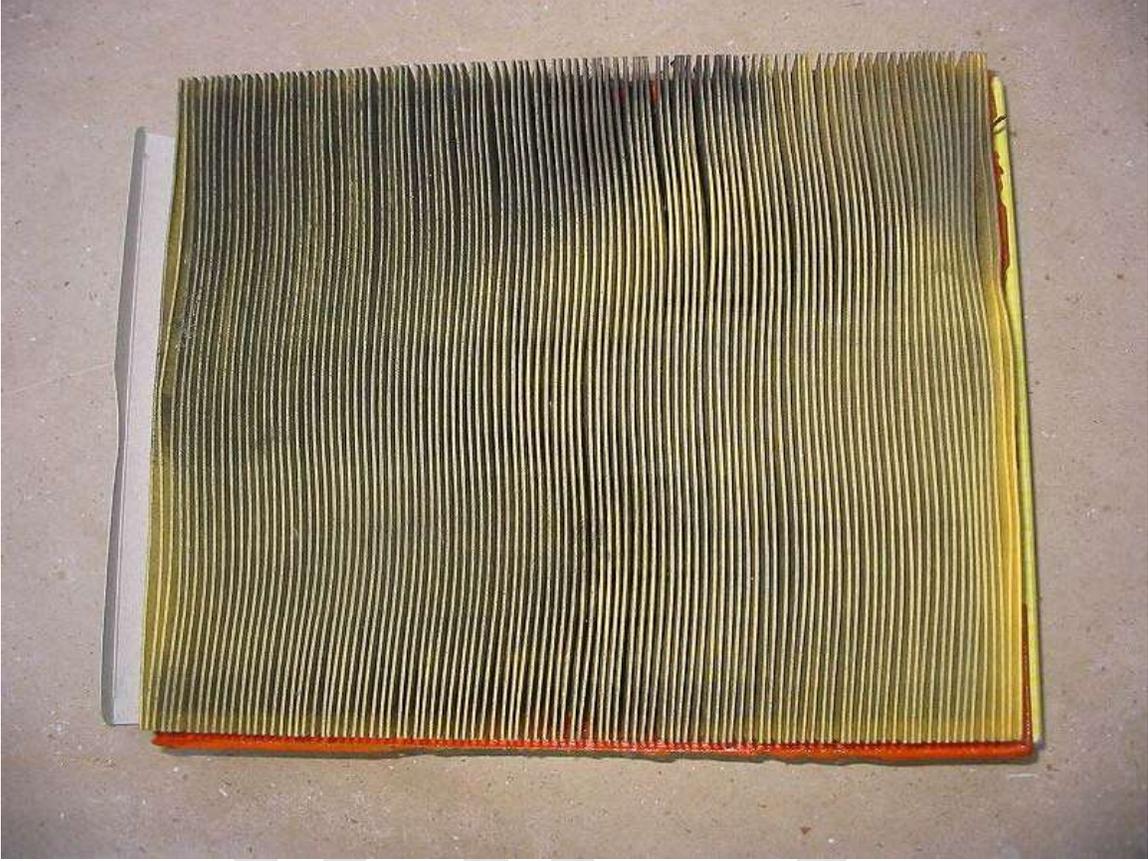
Exhaust system of diesel telescopic-arm vehicle

## Chapter 3

# Air Filter



Used auto engine air filter, clean side



Used auto engine air filter, dirty side



Auto engine air filter clogged with dust and grime

A particulate **air filter** is a device composed of fibrous materials which removes solid particulates such as dust, pollen, mold, and bacteria from the air. A chemical air filter consists of an absorbent or catalyst for the removal of airborne molecular contaminants such as volatile organic compounds or ozone. Air filters are used in applications where air quality is important, notably in building ventilation systems and in engines.

Some buildings, as well as aircraft and other man-made environments (e.g., satellites and space shuttles) use foam, pleated paper, or spun fiberglass filter elements. Another method, air ionisers, use fibers or elements with a static electric charge, which attract dust particles. The air intakes of internal combustion engines and compressors tend to use either paper, foam, or cotton filters. Oil bath filters have fallen out of favor. The technology of air intake filters of gas turbines has improved significantly in recent years, due to improvements in the aerodynamics and fluid-dynamics of the air-compressor part of the Gas Turbines.

### ***Automotive cabin air filters***

The cabin air filter is typically a pleated-paper filter that is placed in the outside-air intake for the vehicle's passenger compartment. Some of these filters are rectangular and similar in shape to the combustion air filter. Others are uniquely shaped to fit the available space of particular vehicles' outside-air intakes. Being a relatively recent addition to automobile equipment, this filter is often overlooked. Clogged or dirty cabin air filters can

significantly reduce airflow from the cabin vents, as well as introduce allergens into the cabin air stream.

### ***Internal combustion air filters***

The combustion air filter prevents abrasive particulate matter from entering the engine's cylinders, where it would cause mechanical wear and oil contamination. Known as Engine air induction systems (AIS), they are typically constructed of paper or felt.

Most fuel injected vehicles use a pleated paper filter element in the form of a flat panel. This filter is usually placed inside a plastic box connected to the throttle body with an intake tube.

Older vehicles that use carburetors or throttle body fuel injection typically use a cylindrical air filter, usually a few inches high and between 6 inches (150 mm) and 16 inches (410 mm) in diameter. This is positioned above the carburetor or throttle body, usually in a metal or plastic container which may incorporate ducting to provide cool and/or warm inlet air, and secured with a metal or plastic lid.

### **Long Life Filtration System**

In 2003 Ford Motor company introduced the Visteon Long Life Filtration System to the Ford Focus. This system has a foam filter placed in the bumper of the car and is stated to have a 150,000-mile (240,000 km) service interval. According to a technical paper published by Society of Automotive Engineers, this design offers higher and more stable filtration efficiency than conventional air filters.

### **Paper**

Pleated paper filter elements are the nearly exclusive choice for automobile engine air cleaners, because they are efficient, easy to service, and cost-effective. The "paper" term is somewhat misleading, as the filter media are considerably different from papers used for writing or packaging, etc. There is a persistent belief amongst tuners, fomented by advertising for aftermarket non-paper replacement filters, that paper filters flow poorly and thus restrict engine performance. In fact, as long as a pleated-paper filter is sized appropriately for the airflow volumes encountered in a particular application, such filters present only trivial restriction to flow until the filter has become significantly clogged with dirt. Construction equipment engines also use this.

### **Foam**

Oil-wetted polyurethane foam elements are used in some aftermarket replacement automobile air filters. Foam was in the past widely used in air cleaners on small engines on lawnmowers and other power equipment, but automotive-type paper filter elements have largely supplanted oil-wetted foam in these applications. Depending on the grade and thickness of foam employed, an oil-wetted foam filter element can offer minimal

airflow restriction or very high dirt capacity, the latter property making foam filters a popular choice in off-road rallying and other motorsport applications where high levels of dust will be encountered.

## **Cotton**

Oiled cotton gauze is employed in a small number of aftermarket automotive air filters marketed as high-performance items. In the past, cotton gauze saw limited use in original-equipment automotive air filters.

## **Oil Bath**

An oil bath air cleaner consists of a round base bowl containing a pool of oil, and a round insert which is filled with fibre, mesh, foam, or another coarse filter media. When the cleaner is assembled, the media-containing body of the insert sits a short distance above the surface of the oil pool. The rim of the insert overlaps the rim of the base bowl. This arrangement forms a labyrinthine path through which the air must travel in a series of U-turns: up through the gap between the rims of the insert and the base bowl, down through the gap between the outer wall of the insert and the inner wall of the base bowl, and up through the filter media in the body of the insert. This U-turn takes the air at high velocity across the surface of the oil pool. Larger and heavier dust and dirt particles in the air cannot make the turn due to their inertia, so they fall into the oil and settle to the bottom of the base bowl. Lighter and smaller particles are trapped by the filtration media in the insert, which is wetted by oil droplets aspirated there into by normal airflow.

Oil bath air cleaners were very widely used in automotive and small-engine applications until the widespread industry adoption of the paper filter in the early 1960s. Such cleaners are still used in off-road equipment where very high levels of dust are encountered, for oil bath air cleaners can sequester a great deal of dirt relative to their overall size, without loss of filtration efficiency or airflow. However, the liquid oil makes cleaning and servicing such air cleaners messy and inconvenient, they must be relatively large to avoid excessive restriction at high airflow rates, and they tend to increase exhaust emissions of unburned hydrocarbons due to oil aspiration when used on spark-ignition engines.

## Chapter 4

# Air-Fuel Ratio Meter and Crankcase

## 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<sub>2</sub> 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).

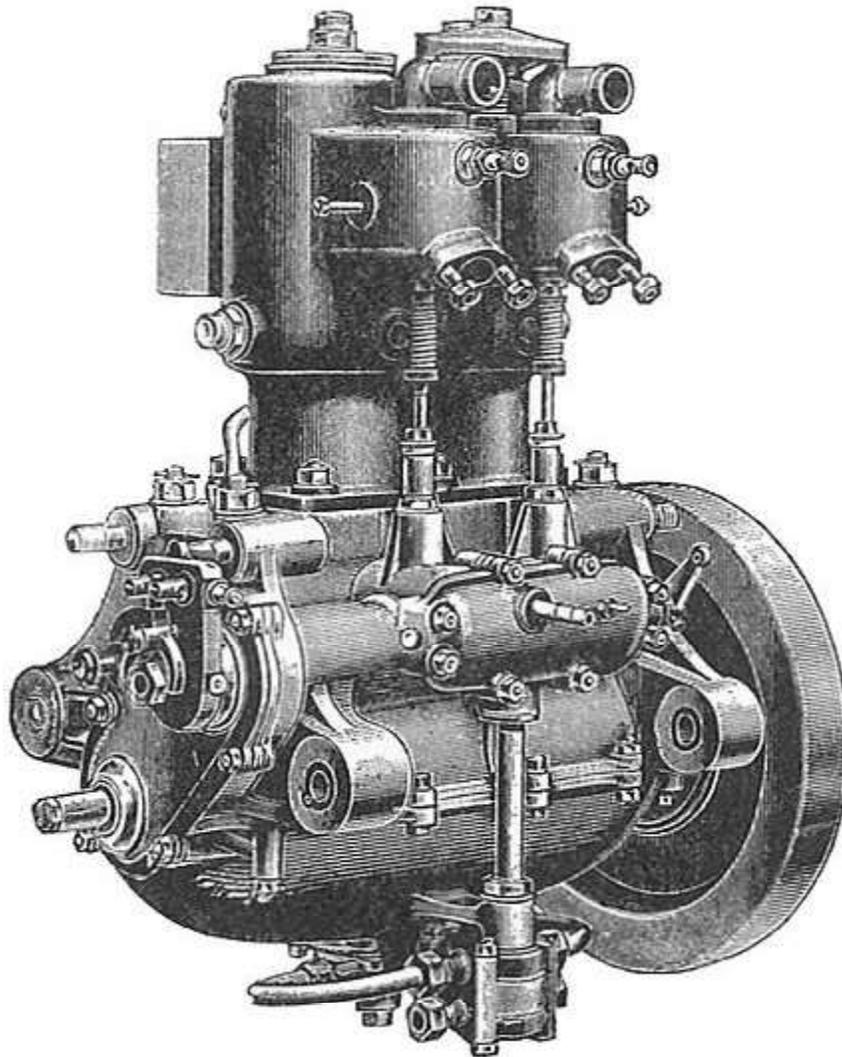
The average level of the sensor is defined as 450 mV. Since narrow band sensors cannot output a fixed voltage level between the lean and the rich areas, the ECU tries to control the engine by controlling the mixture between lean and rich in such a sufficiently fast manner, that the average level becomes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

# Crankcase



De Dion-Bouton engine from about 1905, in which can clearly be seen a discrete crankcase with upper and lower halves (each a casting), with the bottom half constituting both part of the main bearing support and also an oil sump.

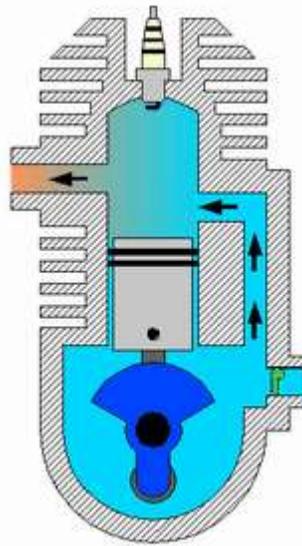
In an internal combustion engine of the reciprocating type, the **crankcase** is the housing for the crankshaft. The enclosure forms the largest cavity in the engine and is located below the cylinder(s), which in a multicylinder engine are usually integrated into one or several cylinder blocks. Crankcases have often been discrete parts, but more often they

are integral with the cylinder bank(s), forming an engine block. Nevertheless, the area around the crankshaft is still usually called the crankcase. Crankcases and other basic engine structural components (e.g., cylinders, cylinder blocks, cylinder heads, and integrated combinations thereof) are typically made of cast iron or cast aluminium via sand casting. Today the foundry processes are usually highly automated, with a few skilled workers to manage the casting of thousands of parts.

A crankcase often has an opening in the bottom to which an oil pan is attached with a gasketed bolted joint. Some crankcase designs fully surround the crank's main bearing journals, whereas many others form only one half, with a bearing cap forming the other. Some crankcase areas require no structural strength from the oil pan itself (in which case the oil pan is typically stamped from sheet steel), whereas other crankcase designs do (in which case the oil pan is a casting in its own right). Both the crankcase and any rigid cast oil pan often have reinforcing ribs cast into them, as well as bosses which are drilled and tapped to receive mounting screws/bolts for various other engine parts.

Besides protecting the crankshaft and connecting rods from foreign objects, the crankcase serves other functions, depending on engine type. These include keeping the motor oil contained, usually hermetically or nearly hermetically (and in the hermetic variety, allowing the oil to be pressurized); providing the rigid structure with which to join the engine to the transmission; and in some cases, even constituting part of the frame of the vehicle (such as in many farm tractors).

### ***Two-stroke engines***



Two-stroke engine

In two-stroke gasoline engines, the crankcase is sealed and is used as a pressurization chamber for the fuel/air mixture. As the piston rises, it pushes out exhaust gases and

produces a partial vacuum in the crankcase which aspirates fuel and air. As the piston travels downward, the fuel/air charge is pushed from the crankcase and into the cylinder.

Unlike four-stroke gasoline engines, the crankcase does not contain engine oil because it handles the fuel/air mixture. Instead, oil is mixed in with the fuel, and the mixture provides lubrication for the cylinder walls, crankshaft and connecting rod bearings.

A majority of ships today use two stroke diesel engines, where the crankcase is completely separated from the cylinders. Unlike smaller engines, they usually have a separate tank below the crankcase as an oil holding tank (sump tank).

### ***Four-stroke engines***



Four-stroke engine

In a four-stroke engine, the crankcase is filled mainly with air and oil, and is largely sealed off from the fuel/air mixture by the pistons.

### **Oil circulation**

Oil circulation is kept separate from the fuel/air mixture, thereby preserving oil rather than burning it as happens in two-stroke engines. Oil moves from its reservoir, is pressurized by an oil pump, and is pumped through the oil filter to remove grit. The oil is then squirted into the crankshaft and connecting rod bearings and onto the cylinder walls, and eventually drips off into the bottom of the crankcase. In a wet sump system, oil remains in a reservoir at the bottom of the crankcase, referred to as the **oil pan**. In a dry sump system, oil is instead pumped to an external reservoir.

Even in a wet sump system, the crankshaft has minimal contact with the sump oil. Otherwise, the high-speed rotation of the crankshaft would cause the oil to froth, making

it difficult for the oil pump to move the oil, which can starve the engine of lubrication. Small amounts of oil may splash onto the crankshaft during rough driving, referred to as windage.

In a wet sump system, the main dipstick and oil filler cap connect to the crankcase.

## **Air ventilation**

During normal operation, a small amount of unburned fuel and exhaust gases escape around the piston rings and enter the crankcase, referred to as "**blow-by**". If these gases had no controlled escape mechanism, the gasketed joints would leak (as they "found their own way out"); also, if the gases remained in the crankcase and condensed, the oil would become diluted and chemically degraded over time, decreasing its ability to lubricate. Condensed water would also cause parts of the engine to rust. To counter this, a crankcase ventilation system exists. In all modern vehicles, this consists of a channel to expel the gases out of the crankcase, through an oil-separating baffle, to the PCV valve, into the intake manifold. In a non-turbo engine, the intake manifold is at a lower pressure than the crankcase, providing the suction to keep the ventilation system going. A turbo engine usually has a check valve somewhere in the tubing to avoid pressurizing the crankcase when the turbo produces boost.

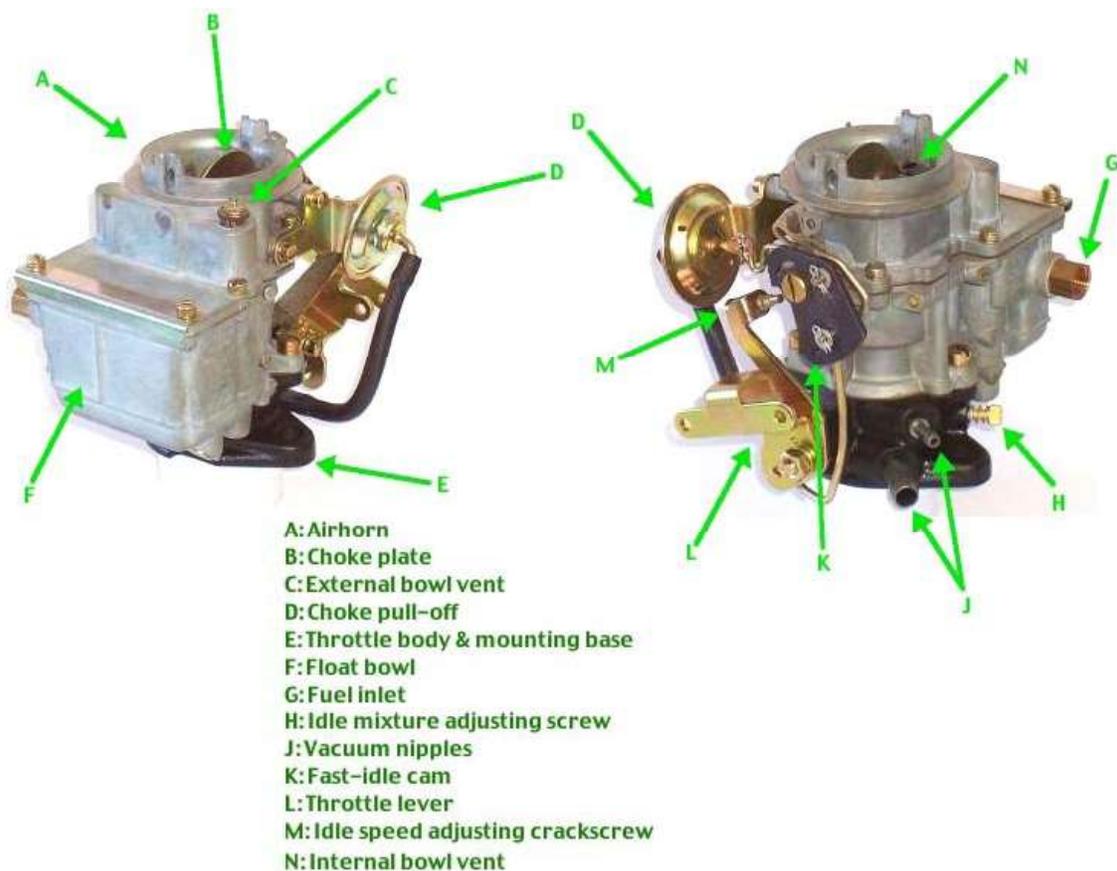
If an engine is damaged or enters old age, gaps can form between the cylinder walls and pistons, resulting in larger amounts of blow-by than the crankcase ventilation system can handle. The gaps cause power loss, and ultimately mean that the engine needs to be rebuilt or replaced. Symptoms of excessive blow-by include oil being pushed up into the air filter, out the dipstick, or out the PCV valve. In rare cases of serious piston or ring damage, the oil filter housing's sheet metal can even burst at its seam.

## ***Open crank engine***

Early internal combustion engines were of the "open crank" style, that is, there was no enclosed crankcase. The crankshaft, connecting rod, camshaft, gears, governor, etc. were all completely exposed and could be viewed in operation when the engine was running. This made for a messy environment as oil was thrown from the engine and could run on the ground. Another disadvantage was that dirt and dust could get on moving engine parts, causing excessive wear and possible malfunction of the engine. Frequent cleaning of the engine was required to keep it in normal working order.

## Chapter 5

# Carburetor



Bendix-Technico (Stromberg) 1-barrel downdraft carburetor model BXUV-3, with nomenclature

A **carburetor** (American spelling), **carburettor**, or **carburetter** (Commonwealth spelling) is a device that blends air and fuel for an internal combustion engine. It is sometimes shortened to *carb* in North America and the United Kingdom.

## **Word origin**

The word *carburetor* comes from the French *carbure* meaning "carbide". *Carburer* means to combine with carbon. In fuel chemistry, the term has the more specific meaning of increasing the carbon (and therefore energy) content of a fuel by mixing it with a volatile hydrocarbon.

## **History and development**

The first carburetors were surface carburetors where the volatility of the petrol was utilized. The Austrian automobile pioneer Siegfried Marcus invented the "rotating brush carburettor". This was further improved by the Hungarian engineers János Csonka and Donát Bánki in 1893.

Frederick William Lanchester of Birmingham, England, experimented with the wick carburetor in cars. In 1896, Frederick and his brother built the first gasoline driven car in England, a single cylinder 5 hp (3.7 kW) internal combustion engine with chain drive. Unhappy with the performance and power, they re-built the engine the next year into a two cylinder horizontally opposed version using his new wick carburetor design.

In 1885, Wilhelm Maybach and Gottlieb Daimler developed a carburetor for their engine based on the Atomizer nozzle.

Carburetors were the usual fuel delivery method for most U.S. made gasoline-fueled engines up until the late 1980s, when fuel injection became the preferred method of automotive fuel delivery. In the U.S. market, the last carbureted cars were:

- 1990 (General public) : Oldsmobile Custom Cruiser, Buick Estate Wagon
- 1991 (Police) : Ford Crown Victoria Police Interceptor with the 5.8 L (351 cu in) engine.
- 1991 (SUV) : Jeep Grand Wagoneer with the AMC 360 engine.
- 1994 (Light truck) : Isuzu

Elsewhere, certain Lada cars used carburetors until 2006. A majority of motorcycles still use carburetors due to lower cost and throttle response problems with early injection setups, but as of 2005 many new models are now being introduced with fuel injection. Carburetors are still found in small engines and in older or specialized automobiles, such as those designed for stock car racing.

## **Principles**

The carburetor works on Bernoulli's principle: the faster air moves, the lower its static pressure, and the higher its dynamic pressure. The throttle (accelerator) linkage does not directly control the flow of liquid fuel. Instead, it actuates carburetor mechanisms which meter the flow of air being pulled into the engine. The speed of this flow, and therefore its pressure, determines the amount of fuel drawn into the airstream.

When carburetors are used in aircraft with piston engines, special designs and features are needed to prevent fuel starvation during inverted flight. Later engines used an early form of fuel injection known as a pressure carburetor.

Most production **carbureted** (as opposed to fuel-injected) engines have a single carburetor and a matching intake manifolds that divides and transports the air fuel mixture to the intake valves, though some engines (like motorcycle engines) use multiple carburetors on split heads. Multiple carburetor engines were also common enhancements for modifying engines in America from the 1950s to mid-1960s, as well as during the following decade of high-performance American muscle cars fueling different chambers of the engine's intake manifold.

Older engines used updraft carburetors, where the air enters from below the carburetor and exits through the top. This had the advantage of never "flooding" the engine, as any liquid fuel droplets would fall out of the carburetor instead of into the intake manifold; it also lent itself to use of an oil bath air cleaner, where a pool of oil below a mesh element below the carburetor is sucked up into the mesh and the air is drawn through the oil-covered mesh; this was an effective system in a time when paper air filters did not exist.

Beginning in the late 1930s, downdraft carburetors were the most popular type for automotive use in the United States. In Europe, the sidedraft carburetors replaced downdraft as free space in the engine bay decreased and the use of the SU-type carburetor (and similar units from other manufacturers) increased. Some small propeller-driven aircraft engines still use the updraft carburetor design.

Outboard motor carburetors are typically sidedraft, because they must be stacked one on top of the other in order to feed the cylinders in a vertically-oriented cylinder block.



1979 Evinrude Type I marine sidedraft carburetor

The main disadvantage of basing a Carburetor's operation on Bernoulli's principle is that, being a fluid dynamic device, the pressure reduction in a venturi tends to be proportional to the square of the intake air speed. The fuel jets are much smaller and limited mainly by viscosity, so that the fuel flow tends to be proportional to the pressure difference. So jets sized for full power tend to starve the engine at lower speed and part throttle. Most commonly this has been corrected by using multiple jets. In SU and other movable jet carburetors, it was corrected by varying the jet size. For cold starting, a different principle was used, in multi-jet carburetors. A flow resisting valve called a choke, similar to the throttle valve, was placed upstream of the main jet to reduce the intake pressure and suck additional fuel out of the jets.

## **Operation**

- **Fixed-venturi**, in which the varying air velocity in the venturi alters the fuel flow; this architecture is employed in most carburetors found on cars.
- **Variable-venturi**, in which the fuel jet opening is varied by the slide (which simultaneously alters air flow). In "constant depression" carburetors, this is done by a vacuum operated piston connected to a tapered needle which slides inside the fuel jet. A simpler version exists, most commonly found on small motorcycles and dirt bikes, where the slide and needle is directly controlled by the throttle position. The most common variable venturi (constant depression) type carburetor is the sidedraft SU carburetor and similar models from Hitachi, Zenith-Stromberg and other makers. The UK location of the SU and Zenith-Stromberg companies helped these carburetors rise to a position of domination in the UK car market, though such carburetors were also very widely used on Volvos and other non-UK makes. Other similar designs have been used on some European and a few Japanese automobiles. These carburetors are also referred to as "constant velocity" or "constant vacuum" carburetors. An interesting variation was Ford's VV (Variable Venturi) carburetor, which was essentially a fixed venturi carburetor with one side of the venturi hinged and movable to give a narrow throat at low rpm and a wider throat at high rpm. This was designed to provide good mixing and airflow over a range of engine speeds, though the VV carburetor proved problematic in service.



A high performance 4-barrel carburetor.

Under all engine operating conditions, the carburetor must:

- Measure the airflow of the engine
- Deliver the correct amount of fuel to keep the fuel/air mixture in the proper range (adjusting for factors such as temperature)
- Mix the two finely and evenly

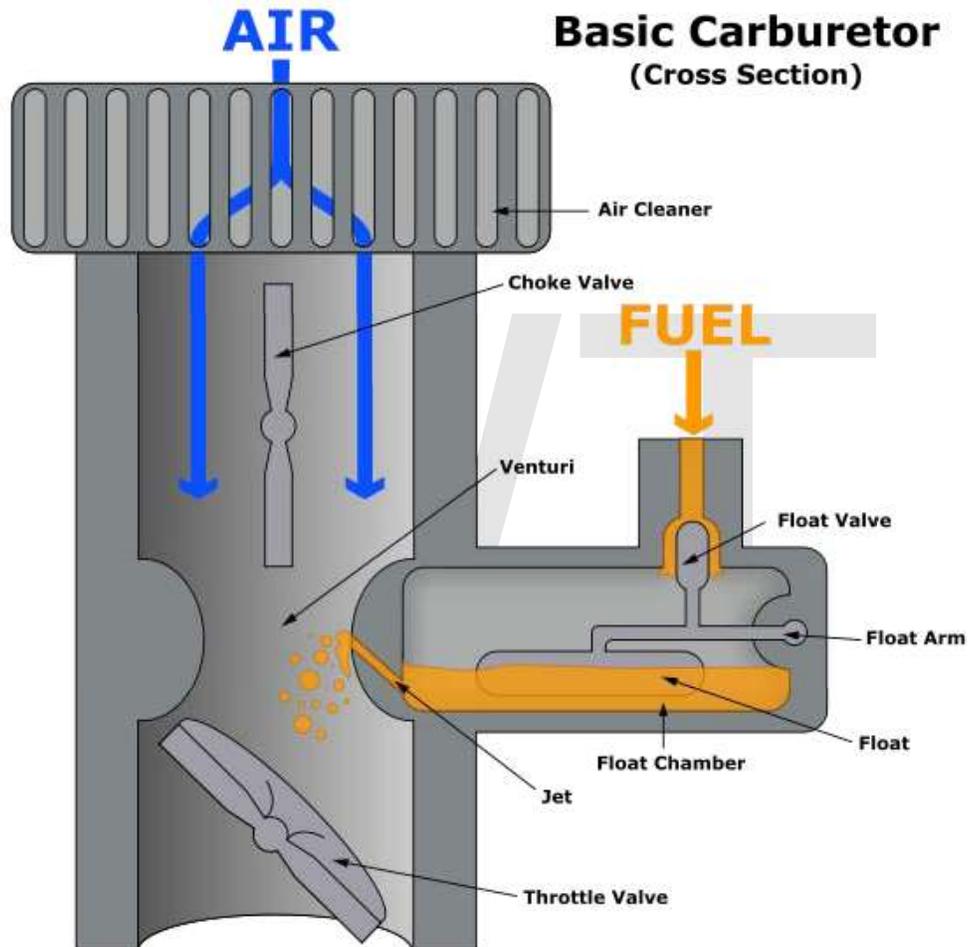
This job would be simple if air and gasoline (petrol) were ideal fluids; in practice, however, their deviations from ideal behavior due to viscosity, fluid drag, inertia, etc. require a great deal of complexity to compensate for exceptionally high or low engine speeds. A carburetor must provide the proper fuel/air mixture across a wide range of ambient temperatures, atmospheric pressures, engine speeds and loads, and centrifugal forces:

- Cold start
- Hot start
- Idling or slow-running
- Acceleration
- High speed / high power at full throttle
- Cruising at part throttle (light load)

In addition, modern carburetors are required to do this while maintaining low rates of exhaust emissions.

To function correctly under all these conditions, most carburetors contain a complex set of mechanisms to support several different operating modes, called *circuits*.

## Basics



Cross Sectional schematic of a Carburetor

A carburetor basically consists of an open pipe through which the air passes into the inlet manifold of the engine. The pipe is in the form of a venturi: it narrows in section and then widens again, causing the airflow to increase in speed in the narrowest part. Below the venturi is a butterfly valve called the throttle valve — a rotating disc that can be turned end-on to the airflow, so as to hardly restrict the flow at all, or can be rotated so that it (almost) completely blocks the flow of air. This valve controls the flow of air through the carburetor throat and thus the quantity of air/fuel mixture the system will deliver, thereby

regulating engine power and speed. The throttle is connected, usually through a cable or a mechanical linkage of rods and joints or rarely by pneumatic link, to the accelerator pedal on a car or the equivalent control on other vehicles or equipment.

Fuel is introduced into the air stream through small holes at the narrowest part of the venturi and at other places where pressure will be lowered when not running on full throttle. Fuel flow is adjusted by means of precisely-calibrated orifices, referred to as *jets*, in the fuel path.

### **Off-idle circuit**

As the throttle is opened up slightly from the fully-closed position, the throttle plate uncovers additional fuel delivery holes behind the throttle plate where there is a low pressure area created by the throttle plate blocking air flow; these allow more fuel to flow as well as compensating for the reduced vacuum that occurs when the throttle is opened, thus smoothing the transition to metering fuel flow through the regular open throttle circuit.

### **Main open-throttle circuit**

As the throttle is progressively opened, the manifold vacuum is lessened since there is less restriction on the airflow, reducing the flow through the idle and off-idle circuits. This is where the venturi shape of the carburetor throat comes into play, due to Bernoulli's principle (*i.e.*, as the velocity increases, pressure falls). The venturi raises the air velocity, and this high speed and thus low pressure sucks fuel into the airstream through a nozzle or nozzles located in the center of the venturi. Sometimes one or more additional **booster venturis** are placed coaxially within the primary venturi to increase the effect.

As the throttle is closed, the airflow through the venturi drops until the lowered pressure is insufficient to maintain this fuel flow, and the idle circuit takes over again, as described above.

Bernoulli's principle, which is a function of the velocity of the fluid, is a dominant effect for large openings and large flow rates, but since fluid flow at small scales and low speeds (low Reynolds number) is dominated by viscosity, Bernoulli's principle is ineffective at idle or slow running and in the very small carburetors of the smallest model engines. Small model engines have flow restrictions ahead of the jets to reduce the pressure enough to suck the fuel into the air flow. Similarly the idle and slow running jets of large carburetors are placed after the throttle valve where the pressure is reduced partly by viscous drag, rather than by Bernoulli's principle. The most common rich mixture device for starting cold engines was the choke, which works on the same principle.

## Power valve

For open throttle operation a richer mixture will produce more power, prevent pre-ignition detonation, and keep the engine cooler. This is usually addressed with a spring-loaded "power valve", which is held shut by engine vacuum. As the throttle opens up, the vacuum decreases and the spring opens the valve to let more fuel into the main circuit. On two-stroke engines, the operation of the power valve is the reverse of normal — it is normally "on" and at a set rpm it is turned "off". It is activated at high rpm to extend the engine's rev range, capitalizing on a two-stroke's tendency to rev higher momentarily when the mixture is lean.

Alternative to employing a power valve, the carburetor may utilize a **metering rod** or **step-up rod** system to enrich the fuel mixture under high-demand conditions. Such systems were originated by Carter Carburetor in the 1950s for the primary two venturis of their four barrel carburetors, and step-up rods were widely used on most 1-, 2-, and 4-barrel Carter carburetors through the end of production in the 1980s. The step-up rods are tapered at the bottom end, which extends into the main metering jets. The tops of the rods are connected to a vacuum piston and/or a mechanical linkage which lifts the rods out of the main jets when the throttle is opened (mechanical linkage) and/or when manifold vacuum drops (vacuum piston). When the step-up rod is lowered into the main jet, it restricts the fuel flow. When the step-up rod is raised out of the jet, more fuel can flow through it. In this manner, the amount of fuel delivered is tailored to the transient demands of the engine. Some 4-barrel carburetors use metering rods only on the primary two venturis, but some use them on both primary and secondary circuits, as in the Rochester Quadrajets.

## Accelerator pump

Liquid gasoline, being denser than air, is slower than air to react to a force applied to it. When the throttle is rapidly opened, airflow through the carburetor increases immediately, faster than the fuel flow rate can increase. This transient oversupply of air causes a lean mixture, which makes the engine misfire (or "stumble")—an effect opposite what was demanded by opening the throttle. This is remedied by the use of a small piston or diaphragm pump which, when actuated by the throttle linkage, forces a small amount of gasoline through a jet into the carburetor throat. This extra shot of fuel counteracts the transient lean condition on throttle tip-in. Most accelerator pumps are adjustable for volume and/or duration by some means. Eventually the seals around the moving parts of the pump wear such that pump output is reduced; this reduction of the accelerator pump shot causes stumbling under acceleration until the seals on the pump are renewed.

The accelerator pump is also used to **prime** the engine with fuel prior to a cold start. Excessive priming, like an improperly-adjusted choke, can cause **flooding**. This is when too much fuel and not enough air are present to support combustion. For this reason, most carburetors are equipped with an **unloader** mechanism: The accelerator is held at wide open throttle while the engine is cranked, the unloader holds the choke open and admits extra air, and eventually the excess fuel is cleared out and the engine starts.

## Choke

When the engine is cold, fuel vaporizes less readily and tends to condense on the walls of the intake manifold, starving the cylinders of fuel and making the engine difficult to start; thus, a **richer mixture** (more fuel to air) is required to start and run the engine until it warms up. A richer mixture is also easier to ignite.

To provide the extra fuel, a **choke** is typically used; this is a device that restricts the flow of air at the entrance to the carburetor, before the venturi. With this restriction in place, extra vacuum is developed in the carburetor barrel, which pulls extra fuel through the main metering system to supplement the fuel being pulled from the idle and off-idle circuits. This provides the rich mixture required to sustain operation at low engine temperatures.

In addition, the choke can be connected to a cam (the **fast idle cam**) or other such device which prevents the throttle plate from closing fully while the choke is in operation. This causes the engine to idle at a higher speed. Fast idle serves as a way to help the engine warm up quickly, and give a more stable idle while cold by increasing airflow throughout the intake system which helps to better atomize the cold fuel.

In many carbureted cars, the choke is controlled by a cable connected to a pull-knob on the dashboard operated by the driver. In some carbureted cars it is automatically controlled by a thermostat employing a bimetallic spring, which is exposed to engine heat, or to an electric heating element. This heat may be transferred to the choke thermostat via simple convection, via engine coolant, or via air heated by the exhaust. More recent designs use the engine heat only indirectly: A sensor detects engine heat and varies electrical current to a small heating element, which acts upon the bimetallic spring to control its tension, thereby controlling the choke. A **choke unloader** is a linkage arrangement that forces the choke open against its spring when the vehicle's accelerator is moved to the end of its travel. This provision allows a "flooded" engine to be cleared out so that it will start.

Some carburetors do not have a choke but instead use a mixture enrichment circuit, or **enrichener**. Typically used on small engines, notably motorcycles, enricheners work by opening a secondary fuel circuit below the throttle valves. This circuit works exactly like the idle circuit, and when engaged it simply supplies extra fuel when the throttle is closed.

Classic British motorcycles, with side-draft slide throttle carburetors, used another type of "cold start device", called a "tickler". This is simply a spring-loaded rod that, when depressed, manually pushes the float down and allows excess fuel to fill the float bowl and flood the intake tract. If the "tickler" is held down too long it also floods the outside of the carburetor and the crankcase below, and is therefore a fire hazard.

## Other elements

The interactions between each circuit may also be affected by various mechanical or air pressure connections and also by temperature sensitive and electrical components. These are introduced for reasons such as response, fuel efficiency or automobile emissions control. Various air bleeds (often chosen from a precisely calibrated range, similarly to the jets) allow air into various portions of the fuel passages to enhance fuel delivery and vaporization. Extra refinements may be included in the carburetor/manifold combination, such as some form of heating to aid fuel vaporization such as an early fuel evaporator.

## Fuel supply

### Float chamber



Holley "Visi-Flo" model #1904 carburetors from the 1950s, factory equipped with transparent glass bowls.

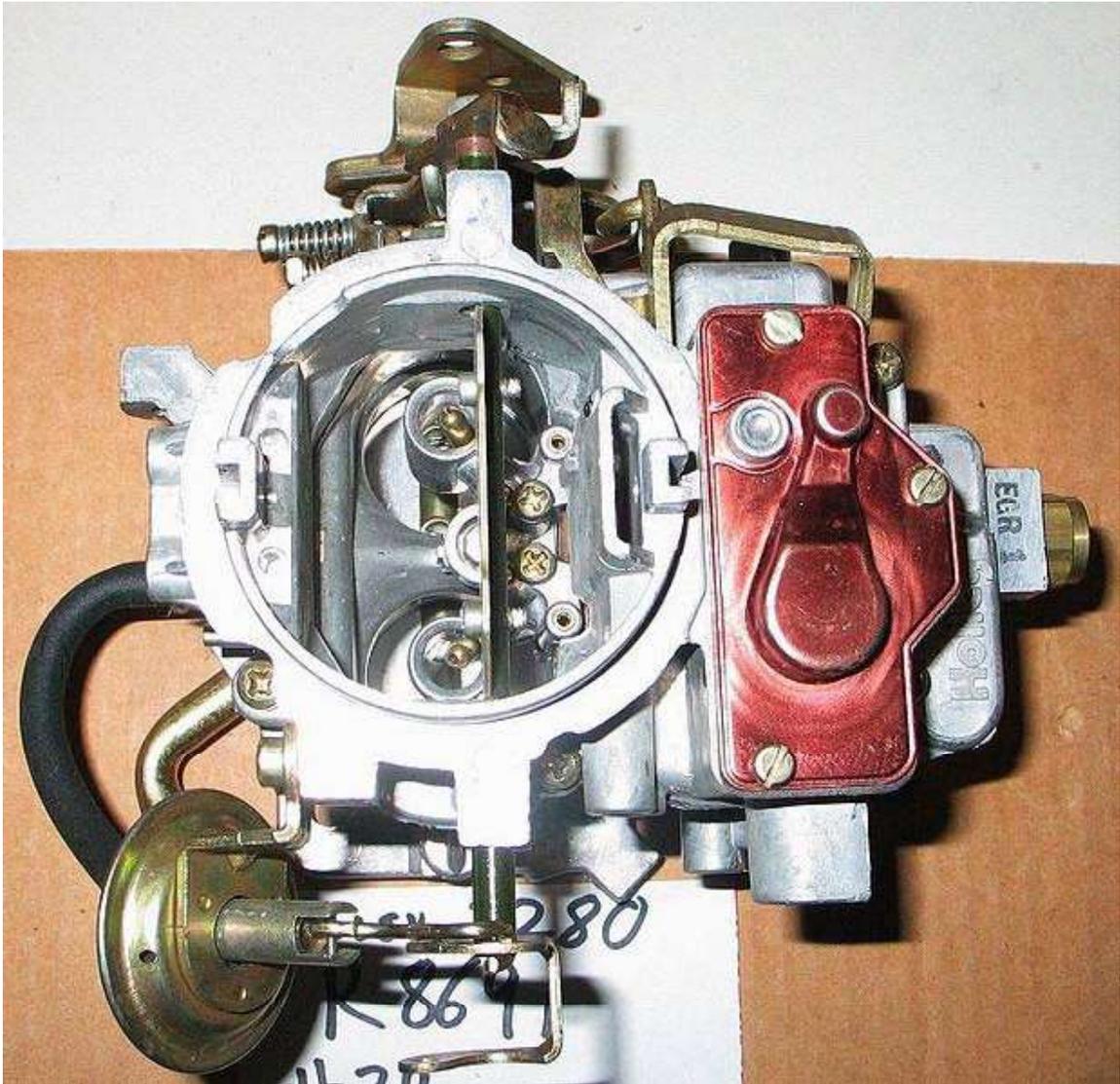
To ensure a ready mixture, the carburetor has a "float chamber" (or "bowl") that contains a quantity of fuel at near-atmospheric pressure, ready for use. This reservoir is constantly replenished with fuel supplied by a fuel pump. The correct fuel level in the bowl is maintained by means of a float controlling an inlet valve, in a manner very similar to that employed in a cistern (e.g. a toilet tank). As fuel is used up, the float drops, opening the inlet valve and admitting fuel. As the fuel level rises, the float rises and closes the inlet valve. The level of fuel maintained in the float bowl can usually be adjusted, whether by a setscrew or by something crude such as bending the arm to which the float is connected. This is usually a critical adjustment, and the proper adjustment is indicated by lines inscribed into a window on the float bowl, or a measurement of how far the float hangs below the top of the carburetor when disassembled, or similar. Floats can be made of different materials, such as sheet brass soldered into a hollow shape, or of plastic; hollow floats can spring small leaks and plastic floats can eventually become porous and

lose their flotation; in either case the float will fail to float, fuel level will be too high, and the engine will not run unless the float is replaced. The valve itself becomes worn on its sides by its motion in its "seat" and will eventually try to close at an angle, and thus fails to shut off the fuel completely; again, this will cause excessive fuel flow and poor engine operation. Conversely, as the fuel evaporates from the float bowl, it leaves sediment, residue, and varnishes behind, which clog the passages and can interfere with the float operation. This is particularly a problem in automobiles operated for only part of the year and left to stand with full float chambers for months at a time; commercial fuel stabilizer additives are available that reduce this problem.

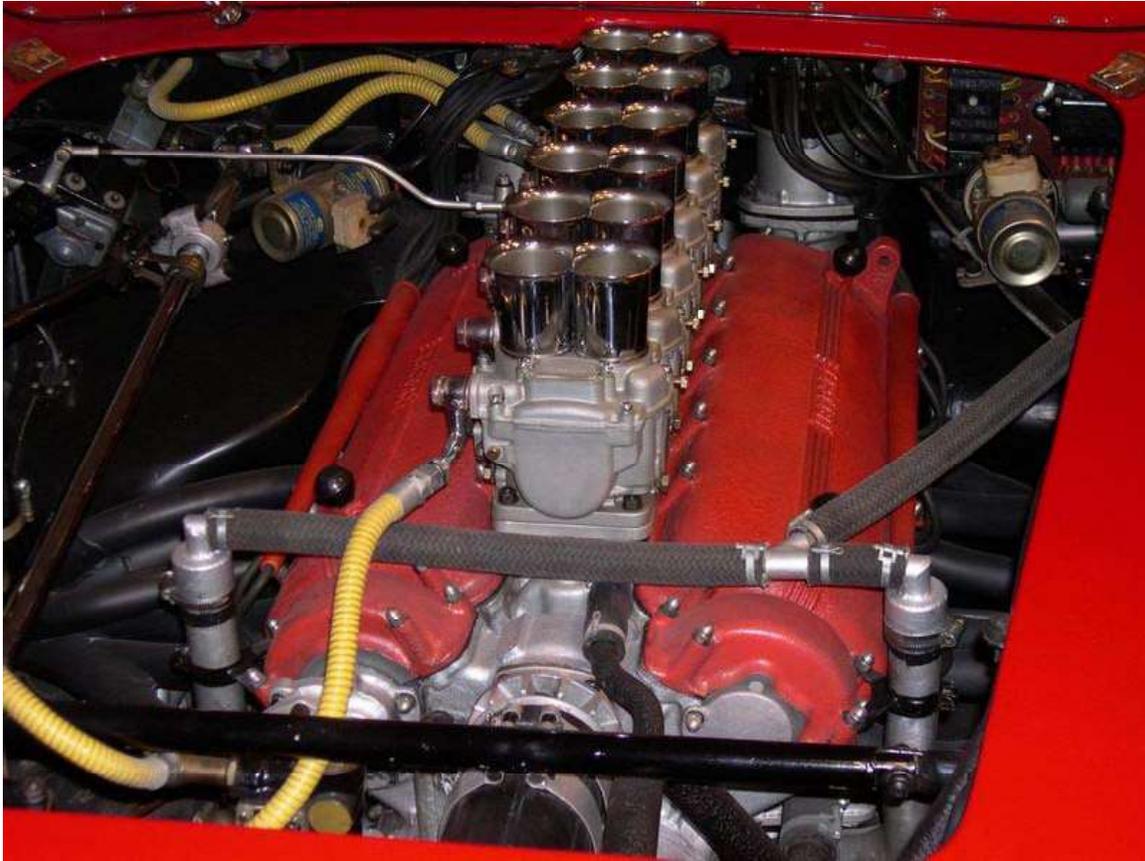
Usually, special vent tubes allow air to escape from the chamber as it fills or enter as it empties, maintaining atmospheric pressure within the float chamber; these usually extend into the carburetor throat. Placement of these vent tubes can be somewhat critical to prevent fuel from sloshing out of them into the carburetor, and sometimes they are modified with longer tubing. Note that this leaves the fuel at atmospheric pressure, and therefore it cannot travel into a throat which has been pressurized by a supercharger mounted upstream; in such cases, the entire carburetor must be contained in an airtight pressurized box to operate. This is not necessary in installations where the carburetor is mounted upstream of the supercharger, which is for this reason the more frequent system. However, this results in the supercharger being filled with compressed fuel/air mixture, with a strong tendency to explode should the engine backfire; this type of explosion is frequently seen in drag races, which for safety reasons now incorporate pressure releasing blow-off plates on the intake manifold, breakaway bolts holding the supercharger to the manifold, and shrapnel-catching ballistic nylon blankets surrounding the superchargers.

If the engine must be operated in any orientation (for example a chain saw), a float chamber cannot work. Instead, a diaphragm chamber is used. A flexible diaphragm forms one side of the fuel chamber and is arranged so that as fuel is drawn out into the engine the diaphragm is forced inward by ambient air pressure. The diaphragm is connected to the needle valve and as it moves inward it opens the needle valve to admit more fuel, thus replenishing the fuel as it is consumed. As fuel is replenished the diaphragm moves out due to fuel pressure and a small spring, closing the needle valve. A balanced state is reached which creates a steady fuel reservoir level, which remains constant in any orientation.

**Multiple carburetor barrels**



Holley model #2280 2-barrel carburetor



Colombo Type 125 "Testa Rossa" engine in a 1961 Ferrari 250TR Spider with six Weber two-barrel carburetors inducting air through 12 air horns; one individually adjustable barrel for each cylinder.

While basic carburetors have only one venturi, many carburetors have more than one venturi, or "barrel". Two barrel and four barrel configurations are commonly used to accommodate the higher air flow rate with large engine displacement. Multi-barrel carburetors can have non-identical primary and secondary barrel(s) of different sizes and calibrated to deliver different air/fuel mixtures; they can be actuated by the linkage or by engine vacuum in "progressive" fashion, so that the secondary barrels do not begin to open until the primaries are almost completely open. This is a desirable characteristic which maximizes airflow through the primary barrel(s) at most engine speeds, thereby maximizing the pressure "signal" from the venturis, but reduces the restriction in airflow at high speeds by adding cross-sectional area for greater airflow. These advantages may not be important in high-performance applications where part throttle operation is irrelevant, and the primaries and secondaries may all open at once, for simplicity and reliability; also, V-configuration engines, with two cylinder banks fed by a single carburetor, may be configured with two identical barrels, each supplying one cylinder bank. In the widely seen V8 and 4-barrel carburetor combination, there are often two primary and two secondary barrels.

The **spread-bore** 4-barrel carburetor, first released by Rochester in the 1965 model year as the "Quadrajets" has a much greater *spread* between the sizes of the primary and secondary throttle bores. The primaries in such a carburetor are quite small relative to conventional 4-barrel practice, while the secondaries are quite large. The small primaries aid low-speed fuel economy and drivability, while the large secondaries permit maximum performance when it is called for. To tailor airflow through the secondary venturis, each of the secondary throats has an air valve at the top. This is configured much like a choke plate, and is lightly spring-loaded into the closed position. The air valve opens progressively in response to engine speed and throttle opening, gradually allowing more air to flow through the secondary side of the carburetor. Typically, the air valve is linked to metering rods which are raised as the air valve opens, thereby adjusting secondary fuel flow.

Multiple carburetors can be mounted on a single engine, often with progressive linkages; two four-barrel carburetors were frequently seen on high performance American V8s, and multiple two barrel carburetors are often now seen on very high performance engines. Large numbers of small carburetors have also been used, though this configuration can limit the maximum air flow through the engine due to the lack of a common plenum; with individual intake tracts, not all cylinders are drawing air at once as the engine's crankshaft rotates.

### ***Carburetor adjustment***

Too much fuel in the fuel-air mixture is referred to as too **rich**, and not enough fuel is too **lean**. The mixture is normally adjusted by one or more needle valves on an automotive carburetor, or a pilot-operated lever on piston-engined aircraft (since mixture is air density (altitude) dependent). The (stoichiometric) air to gasoline ratio is 14.7:1, meaning that for each weight unit of gasoline, 14.7 units of air will be consumed. Stoichiometric mixture are different for various fuels other than gasoline.

Ways to check carburetor mixture adjustment include: measuring the carbon monoxide, hydrocarbon, and oxygen content of the exhaust using a gas analyzer, or directly viewing the colour of the flame in the combustion chamber through a special glass-bodied spark plug sold under the name "Colortune" for this purpose. The flame colour of stoichiometric burning is described as a "bunsen blue", turning to yellow if the mixture is rich and whitish-blue if too lean.

The mixture can also be judged after engine running by the state and color of the spark plugs: black, dry sooty plugs indicate a too rich mixture, white to light gray deposits on the plugs indicate a lean mixture. The correct color should be a brownish gray.

In the early 1980s, many American-market vehicles used special "feedback" carburetors that could change the base mixture in response to signals from an exhaust gas oxygen sensor. These were mainly used to save costs (since they worked well enough to meet 1980s emissions requirements and were based on existing carburetor designs), but

eventually disappeared as falling hardware prices and tighter emissions standards made fuel injection a standard item.

Where multiple carburetors are used the mechanical linkage of their throttles must be synchronized for smooth engine running.

### ***Catalytic carburetors***

A catalytic carburetor mixes fuel fumes with water and air in the presence of heated catalysts such as nickel or platinum. This breaks the fuel down into methane, alcohols, and other lighter-weight fuels. The original catalytic carburetor was introduced to permit farmers to run tractors from modified and enriched kerosene. The U.S. Army also used catalytic carburetors with great success in World War II, in the North African desert campaign.

While catalytic carburetors were made commercially available in the early 1930s, two major factors limited their widespread public use. First, the addition of additives to commercial gasoline made it unsuitable for use in engines with catalytic carburetors. (Tetra-ethyl lead, for example, was introduced in 1932 to raise gasoline's resistance to engine knock, thereby permitting the use of higher compression ratios.) Second, the economic advantage of using kerosene over gasoline faded in the 1930s, eliminating the catalytic carburetor's primary advantage.

## Chapter 6

# Distributor and Electronic Control Unit

## Distributor



Typical Distributor with distributor cap  
Also visible are mounting/drive shaft(bottom), vacuum advance unit (right) and capacitor(centre)



Breaker arm with contact points at the left. The pivot is on the right and the cam follower is in the middle of the breaker arm.



Distributor cap. At the center is a spring loaded carbon button that bears upon the rotor. The number of distribution points (in this case 4) is determined by the number of cylinders in the engine



Rotor. This rotates at the same speed as the camshaft, one half the speed of the crankshaft

A **distributor** is a device in the ignition system of an internal combustion engine that routes high voltage from the ignition coil to the spark plugs in the correct firing order. The first reliable battery operated ignition was developed by Dayton Engineering Laboratories Co. (Delco) and introduced in the 1910 Cadillac. This ignition was developed by Charles Kettering and was considered a wonder in its day.

### ***Description***

It consists of a rotating arm or rotor inside the distributor cap, on top of the distributor shaft, but insulated from it and the body of the vehicle (ground). The distributor shaft is driven by a gear on the camshaft. (Usually the distributor shaft extends to also drive the oil pump.) The metal part of the rotor contacts the central high voltage cable from the coil via a spring loaded carbon brush. The metal part of the rotor arm passes close to (but does not touch) the output contacts which connect via high tension leads to the spark plug of each cylinder. As the rotor spins within the distributor, electrical current is able to jump the small gaps created between the rotor arm and the contacts due to the high voltage created by the ignition coil.

The distributor shaft has a cam that operates the contact breaker. Opening the points causes a high induction voltage in the system's ignition coil.

The distributor also houses the centrifugal advance unit: a set of hinged weights attached to the distributor shaft, that cause the breaker points mounting plate to slightly rotate and advance the spark timing with higher engine rpm. In addition, the distributor has a

vacuum advance unit that advances the timing even further as a function of the vacuum in the inlet manifold. Usually there is also a capacitor attached to the distributor. The capacitor is connected parallel to the breaker points, to suppress sparking and prevent wear of the points.

Around the 1970s the primary breaker points were largely replaced with Hall effect sensors. As this is a non-contacting device and the primary circuit is controlled by solid state electronics, a great amount of maintenance in point adjustment and replacement was eliminated. This also eliminates any problem with breaker follower or cam wear, and by eliminating a side load extends distributor shaft bearing life. The remaining secondary (high voltage) circuit was as described above, using a single coil and a rotary distributor.

### ***Distributor cap***

A distributor cap is used in an automobile's engine to cover the distributor and its internal rotor.

The distributor cap has one post for each cylinder, and in points ignition systems there is a central post for the current from the ignition coil coming into the distributor. In high energy ignition (HEI) systems there is no central post and the ignition coil sits on top of the distributor. On the inside of the cap there is a terminal that corresponds to each post, and the plug terminals are arranged around the circumference of the cap according to the firing order in order to send the secondary voltage to the proper spark plug at the right time.

The rotor is attached to the top of the distributor shaft which is driven by a gear on the engine's camshaft and thus synchronized to it. Synchronization to the camshaft is required as the rotor must turn at exactly half the speed of the main crankshaft in the 4-stroke cycle. Often, the rotor and distributor are attached directly to the end of the one of (or the only) camshaft, at the opposite end to the timing drive belt. This rotor is pressed against a carbon brush on the center terminal of the distributor cap which connects to the ignition coil either through the top and wired directly to the coil in HEI systems, or via the center terminal in points ignition systems and remotely connected to the coil. The rotor is constructed such that the center tab is electrically connected to its outer edge so the current coming in to the center post travels through the carbon point to the outer edge of the rotor. As the camshaft rotates, the rotor spins and its outer edge passes each of the internal plug terminals to fire each spark plug in sequence.

Car engines that use a mechanical distributor may fail if they run into deep puddles because any water that leaks into the distributor can short out the electric current that should go through the spark plug, rerouting it directly to the body of the vehicle. This in turn causes the engine to stop as the fuel is not ignited in the cylinders. This problem can be fixed by removing the distributor's cap and drying the cap, cam, rotor and the contacts by: wiping with tissue paper or a clean rag, by blowing hot air on them, or using a moisture displacement spray i.e. WD 40 or similar. Oil, dirt or other contaminants can

cause similar problems, so the distributor should be kept clean inside and outside to ensure reliable operation.

The distributor cap is a prime example of a component that eventually succumbs to heat and vibration. It is a relatively easy and inexpensive part to replace if its bakelite housing does not break or crack first. Carbon deposit accumulation or erosion of its metal terminals may also cause distributor-cap failure.

### ***Direct & distributorless ignition***

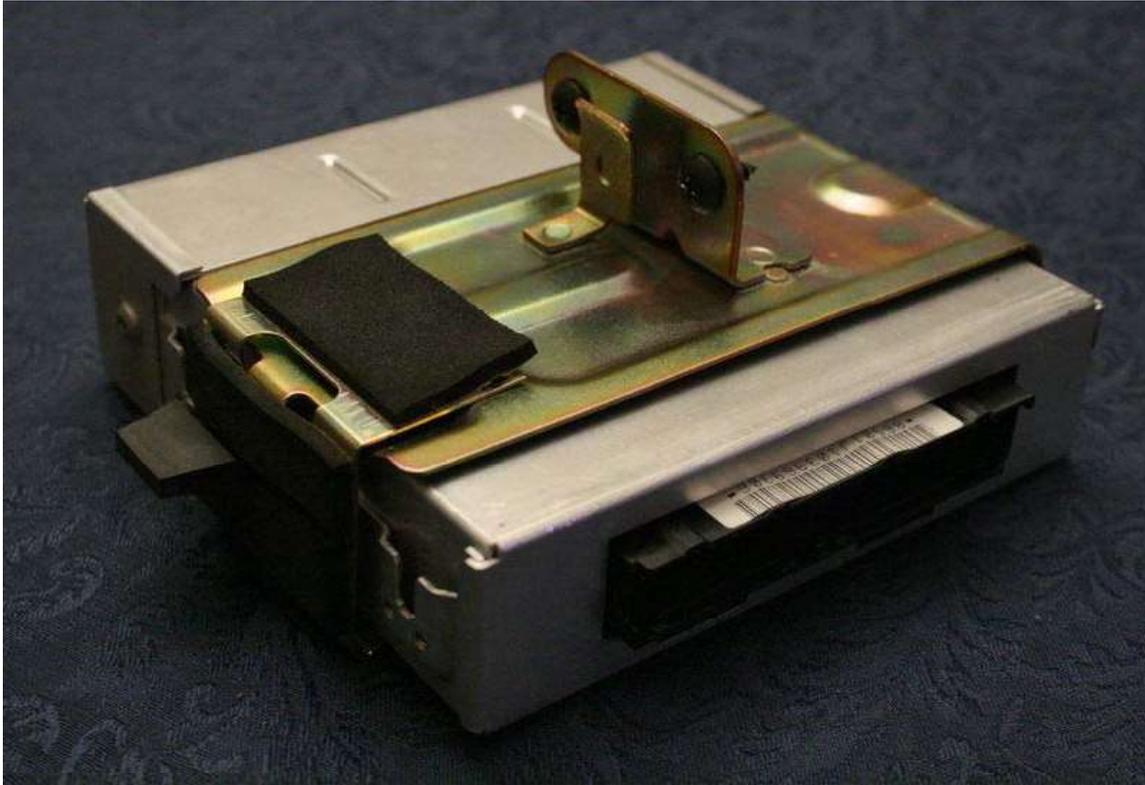
Modern engine designs have abandoned the high-voltage distributor and coil, instead performing the distribution function in the primary circuit electronically and applying the primary (low-voltage) pulse to individual coils for each spark plug, or one coil for each pair of companion cylinders in an engine (two coils for a four-cylinder, three coils for a six-cylinder, four coils for an eight-cylinder, and so on). In traditional remote distributorless systems, the coils are mounted together in a transformer oil filled 'coil pack', or separate coils for each cylinder, which are secured in a specified place in the engine compartment with wires to the spark plugs, similar to a distributor setup. Coil packs by Delco for use with General Motors engines allow removal of the individual coils in case one should fail, but in most other remote distributorless setups, if a coil were to fail, replacement of the whole pack would be required to fix the problem. More recent layouts utilize a coil located very near to or directly on top of each spark plug (**Direct Ignition**, 'DI' or coil-on-plug). This setup avoids the need to switch very high voltages, which is very often a source of trouble, especially in damp conditions. Both direct and remote distributorless systems also allow finer levels of ignition control by the engine computer, which assists in increasing power output, decreasing fuel consumption and emissions, and implementing features such as Active Fuel Management. Spark plug wires, which need routine replacement due to wear, are also eliminated when the individual coils are set directly on top of each plug, with the spark being transported a short distance from the coil through a rubber boot to the plug.

Four-stroke 2-cylinder engines can be built without a distributor, as in the Citroen 2CV of 1948 and BMW boxer twin motorcycles. Both spark plugs of the boxer twin are fired simultaneously, resulting in a wasted spark on the cylinder currently on its exhaust stroke.

Four-stroke 4-cylinder engines can be built without a distributor, as in the Citroen ID19. Two coils are used with one coil firing two of the spark plugs simultaneously, resulting in a wasted spark on the cylinder currently on its exhaust stroke, and the other coil used for the other two cylinders.

Four-stroke one-cylinder engines can be built without a distributor, as in many mowers. The spark plug is fired on every stroke, resulting in a wasted spark in the cylinder when on its exhaust stroke.

# Electronic control unit



An ECU from a Geo Storm.

In automotive electronics, **electronic control unit (ECU)** is a generic term for any embedded system that controls one or more of the electrical systems or subsystems in a motor vehicle.

Other terms for ECU include electronic control module (ECM), central control module (CCM), control unit, or control module. Taken together, these systems are sometimes referred to as the car's computer. (Technically there is no single computer but multiple ones.)

Some modern motor vehicles have up to 80 ECUs. Embedded software in ECUs continue to increase in line count, complexity, and sophistication. Managing the increasing complexity and number of ECUs in a vehicle has become a key challenge for original equipment manufacturers (OEMs).

## ***Types of electronic control units***

- Airbag Control Unit (ACU)
- Body Control Module controls door locks, electric windows, courtesy lights, etc.
- Convenience Control Unit (CCU)

- Door Control Unit
- Engine Control Unit (ECU)—not to be confused with *electronic* control unit, the generic term for all these devices
- Man Machine Interface (MMI)
- Powertrain Control Module (PCM): Sometimes the functions of the Engine Control Unit and Transmission Control Unit are combined into a single unit called the Powertrain Control Module.
- Seat Control Unit
- Speed Control Unit
- Telephone Control Unit (TCU)
- Transmission Control Unit (TCU)

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## Chapter 7

# 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 8

# Internal Combustion Engine Cooling

**Internal combustion engine cooling** refers to the cooling of an internal combustion engine, typically using either air or a liquid.

### Overview

Heat engines generate mechanical power by extracting energy from heat flows, much as a water wheel extracts mechanical power from a flow of mass falling through a distance. Engines are inefficient, so more heat energy enters the engine than comes out as mechanical power; the difference is waste heat which must be removed. Internal combustion engines remove waste heat through cool intake air, hot exhaust gases, and explicit engine cooling.

Engines with higher efficiency have more energy leave as mechanical motion and less as waste heat. Some waste heat is essential: it guides heat through the engine, much as a water wheel works only if there is some exit velocity (energy) in the waste water to carry it away and make room for more water. Thus, all heat engines need cooling to operate.

Cooling is also needed because high temperatures damage engine materials and lubricants. Internal-combustion engines burn fuel hotter than the melting temperature of engine materials, and hot enough to set fire to lubricants. Engine cooling removes energy fast enough to keep temperatures low so the engine can survive.

Some high-efficiency engines run without explicit cooling and with only accidental heat loss, a design called adiabatic. For example, 10,000 mile-per-gallon "cars" for the Shell economy challenge are insulated, both to transfer as much energy as possible from hot gases to mechanical motion, and to reduce reheat losses when restarting. Such engines can achieve high efficiency but compromise power output, duty cycle, engine weight, durability, and emissions.

## ***Basic principles***

Most internal combustion engines are fluid cooled using either air (a gaseous fluid) or a liquid coolant run through a heat exchanger (radiator) cooled by air. Marine engines and some stationary engines have ready access to a large volume of water at a suitable temperature. The water may be used directly to cool the engine, but often has sediment, which can clog coolant passages, or chemicals, such as salt, that can chemically damage the engine. Thus, engine coolant may be run through a heat exchanger that is cooled by the body of water.

Most liquid-cooled engines use a mixture of water and chemicals such as antifreeze and rust inhibitors. The industry term for the antifreeze mixture is *engine coolant*. Some antifreezes use no water at all, instead using a liquid with different properties, such as propylene glycol or a combination of propylene glycol and ethylene glycol. Most "air-cooled" engines use some liquid oil cooling, to maintain acceptable temperatures for both critical engine parts and the oil itself. Most "liquid-cooled" engines use some air cooling, with the intake stroke of air cooling the combustion chamber. An exception is Wankel engines, where some parts of the combustion chamber are never cooled by intake, requiring extra effort for successful operation.

There are many demands on a cooling system. One key requirement is that an engine fails if just one part overheats. Therefore, it is vital that the cooling system keep *all* parts at suitably low temperatures. Liquid-cooled engines are able to vary the size of their passageways through the engine block so that coolant flow may be tailored to the needs of each area. Locations with either high peak temperatures (narrow islands around the combustion chamber) or high heat flow (around exhaust ports) may require generous cooling. This reduces the occurrence of hot spots, which are more difficult to avoid with air cooling. Air cooled engines may also vary their cooling capacity by using more closely-spaced cooling fins in that area, but this can make their manufacture difficult and expensive.

Only the fixed parts of the engine, such as the block and head, are cooled directly by the main coolant system. Moving parts such as the pistons, and to a lesser extent the crank and rods, must rely on the lubrication oil as a coolant, or to a very limited amount of conduction into the block and thence the main coolant. High performance engines frequently have additional oil, beyond the amount needed for lubrication, sprayed upwards onto the bottom of the piston just for extra cooling. Air-cooled motorcycles often rely heavily on oil-cooling in addition to air-cooling of the cylinder barrels.

Liquid-cooled engines usually have a circulation pump. The first engines relied on thermo-syphon cooling alone, where hot coolant left the top of the engine block and passed to the radiator, where it was cooled before returning to the bottom of the engine. Circulation was powered by convection alone.

Other demands include cost, weight, reliability, and durability of the cooling system itself.

Conductive heat transfer is proportional to the temperature difference between materials. If engine metal is at 250 °C and the air is at 20°C, then there is a 230°C temperature difference for cooling. An air-cooled engine uses all of this difference. In contrast, a liquid-cooled engine might dump heat from the engine to a liquid, heating the liquid to 135°C (Water's standard boiling point of 100°C can be exceeded as the cooling system is both pressurised, and uses a mixture with antifreeze) which is then cooled with 20°C air. In each step, the liquid-cooled engine has half the temperature difference and so at first appears to need twice the cooling area.

However, properties of the coolant (water, oil, or air) also affect cooling. As example, comparing water and oil as coolants, one gram of oil can absorb about 55% of the heat for the same rise in temperature (called the specific heat capacity). Oil has about 90% the density of water, so a given volume of oil can absorb only about 50% of the energy of the same volume of water. The thermal conductivity of water is about 4 times that of oil, which can aid heat transfer. The viscosity of oil can be ten times greater than water, increasing the energy required to pump oil for cooling, and reducing the net power output of the engine.

Comparing air and water, air has vastly lower heat capacity per gram and per volume (4000) and less than a tenth the conductivity, but also much lower viscosity (about 200 times lower:  $17.4 \times 10^{-6}$  Pa·s for air vs  $8.94 \times 10^{-4}$  Pa·s for water). Continuing the calculation from two paragraphs above, air cooling needs ten times of the surface area, therefore the fins, and air needs 2000 times the flow velocity and thus a recirculating air fan needs ten times the power of a recirculating water pump. Moving heat from the cylinder to a large surface area for air cooling can present problems such as difficulties manufacturing the shapes needed for good heat transfer and the space needed for free flow of a large volume of air. Water boils at about the same temperature desired for engine cooling. This has the advantage that it absorbs a great deal of energy with very little rise in temperature (called heat of vaporization), which is good for keeping things cool, especially for passing one stream of coolant over several hot objects and achieving uniform temperature. In contrast, passing air over several hot objects in series warms the air at each step, so the first may be over-cooled and the last under-cooled. However, once water boils, it is an insulator, leading to a sudden loss of cooling where steam bubbles form. Unfortunately, steam may return to water as it mixes with other coolant, so an engine temperature gauge can indicate an acceptable temperature even though local temperatures are high enough that damage is being done.

An engine needs different temperatures. The inlet including the compressor of a turbo and in the inlet trumpets and the inlet valves need to be as cold as possible. A countercurrent heat exchange with forced cooling air does the job. The cylinder-walls should not heat up the air before compression, but also not cool down the gas at the combustion. A compromise is a wall temperature of 90°C. The viscosity of the oil is optimized for just this temperature. Any cooling of the exhaust and the turbine of the turbocharger reduces the amount of power available to the turbine, so the exhaust system is often insulated between engine and turbocharger to keep the exhaust gases as hot as possible.

The temperature of the cooling air may range from well below freezing to 50°C. Further, while engines in long-haul boat or rail service may operate at a steady load, road vehicles often see widely-varying and quickly-varying load. Thus, the cooling system is designed to vary cooling so the engine is neither too hot nor too cold. Cooling system regulation includes adjustable baffles in the air flow (sometimes called 'shutters' and commonly run by a pneumatic 'shutterstat'); a fan which operates either independently of the engine, such as an electric fan, or which has an adjustable clutch; a thermostatic valve or just 'thermostat' that can block the coolant flow when too cool. In addition, the motor, coolant, and heat exchanger have some heat capacity which smooths out temperature increase in short sprints. Some engine controls shut down an engine or limit it to half throttle if it overheats. Modern electronic engine controls adjust cooling based on throttle to anticipate a temperature rise, and limit engine power output to compensate for finite cooling.

Finally, other concerns may dominate cooling system design. As example, air is a relatively poor coolant, but air cooling systems are simple, and failure rates typically rise as the square of the number of failure points. Also, cooling capacity is reduced only slightly by small air coolant leaks. Where reliability is of utmost importance, as in aircraft, it may be a good trade-off to give up efficiency, durability (interval between engine rebuilds), and quietness in order to achieve slightly higher reliability — the consequences of a broken airplane engine are so severe, even a slight increase in reliability is worth giving up other good properties to achieve it.

Air cooled and liquid-cooled engines are both used commonly. Each principle has advantages and disadvantages, and particular applications may favor one over the other. For example, most cars and trucks use liquid-cooled engines, while many small airplane and low-cost engines are air-cooled.

### ***Generalization difficulties***

It is difficult to make generalizations about air-cooled and liquid-cooled engines. Air-cooled Volkswagen kombis are known for rapid wear in normal use and sometimes sudden failure when driven in hot weather. Alternately, air-cooled Deutz diesel engines are known for reliability even in extreme heat, and are often used in situations where the engine runs unattended for months at a time.

Similarly, it is usually desirable to minimize the number of heat transfer stages in order to maximize the temperature difference at each stage. However, Detroit Diesel 2-stroke cycle engines commonly use oil cooled by water, with the water in turn cooled by air.

The coolant used in many liquid-cooled engines must be renewed periodically, and can freeze at ordinary temperatures thus causing permanent engine damage. Air-cooled engines do not require coolant service, and do not suffer engine damage from freezing, two commonly-cited advantages for air-cooled engines. However, coolant based on propylene glycol is liquid to -55 °C, colder than is encountered by many engines; shrinks

slightly when it crystallizes, thus avoiding engine damage; and has a service life over 10,000 hours, essentially the lifetime of many engines.

It is usually more difficult to achieve either low emissions or low noise from an air-cooled engine, two more reasons most road vehicles use liquid-cooled engines. It is also often difficult to build large air-cooled engines, so nearly all air-cooled engines are under 500 kW (670 hp), whereas large liquid-cooled engines exceed 80 MW (107000 hp) (Wärtsilä-Sulzer RTA96-C 14-cylinder diesel).

### ***Air-cooling***

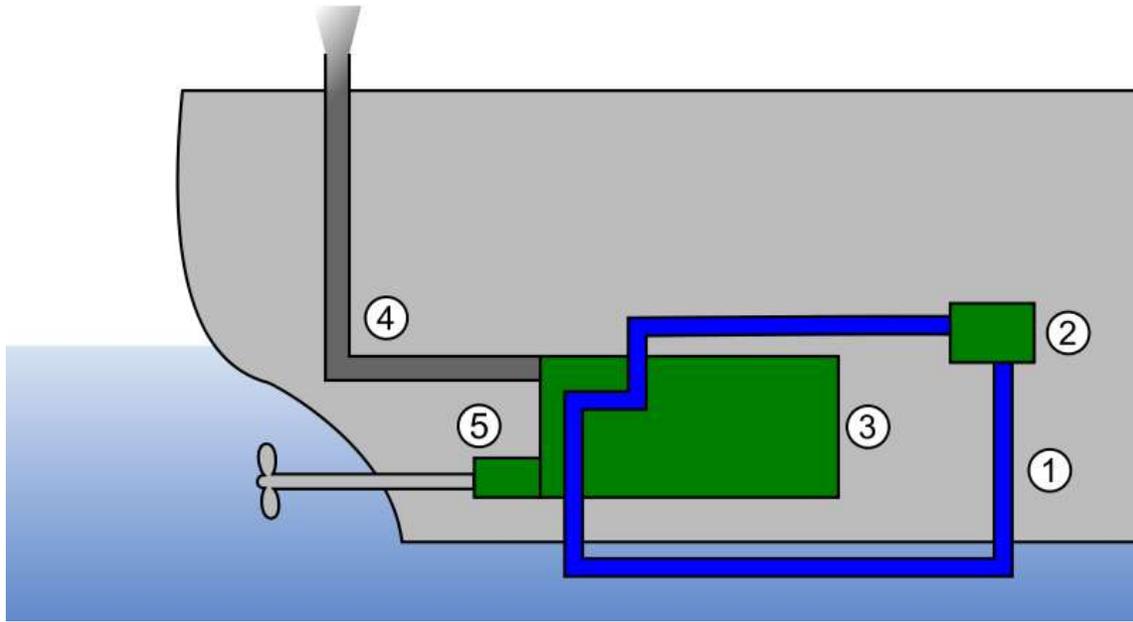
Cars and trucks using direct air cooling (without an intermediate liquid) were built over a long period beginning with the advent of mass produced passenger cars and ending with a small and generally unrecognized technical change. Before World War II, water cooled cars and trucks routinely overheated while climbing mountain roads, creating geysers of boiling cooling water. This was considered normal, and at the time, most noted mountain roads had auto repair shops to minister to overheating engines.

ACS (Auto Club Suisse) maintains historical monuments to that era on the Susten Pass where two radiator refill stations remain. These have instructions on a cast metal plaque and a spherical bottom watering can hanging next to a water spigot. The spherical bottom was intended to keep it from being set down and, therefore, be useless around the house, in spite of which it was stolen, as the picture shows.

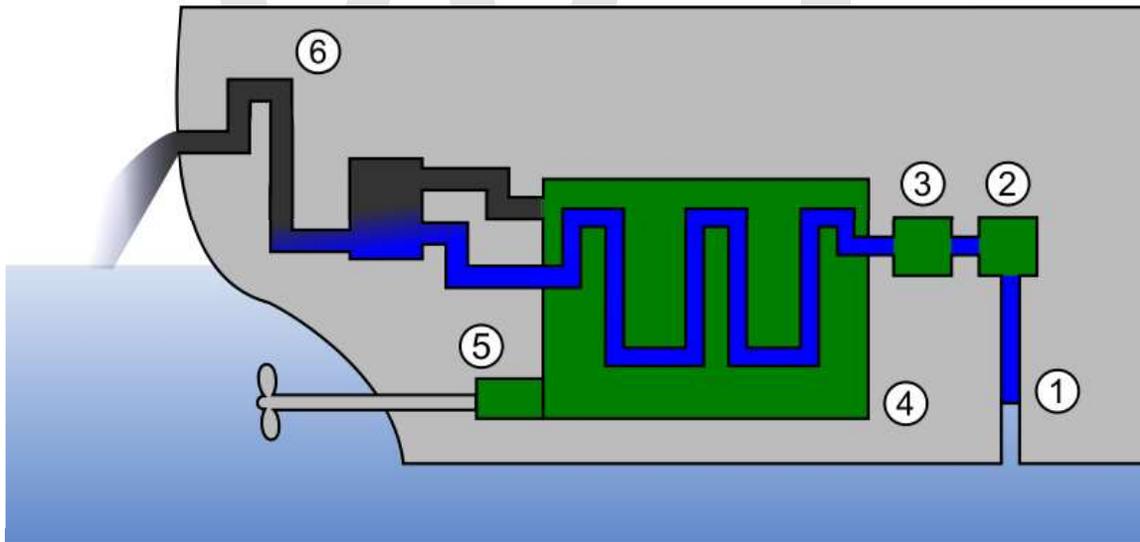
During that period, European firms such as Magirus-Deutz built air-cooled diesel trucks, Porsche built air-cooled farm tractors, and Volkswagen became famous with air-cooled passenger cars. In the USA, Franklin built air-cooled engines. The Czechoslovakia based company Tatra is known for their big size air cooled V8 car engines, Tatra engineer Julius Mackerle published a book on it. Air cooled engines are better adapted to extremely cold and hot environmental weather temperatures, you can see air cooled engines starting and running in freezing conditions that stuck water cooled engines and continue working when water cooled ones start producing steam jets.

### ***Liquid cooling***

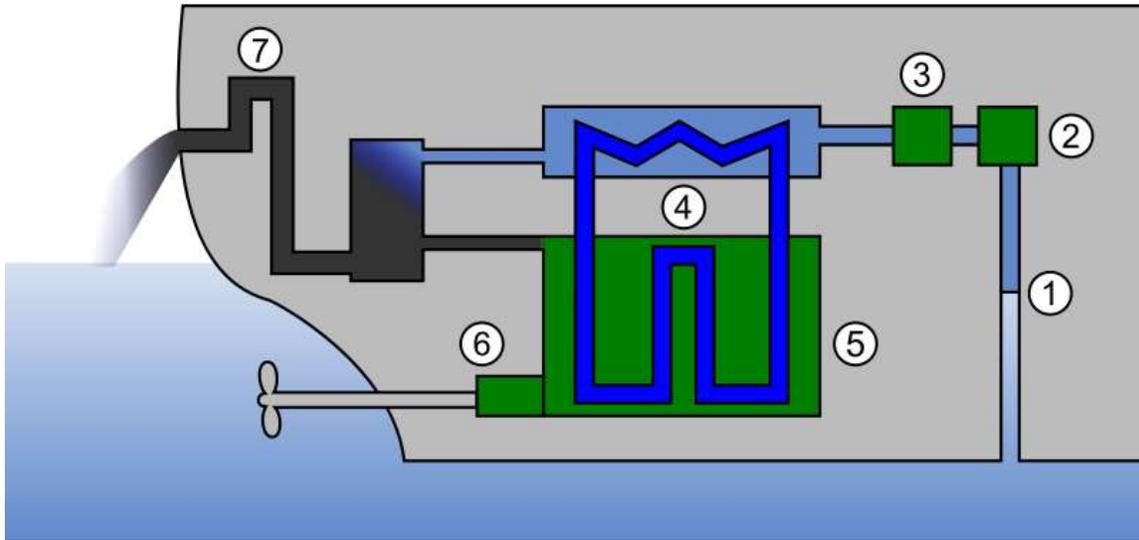
Today, most engines are liquid-cooled.



A fully closed IC engine cooling system



Open IC engine cooling system



Semiclosed IC engine cooling system

Liquid cooling is also employed in maritime vehicles (vessels, ...). For vessels, the seawater itself is mostly used for cooling. In some cases, chemical coolants are also employed (in closed systems) or they are mixed with seawater cooling.

### ***Transition Away From Air Cooling***

The change of air cooling to liquid cooling occurred at the start of World War II when the US military needed reliable vehicles. The subject of boiling engines was addressed, researched, and a solution found. Previous radiators and engine blocks were properly designed and survived durability tests, but used water pumps with a leaky graphite-lubricated "rope" seal (gland) on the pump shaft. The seal was inherited from steam engines, where water loss is accepted, since steam engines already expend large volumes of water. Because the pump seal leaked mainly when the pump was running and the engine was hot, the water loss evaporated inconspicuously, leaving at best a small rusty trace when the engine stopped and cooled, thereby not revealing significant water loss. Automobile radiators (or heat exchangers) have an outlet that feeds cooled water to the engine and the engine has an outlet that feeds heated water to the top of the radiator. Water circulation is aided by a rotary pump that has only a slight effect, having to work over such a wide range of speeds that its impeller has only a minimal effect as a pump. While running, the leaking pump seal drained cooling water to a level where the pump could no longer return water to the top of the radiator, so water circulation ceased and water in the engine boiled. However, since water loss led to overheat and further water loss from boil-over, the original water loss was hidden.

After isolating the pump problem, cars and trucks built for the war effort (no civilian cars were built during that time) were equipped with carbon-seal water pumps that did not

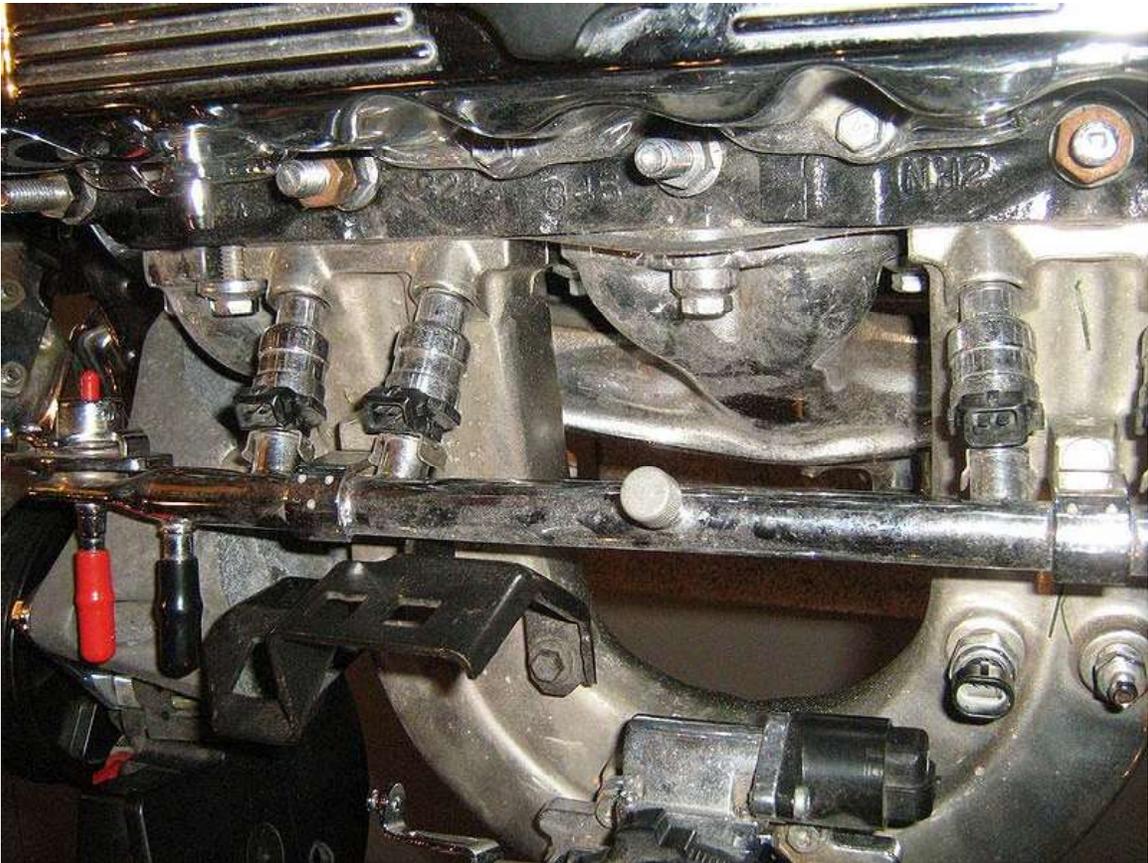
leak and caused no more geysers. Meanwhile, air cooling advanced in memory of boiling engines... even though boil-over was no longer a common problem. Air-cooled engines became popular throughout Europe. After the war, Volkswagen advertised in the USA as not boiling over, even though new water-cooled cars no longer boiled over, but these cars sold well, and without question. But as air quality awareness rose in the 1960s, and laws governing exhaust emissions were passed, unleaded gas replaced leaded gas and leaner fuel mixtures became the norm. These reductions in the cooling effects of both the lead and the formerly rich fuel mixture, led to overheating in the air-cooled engines. Valve failures and other engine damage was the result. Volkswagen responded by abandoning their (flat) horizontally opposed air-cooled engines, while Subaru took a different course and chose liquid-cooling for their (flat) engines.

Today practically no air-cooled automotive engines are built, air cooling being fraught with manufacturing expense and maintenance problems. Motorcycles had an additional problem in that a water leak presented a greater threat to reliability, their engines having small cooling water volume, so they were loath to change; today most larger motorcycles are water cooled with many relying on convection circulation with no pump.

WWT

## Chapter 9

# Fuel Injection



Fuel rail connected to the injectors that are mounted just above the intake manifold on a four cylinder engine.

**Fuel injection** is a system for mixing fuel with air in an internal combustion engine. It has become the primary fuel delivery system used in automotive petrol engines, having almost completely replaced carburetors in the late 1980s.

A fuel injection system is designed and calibrated specifically for the type(s) of fuel it will handle. Most fuel injection systems are for gasoline or diesel applications. With the advent of electronic fuel injection (EFI), the diesel and gasoline hardware has become similar. EFI's programmable firmware has permitted common hardware to be used with different fuels.

Carburetors were the predominant method used to meter fuel on gasoline engines before the widespread use of fuel injection. A variety of injection systems have existed since the earliest usage of the internal combustion engine.

The primary difference between carburetors and fuel injection is that fuel injection atomizes the fuel by forcibly pumping it through a small nozzle under high pressure, while a carburetor relies on low pressure created by intake air rushing through it to add the fuel to the airstream.

The fuel injector is only a nozzle and a valve: the power to inject the fuel comes from a pump or a pressure container farther back in the fuel supply.

## **Objectives**

The functional objectives for fuel injection systems can vary. All share the central task of supplying fuel to the combustion process, but it is a design decision how a particular system will be optimized. There are several competing objectives such as:

- power output
- fuel efficiency
- emissions performance
- ability to accommodate alternative fuels
- reliability
- driveability and smooth operation
- initial cost
- maintenance cost
- diagnostic capability
- range of environmental operation
- Engine tuning

Certain combinations of these goals are conflicting, and it is impractical for a single engine control system to fully optimize all criteria simultaneously. In practice, automotive engineers strive to best satisfy a customer's needs competitively. The modern digital electronic fuel injection system is far more capable at optimizing these competing objectives consistently than a carburetor. Carburetors have the potential to atomize fuel better.

## **Benefits**

### **Engine operation**

Operational benefits to the driver of a fuel-injected car include smoother and more dependable engine response during quick throttle transitions, easier and more dependable engine starting, better operation at extremely high or low ambient temperatures, increased maintenance intervals, and increased fuel efficiency. On a more basic level, fuel injection does away with the choke which on carburetor-equipped vehicles must be operated when starting the engine from cold and then adjusted as the engine warms up.

An engine's air/fuel ratio must be precisely controlled under all operating conditions to achieve the desired engine performance, emissions, driveability, and fuel economy. Modern electronic fuel-injection systems meter fuel very accurately, and use closed loop fuel-injection quantity-control based on a variety of feedback signals from an oxygen sensor, a mass airflow (MAF) or manifold absolute pressure (MAP) sensor, a throttle position (TPS), and at least one sensor on the crankshaft and/or camshaft(s) to monitor the engine's rotational position. Fuel injection systems can react rapidly to changing inputs such as sudden throttle movements, and control the amount of fuel injected to match the engine's dynamic needs across a wide range of operating conditions such as engine load, ambient air temperature, engine temperature, fuel octane level, and atmospheric pressure.

A multipoint fuel injection system generally delivers a more accurate and equal mass of fuel to each cylinder than can a carburetor, thus improving the cylinder-to-cylinder distribution. Exhaust emissions are cleaner because the more precise and accurate fuel metering reduces the concentration of toxic combustion byproducts leaving the engine, and because exhaust cleanup devices such as the catalytic converter can be optimized to operate more efficiently since the exhaust is of consistent and predictable composition.

Fuel injection generally increases engine fuel efficiency. With the improved cylinder-to-cylinder fuel distribution, less fuel is needed for the same power output. When cylinder-to-cylinder distribution is less than ideal, as is always the case to some degree with a carburetor or throttle body fuel injection, some cylinders receive excess fuel as a side effect of ensuring that all cylinders receive *sufficient* fuel. Power output is asymmetrical with respect to air/fuel ratio; burning extra fuel in the rich cylinders does not reduce power nearly as quickly as burning too little fuel in the lean cylinders. However, rich-running cylinders are undesirable from the standpoint of exhaust emissions, fuel efficiency, engine wear, and engine oil contamination. Deviations from perfect air/fuel distribution, however subtle, affect the emissions, by not letting the combustion events be at the chemically ideal (stoichiometric) air/fuel ratio. Grosser distribution problems eventually begin to reduce efficiency, and the grossest distribution issues finally affect power. Increasingly poorer air/fuel distribution affects emissions, efficiency, and power, in that order. By optimizing the homogeneity of cylinder-to-cylinder mixture distribution, all the cylinders approach their maximum power potential and the engine's overall power output improves.

A fuel-injected engine often produces more power than an equivalent carbureted engine. Fuel injection alone does not necessarily increase an engine's maximum potential output. Increased airflow is needed to burn more fuel, which in turn releases more energy and produces more power. The combustion process converts the fuel's chemical energy into heat energy, whether the fuel is supplied by fuel injectors or a carburetor. However, airflow is often improved with fuel injection, the components of which allow more design freedom to improve the air's path into the engine. In contrast, a carburetor's mounting options are limited because it is larger, it must be carefully oriented with respect to gravity, and it must be equidistant from each of the engine's cylinders to the maximum practicable degree. These design constraints generally compromise airflow into the engine. Furthermore, a carburetor relies on a restrictive venturi to create a local air pressure difference, which forces the fuel into the air stream. The flow loss caused by the venturi, however, is small compared to other flow losses in the induction system. In a well-designed carburetor induction system, the venturi is not a significant airflow restriction.

Fuel is saved while the car is coasting because the car's movement is helping to keep the engine rotating, so less fuel is used for this purpose. Control units on modern cars react to this and reduce or stop fuel flow to the engine reducing wear on the brakes.

### ***History and development***

Herbert Akroyd Stuart developed the first system laid out on modern lines (with a highly-accurate 'jerk pump' to meter out fuel oil at high pressure to an injector. This system was used on the hot bulb engine and was adapted and improved by Robert Bosch for use on diesel engines — Rudolf Diesel's original system employed a cumbersome 'air-blast' system using highly compressed air.

The first use of direct gasoline injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925. Hesselman engines use the ultra lean burn principle; fuel is injected toward the end of the compression stroke, then ignited with a spark plug. They are often started on gasoline and then switched to diesel or kerosene. Fuel injection was in widespread commercial use in diesel engines by the mid-1920s. Because of its greater immunity to wildly changing g-forces on the engine, the concept was adapted for use in gasoline-powered aircraft during World War II, and direct injection was employed in some notable designs like the Junkers Jumo 210, the Daimler-Benz DB 601, the BMW 801, the Shvetsov ASh-82FN (M-82FN) and later versions of the Wright R-3350 used in the B-29 Superfortress.

Alfa Romeo tested one of the very first electric injection systems (Caproni-Fuscaldo) in Alfa Romeo 6C2500 with "Ala spessa" body in 1940 Mille Miglia. The engine had six electrically operated injectors and were fed by a semi-high pressure circulating fuel pump system.

## Mechanical

The term **Mechanical** when applied to fuel injection is used to indicate that *metering functions* of the fuel injection (how the correct amount of fuel for any given situation is determined and delivered) is not achieved electronically but rather through mechanical means alone.

In the 1940s, hot rodder Stuart Hilborn offered mechanical injection for racers, salt cars, and midgets.

One of the first commercial gasoline injection systems was a mechanical system developed by Bosch and introduced in 1952 on the Goliath GP700 and Gutbrod Superior 600. This was basically a high pressure diesel direct-injection pump with an intake throttle valve set up. (Diesels only change amount of fuel injected to vary output; there is no throttle.) This system used a normal gasoline fuel pump, to provide fuel to a mechanically driven injection pump, which had separate plungers per injector to deliver a very high injection pressure directly into the combustion chamber.

Another mechanical system, also by Bosch, but injecting the fuel into the port above the intake valve was later used by Porsche from 1969 until 1973 for the 911 production range and until 1975 on the Carrera 3.0 in Europe. Porsche continued using it on its racing cars into the late seventies and early eighties. Porsche racing variants such as the 911 RSR 2.7 & 3.0, 904/6, 906, 907, 908, 910, 917 (in its regular normally aspirated or 5.5 Liter/1500 HP Turbocharged form), and 935 all used Bosch or Kugelfischer built variants of injection. The Kugelfischer system was also used by the BMW 2000/2002 Tii and some versions of the Peugeot 404/504 and Lancia Flavia. Lucas also offered a mechanical system which was used by some Maserati, Aston Martin and Triumph models between ca. 1963 and 1973.

A system similar to the Bosch inline mechanical pump was built by SPICA for Alfa Romeo, used on the Alfa Romeo Montreal and on US market 1750 and 2000 models from 1969-1981. This was specifically designed to meet the US emission requirements, and allowed Alfa to meet these requirements with no loss in performance and a reduction in fuel consumption.

Chevrolet introduced a mechanical fuel injection option, made by General Motors' Rochester Products division, for its 283 V8 engine in 1956 (1957 US model year). This system directed the inducted engine air across a "spoon shaped" plunger that moved in proportion to the air volume. The plunger connected to the fuel metering system which mechanically dispensed fuel to the cylinders via distribution tubes. This system was not a "pulse" or intermittent injection, but rather a constant flow system, metering fuel to all cylinders simultaneously from a central "spider" of injection lines. The fuel meter adjusted the amount of flow according to engine speed and load, and included a fuel reservoir, which was similar to a carburetor's float chamber. With its own high-pressure fuel pump driven by a cable from the distributor to the fuel meter, the system supplied the necessary pressure for injection. This was "port" injection, however, in which the

injectors are located in the intake manifold, very near the intake valve. (Direct fuel injection is a fairly recent innovation for automobile engines. As recent as 1954 in the aforementioned Mercedes-Benz 300SL or the Gutbrod in 1953.) The highest performance version of the fuel injected engine was rated at 283 bhp (211.0 kW) from 283 cubic inches (4.6 L). This made it among the early production engines in history to exceed 1 hp/in<sup>3</sup> (45.5 kW/L), after Chrysler's Hemi engine and a number of others. General Motors' fuel injected engine — usually referred to as the "fuelie" — was optional on the Corvette for the 1957 model year.

During the 1960s, other mechanical injection systems such as Hilborn were occasionally used on modified American V8 engines in various racing applications such as drag racing, oval racing, and road racing. These racing-derived systems were not suitable for everyday street use, having no provisions for low speed metering or even starting (fuel had to be squirted into the injector tubes while cranking the engine in order to start it). However they were a favorite in the aforementioned competition trials in which essentially wide-open throttle operation was prevalent.

## Electronic

The first commercial electronic fuel injection (EFI) system was **Electrojector**, developed by the Bendix Corporation and was to be offered by American Motors (AMC) in 1957. A special muscle car model, the Rambler Rebel, showcased AMC's new 327 cu in (5.4 L) engine. The Electrojector was an option and rated at 288 bhp (214.8 kW). With no Venturi effect or heated carburetor (to help vaporize the gasoline) AMC's EFI equipped engine breathed easier with denser cold air to pack more power sooner, reaching peak torque at 500 rpm lower than the equivalent no-fuel injection engine. The Rebel Owners Manual described the design and operation of the new system. Initial press information about the Bendix system in December 1956 was followed in March 1957 by a price bulletin that pegged the option at US\$395, but due to supplier difficulties, fuel-injected Rebels would only be available after June 15. This was to have been the first production EFI engine, but Electrojector's teething problems meant only pre-production cars were so equipped: thus, very few cars so equipped were ever sold and none were made available to the public. The EFI system in the Rambler was a far more-advanced setup than the mechanical types then appearing on the market and the engines ran fine in warm weather, but suffered hard starting in cooler temperatures.

Chrysler offered Electrojector on the 1958 Chrysler 300D, Dodge D500, Plymouth Fury, and DeSoto Adventurer, arguably the first series-production cars equipped with an EFI system. It was jointly engineered by Chrysler and Bendix. The early electronic components were not equal to the rigors of underhood service, however, and were too slow to keep up with the demands of "on the fly" engine control. Most of the 35 vehicles originally so equipped were field-retrofitted with 4-barrel carburetors. The Electrojector patents were subsequently sold to Bosch.

Bosch developed an electronic fuel injection system, called *D-Jetronic* (*D* for *Druck*, German for "pressure"), which was first used on the VW 1600TL/E in 1967. This was a

speed/density system, using engine speed and intake manifold air density to calculate "air mass" flow rate and thus fuel requirements. This system was adopted by VW, Mercedes-Benz, Porsche, Citroën, Saab, and Volvo. Lucas licensed the system for production with Jaguar. Bosch superseded the D-Jetronic system with the *K-Jetronic* and *L-Jetronic* systems for 1974, though some cars (such as the Volvo 164) continued using D-Jetronic for the following several years.



Chevrolet Cosworth Vega engine showing Bendix electronic fuel injection

The Cadillac Seville was introduced in 1975 with an EFI system made by Bendix and modelled very closely on Bosch's D-Jetronic. L-Jetronic first appeared on the 1974 Porsche 914, and uses a mechanical airflow meter (L for *Luft*, German for "air") that produces a signal that is proportional to "air volume". This approach required additional sensors to measure the atmospheric pressure and temperature, to ultimately calculate "air mass". L-Jetronic was widely adopted on European cars of that period, and a few Japanese models a short time later.

The limited production Chevrolet Cosworth Vega was introduced in March 1975 using a Bendix EFI system with pulse-time manifold injection, four injector valves, an electronic control unit (ECU), five independent sensors and two fuel pumps. The EFI system was developed to satisfy stringent emission control requirements and market demands for a technologically advanced responsive vehicle, but only 3508 were produced through 1976.

In 1982, Bosch introduced a sensor that directly measures the air mass flow into the engine, on their L-Jetronic system. Bosch called this *LH-Jetronic* (L for *Luftmasse* and H for *Hitzdraht*, German for "air mass" and "hot wire", respectively). The mass air sensor utilizes a heated platinum wire placed in the incoming air flow. The rate of the wire's cooling is proportional to the air mass flowing across the wire. Since the hot wire sensor directly measures air mass, the need for additional temperature and pressure sensors is eliminated. The LH-Jetronic system was also the first fully-digital EFI system, which is now the standard approach. The advent of the digital microprocessor permitted the integration of all powertrain sub-systems into a single control module.

## ***Supersession of carburetors***

When efficient combustion takes place in an internal combustion engine, the proper number of fuel molecules and oxygen molecules are sent to the engine's combustion chamber(s), where fuel combustion (i.e., fuel oxidation) takes place. When efficient combustion takes place, neither extra fuel or extra oxygen molecules remain: each fuel molecule is matched with the appropriate number of oxygen molecules. This balanced condition is called stoichiometry.

In the 1970s and 1980s in the US, the federal government imposed increasingly strict exhaust emission regulations. During that time period, the vast majority of gasoline-fueled automobile and light truck engines did not use fuel injection. To comply with the new regulations, automobile manufacturers often made extensive and complex modifications to the engine carburetor(s). While a simple carburetor system has certain advantages compared to the fuel injection systems that were available during the 1970s and 1980s (including lower manufacturing cost), the more complex carburetor systems installed on many engines beginning in the early 1970s did not usually have these advantages. So in order to more easily comply with government emissions control regulations, automobile manufacturers, beginning in the late 1970s, furnished more of their gasoline-fueled engines with fuel injection systems, and fewer with complex carburetor systems.

There are three primary types of toxic emissions from an internal combustion engine: Carbon Monoxide (CO), unburnt hydrocarbons (HC), and oxides of nitrogen (NOx). CO and HC result from incomplete combustion of fuel due to insufficient oxygen in the combustion chamber. NOx, in contrast, results from excessive oxygen in the combustion chamber. The opposite causes of these pollutants makes it difficult to control all three simultaneously. Once the permissible emission levels dropped below a certain point, catalytic treatment of these three main pollutants became necessary. This required a particularly large increase in fuel metering accuracy and precision, for simultaneous catalysis of all three pollutants requires that the fuel/air mixture be held within a very narrow range of stoichiometry. The open loop fuel injection systems had already improved cylinder-to-cylinder fuel distribution and engine operation over a wide temperature range, but did not offer sufficient fuel/air mixture control to enable effective exhaust catalysis. **Closed loop** fuel injection systems improved the air/fuel mixture control with an exhaust gas oxygen sensor. The O<sub>2</sub> sensor is mounted in the exhaust

system upstream of the catalytic converter, and enables the engine management computer to determine and adjust the air/fuel ratio precisely and quickly.

Fuel injection was phased in through the latter '70s and '80s at an accelerating rate, with the US, French and German markets leading and the UK and Commonwealth markets lagging somewhat, and since the early 1990s, almost all gasoline passenger cars sold in first world markets like the United States, Canada, Europe, Japan, and Australia have come equipped with electronic fuel injection (EFI). Many motorcycles still utilize carbureted engines, though all current high-performance designs have switched to EFI.

Fuel injection systems have evolved significantly since the mid-1980s. Current systems provide an accurate, reliable and cost-effective method of metering fuel and providing maximum engine efficiency with clean exhaust emissions, which is why EFI systems have replaced carburetors in the marketplace. EFI is becoming more reliable and less expensive through widespread usage. At the same time, carburetors are becoming less available, and more expensive. Even marine applications are adopting EFI as reliability improves. Virtually all internal combustion engines, including motorcycles, off-road vehicles, and outdoor power equipment, may eventually use some form of fuel injection.

The carburetor remains in use in developing countries where vehicle emissions are unregulated and diagnostic and repair infrastructure is sparse. Fuel injection is gradually replacing carburetors in these nations too as they adopt emission regulations conceptually similar to those in force in Europe, Japan, Australia and North America.

### ***Basic function***

The process of determining the necessary amount of fuel, and its delivery into the engine, are known as fuel metering. Early injection systems used mechanical methods to meter fuel (non electronic, or mechanical fuel injection). Modern systems are nearly all electronic, and use an electronic solenoid (the injector) to inject the fuel. An electronic engine control unit calculates the mass of fuel to inject.

Modern fuel injection schemes follow much the same setup. There is a mass airflow sensor or manifold absolute pressure sensor at the intake, typically mounted either in the air tube feeding from the air filter box to the throttle body, or mounted directly to the throttle body itself. The mass airflow sensor does exactly what its name implies; it senses the mass of the air that flows past it, giving the computer an accurate idea of how much air is entering the engine. The next component in line is the Throttle Body. The throttle body has a throttle position sensor mounted onto it, typically on the butterfly valve of the throttle body. The throttle position sensor (TPS) reports to the computer the position of the throttle butterfly valve, which the ECM uses to calculate the load upon the engine. The fuel system consists of a fuel pump (typically mounted in-tank), a fuel pressure regulator, fuel lines (composed of either high strength plastic, metal, or reinforced rubber), a fuel rail that the injectors connect to, and the fuel injector(s). There is a coolant temperature sensor that reports the engine temperature to the ECM, which the engine uses to calculate the proper fuel ratio required. In sequential fuel injection systems there is a

camshaft position sensor, which the ECM uses to determine which fuel injector to fire. The last component is the oxygen sensor. After the vehicle has warmed up, it uses the signal from the oxygen sensor to perform fine tuning of the fuel trim.

The fuel injector acts as the fuel-dispensing nozzle. It injects liquid fuel directly into the engine's air stream. In almost all cases this requires an external pump. The pump and injector are only two of several components in a complete fuel injection system.

In contrast to an EFI system, a carburetor directs the induction air through a venturi, which generates a minute difference in air pressure. The minute air pressure differences both emulsify (premix fuel with air) the fuel, and then acts as the force to push the mixture from the carburetor nozzle into the induction air stream. As more air enters the engine, a greater pressure difference is generated, and more fuel is metered into the engine. A carburetor is a self-contained fuel metering system, and is cost competitive when compared to a complete EFI system.

An EFI system requires several peripheral components in addition to the injector(s), in order to duplicate all the functions of a carburetor. A point worth noting during times of fuel metering repair is that early EFI systems are prone to diagnostic ambiguity. A single carburetor replacement can accomplish what might require numerous repair attempts to identify which one of the several EFI system components is malfunctioning. Newer EFI systems since the advent of OBD II diagnostic systems, can be very easy to diagnose due to the increased ability to monitor the realtime data streams from the individual sensors. This gives the diagnosing technician realtime feedback as to the cause of the drivability concern, and can dramatically shorten the number of diagnostic steps required to ascertain the cause of failure, something which isn't as simple to do with a carburetor. On the other hand, EFI systems require little regular maintenance; a carburetor typically requires seasonal and/or altitude adjustments.

## Detailed function

### Typical EFI components

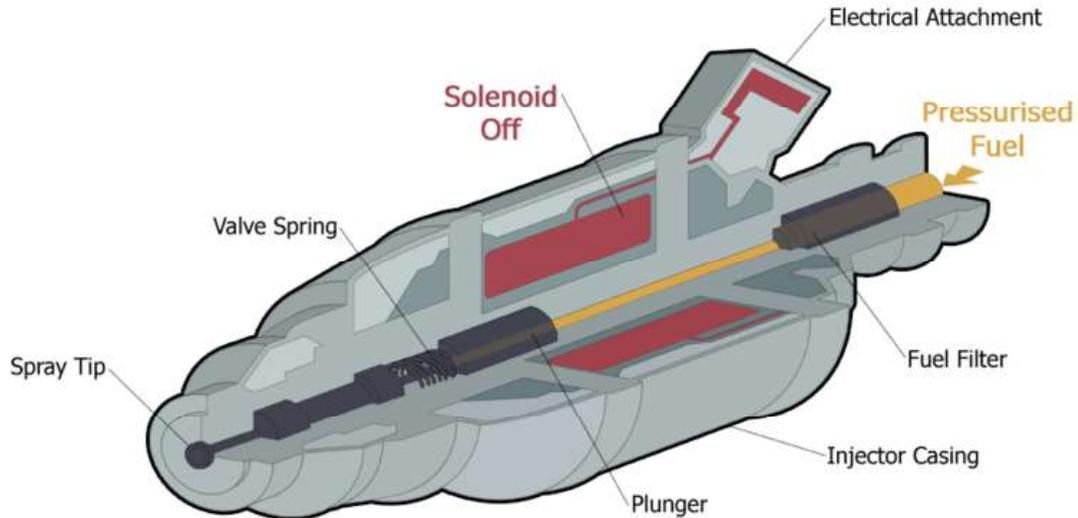


Diagram of a typical fuel injector.

- Injectors
- Fuel Pump
- Fuel Pressure Regulator
- ECM - Engine Control Module; includes a digital computer and circuitry to communicate with sensors and control outputs.
- Wiring Harness
- Various Sensors (Some of the sensors required are listed here.)
  - Crank/Cam Position: Hall effect sensor
  - Airflow: MAF sensor, sometimes this is inferred with a MAP sensor
  - Exhaust Gas Oxygen: Oxygen sensor, EGO sensor, UEGO sensor

### Functional description

Central to an EFI system is a computer called the Engine Control Unit (ECU), which monitors engine operating parameters via various sensors. The ECU interprets these parameters in order to calculate the appropriate amount of fuel to be injected, among other tasks, and controls engine operation by manipulating fuel and/or air flow as well as other variables. The optimum amount of injected fuel depends on conditions such as

engine and ambient temperatures, engine speed and workload, and exhaust gas composition.

The electronic fuel injector is normally closed, and opens to inject pressurized fuel as long as electricity is applied to the injector's solenoid coil. The duration of this operation, called the pulse width, is proportional to the amount of fuel desired. The electric pulse may be applied in closely-controlled sequence with the valve events on each individual cylinder (in a **sequential** fuel injection system), or in groups of less than the total number of injectors (in a **batch fire** system).

Since the nature of fuel injection dispenses fuel in discrete amounts, and since the nature of the 4-stroke engine has discrete induction (air-intake) events, the ECU calculates fuel in discrete amounts. In a sequential system, the injected fuel mass is tailored for each individual induction event. Every induction event, of every cylinder, of the entire engine, is a separate fuel mass calculation, and each injector receives a unique pulse width based on that cylinder's fuel requirements.

It is necessary to know the mass of air the engine "breathes" during each induction event. This is proportional to the intake manifold's air pressure/temperature, which is proportional to throttle position. The amount of air inducted in each intake event is known as "air-charge", and this can be determined using several methods.

The three elemental ingredients for combustion are fuel, air and ignition. However, complete combustion can only occur if the air and fuel is present in the exact stoichiometric ratio, which allows all the carbon and hydrogen from the fuel to combine with all the oxygen in the air, with no undesirable polluting leftovers. Oxygen sensors monitor the amount of oxygen in the exhaust, and the ECU uses this information to adjust the air-to-fuel ratio in real-time.

To achieve stoichiometry, the air mass flow into the engine is measured and multiplied by the stoichiometric air/fuel ratio 14.64:1 (by weight) for gasoline. The required fuel mass that must be injected into the engine is then translated to the required pulse width for the fuel injector. The stoichiometric ratio changes as a function of the fuel; diesel, gasoline, ethanol, methanol, propane, methane (natural gas), or hydrogen.

Deviations from stoichiometry are required during non-standard operating conditions such as heavy load, or cold operation, in which case, the mixture ratio can range from 10:1 to 18:1 (for gasoline). In early fuel injection systems this was accomplished with a thermostime switch.

Pulse width is inversely related to pressure difference across the injector inlet and outlet. For example, if the fuel line pressure increases (injector inlet), or the manifold pressure decreases (injector outlet), a smaller pulse width will admit the same fuel. Fuel injectors are available in various sizes and spray characteristics as well. Compensation for these and many other factors are programmed into the ECU's software.

## Sample pulsewidth calculations

*Note: These calculations are based on a 4-stroke-cycle, 5.0L, V-8, gasoline engine. The variables used are real data.*

### Calculate injector pulsewidth from airflow

First the CPU determines the air mass flow rate from the sensors -  $Mass_{air} / Minute$ .

$$\frac{Mass_{air}}{Minute} \times \frac{Minutes}{Revolution} \times \frac{Revolutions}{Stroke} = \frac{Mass_{air}}{Stroke}$$

$Minutes / Revolution$  is the reciprocal of engine speed (RPM).

The term  $Revolutions / Stroke = 1 / 2$ , whether it's a four stroke or a two-stroke engine.

$$\frac{Mass_{air}}{Stroke_{intake}} \times \frac{Mass_{Fuel}}{Mass_{Air}} = \frac{Mass_{Fuel}}{Stroke_{intake}}$$

$Mass_{Fuel} / Mass_{Air}$  is the desired mixture ratio, usually stoichiometric, but often different depending on operating conditions.

$$\frac{Mass_{Fuel}}{Stroke_{intake}} \times \frac{1}{Mass_{Fuel}/Minute} = \frac{Minutes}{Stroke_{intake}} = Pulsewidth$$

$1 / (Mass_{Fuel} / Minute)$  is the flow capacity of the injector, or its size.

Combining the above three terms . . .

$$\frac{Mass_{air}}{Minute} \times \frac{Minutes}{Revolution} \times \frac{Revolutions}{Stroke} \times \frac{Mass_{Fuel}}{Mass_{Air}} \times \frac{1}{Mass_{Fuel}/Minute} = Pulsewidth$$

Substituting real variables for the 5.0 L engine at idle.

\*

Substituting real variables for the 5.0 L engine at maximum power.

\*

$$28 \frac{lb}{min} \times \frac{1min}{5500rev} \times \frac{1revolution}{2strokes} \times \frac{1}{11.00} \times 2.5 \frac{min}{lb} = 57.9 \times 10^{-5} min = 35ms$$

*Injector pulsewidth typically ranges from 4 ms/engine-cycle at idle, to 35 ms per engine-cycle at wide-open throttle. The pulsewidth accuracy is approximately 0.01 ms.*

### Calculate fuel-flow rate from pulsewidth

- (Fuel flow rate)  $\approx$  (pulsewidth)  $\times$  (engine speed)  $\times$  (number of fuel injectors)

*Looking at it another way:*

- (Fuel flow rate)  $\approx$  (throttle position)  $\times$  (rpm)  $\times$  (cylinders)

*Looking at it another way:*

- (Fuel flow rate)  $\approx$  (air-charge)  $\times$  (fuel/air)  $\times$  (rpm)  $\times$  (cylinders)

#### **Substituting real variables for the 5.0 L engine at idle.**

- (Fuel flow rate) = (2.0 ms/intake-stroke)  $\times$  (hour/3,600,000 ms)  $\times$  (24 lb-fuel/hour)  $\times$  (4-intake-stroke/rev)  $\times$  (700 rev/min)  $\times$  (60 min/h) = (2.24 lb/h)

#### **Substituting real variables for the 5.0L engine at maximum power.**

- (Fuel flow rate) = (17.3 ms/intake-stroke)  $\times$  (hour/3,600,000-ms)  $\times$  (24 lb-fuel/hour)  $\times$  (4-intake-stroke/rev)  $\times$  (5500-rev/min)  $\times$  (60-min/hour) = (152 lb/h)

*The fuel consumption rate is 68 times greater at maximum engine output than at idle. This dynamic range of fuel flow is typical of a naturally aspirated passenger car engine. The dynamic range is greater on a supercharged or turbocharged engine. It is interesting to note that 15 gallons of gasoline will be consumed in 37 minutes if maximum output is sustained. On the other hand, this engine could continuously idle for almost 42 hours on the same 15 gallons.*

## **Various injection schemes**

### **Single-point injection**

**Single-point injection**, called **Throttle-body injection (TBI)** by General Motors and **Central Fuel Injection (CFI)** by Ford, was introduced in the 1940s in large aircraft engines (then called the pressure carburetor) and in the 1980s in the automotive world. The SPI system injects fuel at the throttle body (the same location where a carburetor introduced fuel). The induction mixture passes through the intake runners like a carburetor system, and is thus labelled a "wet manifold system". Fuel pressure is usually specified to be in the area of 10-15 psi. The justification for single-point injection was low cost. Many of the carburetor's supporting components could be reused such as the air cleaner, intake manifold, and fuel line routing. This postponed the redesign and tooling costs of these components. Most of these components were later redesigned for the next phase of fuel injection's evolution, which is individual port injection, commonly known as MPFI or "multi-point fuel injection". TBI was used extensively on American-made passenger cars and light trucks in the 1980-1995 timeframe and some transition-engined European cars throughout the early and mid-1990s. Mazda called their system EGI, and even introduced an electronically controlled version called the EGI-S.

### **Continuous injection**

In a continuous injection system, fuel flows at all times from the fuel injectors, but at a variable rate. This is in contrast to most fuel injection systems, which provide fuel during

short pulses of varying duration, with a constant rate of flow during each pulse. Continuous injection systems can be multi-point or single-point, but not direct.

The most common automotive continuous injection system is Bosch's **K-Jetronic** (K for *kontinuierlich*, German for "continuous" — a.k.a. CIS — Continuous Injection System), introduced in 1974. Gasoline is pumped from the fuel tank to a large control valve called a *fuel distributor*, which separates the single fuel supply pipe from the tank into smaller pipes, one for each injector. The fuel distributor is mounted atop a control vane through which all intake air must pass, and the system works by varying fuel volume supplied to the injectors based on the angle of the air vane, which in turn is determined by the volume flowrate of air past the vane, and by the control pressure. The control pressure is regulated with a mechanical device called the control pressure regulator (CPR) or the warm-up regulator (WUR). Depending on the model, the CPR may be used to compensate for altitude, full load, and/or a cold engine. On cars equipped with an oxygen sensor, the fuel mixture is adjusted by a device called the frequency valve. The injectors are simple spring-loaded check valves with nozzles; once fuel system pressure becomes high enough to overcome the counterspring, the injectors begin spraying. K-Jetronic was used for many years between 1974 and the mid 1990s by BMW, Lamborghini, Ferrari, Mercedes-Benz, Volkswagen, Ford, Porsche, Audi, Saab, DeLorean, and Volvo. There was also a variant of the system called KE-Jetronic with electronic instead of mechanical control of the control pressure. Some Toyotas and other Japanese cars from the 1970s to the early 1990s used an application of Bosch's multipoint L-Jetronic system manufactured under license by DENSO. Chrysler used a similar continuous fuel injection system on the 1981-1983 Imperial.

In piston aircraft engines, continuous-flow fuel injection is the most common type. In contrast to automotive fuel injection systems, aircraft continuous flow fuel injection is all mechanical, requiring no electricity to operate. Two common types exist: the Bendix RSA system, and the TCM system. The Bendix system is a direct descendant of the pressure carburetor. However, instead of having a discharge valve in the barrel, it uses a *flow divider* mounted on top of the engine, which controls the discharge rate and evenly distributes the fuel to stainless steel injection lines which go to the intake ports of each cylinder. The TCM system is even more simple. It has no venturi, no pressure chambers, no diaphragms, and no discharge valve. The control unit is fed by a constant-pressure fuel pump. The control unit simply uses a butterfly valve for the air which is linked by a mechanical linkage to a rotary valve for the fuel. Inside the control unit is another restriction which is used to control the fuel mixture. The pressure drop across the restrictions in the control unit controls the amount of fuel flowing, so that fuel flow is directly proportional to the pressure at the flow divider. In fact, most aircraft using the TCM fuel injection system feature a fuel flow gauge which is actually a pressure gauge that has been calibrated in *gallons per hour* or *pounds per hour* of fuel.

### **Central port injection (CPI)**

General Motors implemented a system called "central port injection" (**CPI**) or "central port fuel injection" (**CPFI**). It uses tubes with poppet valves from a central injector to

spray fuel at each intake port rather than the central throttle-body. Pressure specifications typically mirror that of a TBI system. The two variants were CPFI from 1992 to 1995, and CSFI from 1996 and on. CPFI is a *batch-fire* system, in which fuel is injected to all ports simultaneously. The 1996 and later CSFI system sprays fuel *sequentially*.

## Multi-point fuel injection

Multi-point fuel injection injects fuel into the intake port just upstream of the cylinder's intake valve, rather than at a central point within an intake manifold. MPFI (or just MPI) systems can be **sequential**, in which injection is timed to coincide with each cylinder's intake stroke; **batched**, in which fuel is injected to the cylinders in groups, without precise synchronization to any particular cylinder's intake stroke; or **simultaneous**, in which fuel is injected at the same time to all the cylinders. The intake is only slightly wet, and typical fuel pressure runs between 40-60 psi.

Many modern EFI systems utilize sequential MPFI; however, in newer gasoline engines, direct injection systems are beginning to replace sequential ones.

## Direct injection

Direct fuel injection costs more than indirect injection systems: the injectors are exposed to more heat and pressure, so more costly materials and higher-precision electronic management systems are required. However, the entire intake is dry, making this a very clean system. In a common rail system, the fuel from the fuel tank is supplied to the common header (called the accumulator). This fuel is then sent through tubing to the injectors which inject it into the combustion chamber. The header has a high pressure relief valve to maintain the pressure in the header and return the excess fuel to the fuel tank. The fuel is sprayed with the help of a nozzle which is opened and closed with a needle valve, operated with a solenoid. When the solenoid is not activated, the spring forces the needle valve into the nozzle passage and prevents the injection of fuel into the cylinder. The solenoid lifts the needle valve from the valve seat, and fuel under pressure is sent in the engine cylinder. Third-generation common rail diesels use piezoelectric injectors for increased precision, with fuel pressures up to 1,800 bar/26,000 psi.

Gasoline engines incorporate gasoline direct injection engine technology.

## Diesel engines

Diesel engines must use fuel injection, and it must be timed (unlike on petrol engines). Throughout the early history of diesels, they were always fed by a mechanical pump with a small separate cylinder for each cylinder, feeding separate fuel lines and individual injectors. Most such pumps were in-line, though some were rotary.

Earlier systems, relying on crude injectors, often injected into a sub-chamber shaped to swirl the compressed air and improve combustion; this was known as indirect injection. However, it was less thermally efficient than the now universal direct injection in which

initiation of combustion takes place in a depression (often toroidal) in the crown of the piston.

## **Petrol/gasoline engines**

Modern petrol engines (gasoline engines) also utilise direct injection, which is referred to as gasoline direct injection. This is the next step in evolution from multi-point fuel injection, and offers another magnitude of emission control by eliminating the "wet" portion of the induction system along the inlet tract.

By virtue of better dispersion and homogeneity of the directly injected fuel, the cylinder and piston are cooled, thereby permitting higher compression ratios and more aggressive ignition timing, with resultant enhanced power output. More precise management of the fuel injection event also enables better control of emissions. Finally, the homogeneity of the fuel mixture allows for leaner air/fuel ratios, which together with more precise ignition timing can improve fuel efficiency. Along with this, the engine can operate with stratified (lean burn) mixtures, and hence avoid throttling losses at low and part engine load. Some direct-injection systems incorporate piezoelectric fuel injectors. With their extremely fast response time, multiple injection events can occur during each cycle of each cylinder of the engine.

The first use of direct petrol injection was on the Hesselman engine, invented by Swedish engineer Jonas Hesselman in 1925.

## **Maintenance hazards**

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 psi (6.9 bar) pressure. The first known such injury occurred in 1937 during a diesel engine maintenance operation.

## Chapter 10

# Fuel Filter and Gudgeon Pin

## Fuel filter



A fuel filter on a pickup truck, showing its mounting location on the firewall.



A fuel filter on a Yanmar 2GM20 marine diesel engine.

A **fuel filter** is a filter in the fuel line that screens out dirt and rust particles from the fuel, normally made into cartridges containing a filter paper. They are found in most internal combustion engines.

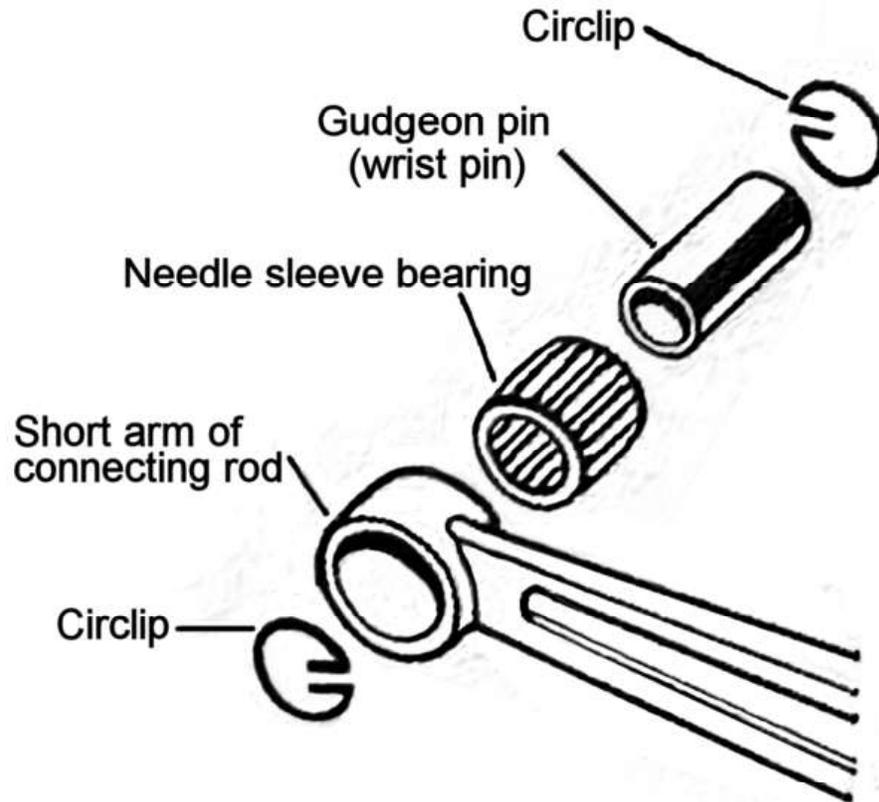
Fuel filters serve a vital function in today's modern, tight-tolerance engine fuel systems. Unfiltered fuel may contain several kinds of contamination, for example paint chips and dirt that has been knocked into the tank while filling, or rust caused by moisture in a steel tank. If these substances are not removed before the fuel enters the system, they will cause rapid wear and failure of the fuel pump and injectors, due to the abrasive action of the particles on the high-precision components used in modern injection systems. Fuel

filters also improve performance, as the fewer contaminants present in the fuel, the more efficiently it can be burnt.

Fuel filters need to be maintained at regular intervals. This is usually a case of simply disconnecting the filter from the fuel line and replacing it with a new one, although some specially designed filters can be cleaned and reused many times. If a filter is not replaced regularly it may become clogged with contaminants and cause a restriction in the fuel flow, causing an appreciable drop in engine performance as the engine struggles to draw enough fuel to continue running normally.

Some filters, especially found on diesel engines, are of a bowl-like design which collect water in the bottom (as water is more dense than diesel). The water can then be drained off by opening a valve in the bottom of the bowl and letting it run out, until the bowl contains only diesel. Many fuel filters contain a water sensor to signal to the engine control unit or directly to the driver (lamp on dashboard) if the water reach the warning level. It is especially undesirable for water to be drawn into a diesel engine fuel system, as the system relies on the diesel for lubrication of the moving parts, and if water gets into a moving part which requires constant lubrication (for example an injector valve), it will quickly cause overheating and unnecessary wear. This type of filter may also include a sensor, which will alert the operator when the filter needs to be drained. In proximity of the diesel fuel filter there might be a fuel heater to avoid the forming of paraffin wax (in case of low temperatures) inside the filtrating element which can stop the fuel flow to the engine.

# Gudgeon pin



Gudgeon pin connection at connecting rod. Gudgeon pin fits into gudgeons inside piston.

In internal combustion engines, the **gudgeon pin** (UK, **wrist pin** US) is that which connects the piston to the connecting rod and provides a bearing for the connecting rod to pivot upon as the piston moves. In very early engine designs (including those driven by steam and also many very large stationary or marine engines), the gudgeon pin is located in a sliding crosshead that connects to the piston via a rod.

The gudgeon pin is typically a forged short hollow rod made of a steel alloy of high strength and hardness that may be physically separated from both the connecting rod and piston or crosshead. The design of the gudgeon pin, especially in the case of small, high-revving automotive engines is challenging. The gudgeon pin has to operate under some of the highest temperatures experienced in the engine, with difficulties in lubrication due to its location, while remaining small and light so as to fit into the piston diameter and not unduly add to the reciprocating mass. The requirements for lightness and compactness demand a small diameter rod that is subject to heavy shear and bending loads, with some of the highest pressure loadings of any bearing in the whole engine. To overcome these

problems, the materials used to make the gudgeon pin and the way it is manufactured are amongst the most highly-engineered of any mechanical component found in internal combustion engines.

## ***Design Options***

Gudgeon pins use two broad design configurations: semi-floating and fully-floating. In the semi-floating configuration, the pin is usually fixed relative to the piston by an interference fit with the journal in the piston. (This replaced the earlier set screw method.) The connecting rod small end bearing thus acts as the bearing alone. In this configuration, only the small end bearing requires a bearing surface, if any. If needed, this is provided by either electroplating the small end bearing journal with a suitable metal, or more usually by inserting a sleeve bearing or needle bearing into the eye of the small end, which has an interference fit with the aperture of the small end. During overhaul, it is usually possible to replace this bearing sleeve if it is badly worn. The reverse configuration, fixing the gudgeon pin to the connecting rod instead of to the piston, is implemented using an interference fit with the small end eye instead, with the gudgeon pin journals in the piston functioning as bearings. This arrangement is usually more difficult to manufacture and service because two bearing surfaces or inserted sleeves complicate the design. In addition, the pin must be precisely set so that the small end eye is central. Because of thermal expansion considerations, this arrangement was more usual for single-cylinder engines as opposed to multiple cylinder engines with long cylinder blocks and crankcases, until precision manufacturing became more commonplace.

In the fully-floating configuration, a bearing surface is created both between the small end eye and gudgeon pin and the journal in the piston. The gudgeon pins are usually secured with circlips. No interference fit is used in any instance and the pin 'floats' entirely on bearing surfaces. The average rubbing speed of each of the three bearings is halved and the load is shared across a bearing that is usually about three times the length of the semi-floating design with an interference fit with the piston.

## Chapter 11

# Intercooler

An **intercooler** (original UK term, sometimes **aftercooler** in US practice), or charge air cooler, is an air-to-air or air-to-liquid heat exchange device used on turbocharged and supercharged (forced induction) internal combustion engines to improve their volumetric efficiency by increasing intake air charge density through nearly isobaric (constant pressure) cooling, which removes the heat of compression (i.e., the temperature rise) that occurs in any gas when its pressure is raised or its unit mass per unit volume (density) is increased. A decrease in intake air charge temperature sustains use of a more dense intake charge into the engine, as a result of supercharging. The lowering of the intake charge air temperature also eliminates the danger of pre-detonation (knock) of the fuel air charge prior to timed spark ignition. Thus preserving the benefits of more fuel/air burn per engine cycle, increasing the output of the engine. Intercoolers increase the efficiency of the induction system by reducing induction air heat created by the turbocharger and promoting more thorough combustion. They also eliminate the need for using the wasteful method of lowering intake charge temperature by the injection of excess fuel into the cylinders' air induction chambers, to cool the intake air charge, prior to its flowing into the cylinders. This wasteful practice (when intercoolers are not used) nearly eliminated the gain in engine efficiency from supercharging, but was necessitated by the greater need to prevent at all costs the engine damage that pre-detonation engine knocking causes.

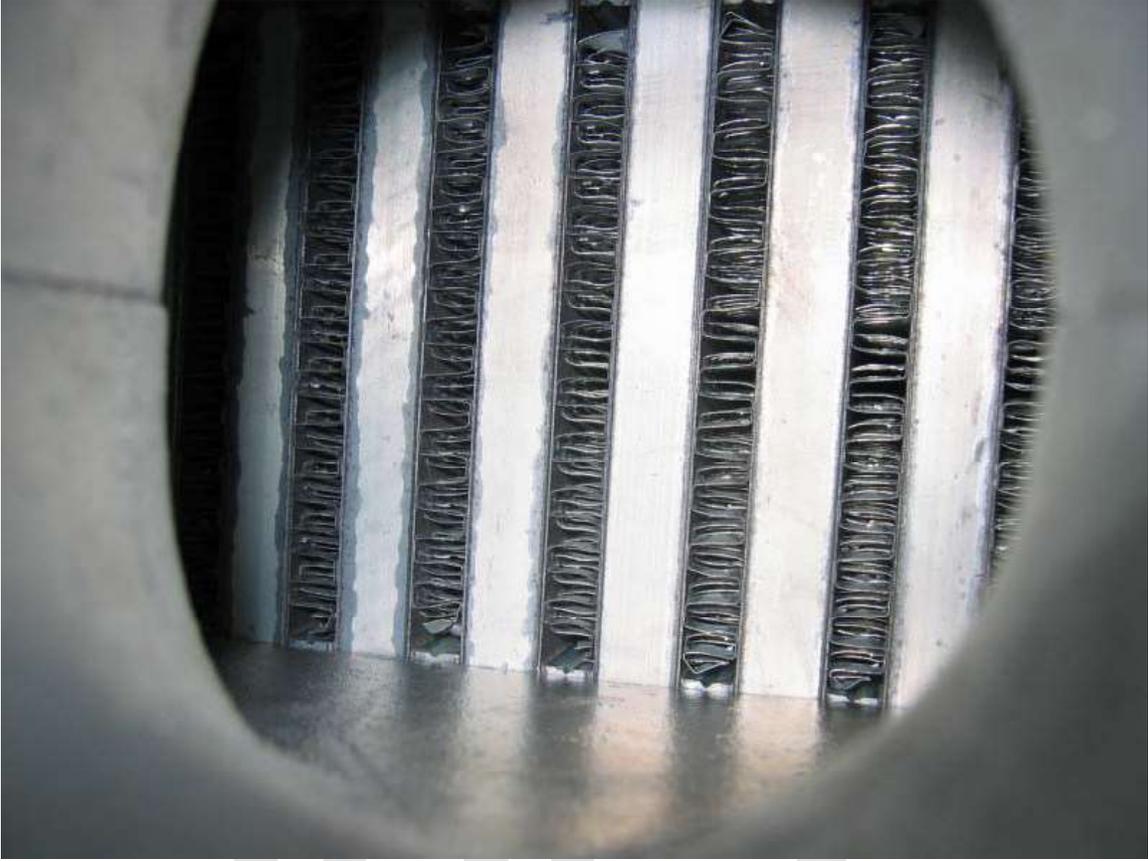
The *inter* prefix in the device name originates from historic compressor designs. In the past, aircraft engines were built with charge air coolers that were installed between multiple stages of supercharging, thus the designation of *inter*. Modern automobile designs are technically designated **aftercoolers** because of their placement at the end of supercharging chain. This term is now considered archaic in modern automobile terminology since most forced induction vehicles have single-stage superchargers or turbochargers although "aftercooler" is still in common use in the piston engined aircraft industry. In a vehicle fitted with two-stage turbocharging, it is possible to have both an intercooler (between the two turbocharger units) and an aftercooler (between the second-stage turbo and the engine). The JCB Dieselmax land speed record-holding car is an example of such a system. In general, an intercooler or aftercooler is said to be a charge air cooler.

Intercoolers can vary dramatically in size, shape and design, depending on the performance and space requirements of the entire supercharger system. Common spatial designs are front mounted intercoolers (FMIC), top mounted intercoolers (TMIC) and hybrid mount intercoolers (HMIC). Each type can be cooled with an air-to-air system, air-to-liquid system, or a combination of both.

### ***Applications to forced induction***



The engine bay of a 2003 MINI Cooper S—the top mounted intercooler is circled in red.



Interior close up view of an air to air intercooler.



Exterior of the same intercooler core.

Turbochargers and superchargers are engineered to force more air mass into an engine's intake manifold and combustion chamber. Intercooling is a method used to compensate for heating caused by supercharging, a natural byproduct of the semi-adiabatic compression process. Increased air pressure can result in an excessively hot intake charge, significantly reducing the performance gains of supercharging due to decreased density. Increased intake charge temperature can also increase the cylinder combustion temperature, causing detonation, excessive wear, or heat damage to an engine block.

Passing a compressed and heated intake charge through an intercooler reduces its temperature (due to heat rejection) and pressure (due to flow restriction of fins). If properly engineered, the relative decrease in temperature is greater than the relative loss in pressure, resulting a net increase in density. This increases system performance by recovering some losses of the inefficient compression process by rejecting heat to the atmosphere. Additional cooling can be provided by externally spraying a fine mist onto the intercooler surface, or even into the intake air itself, to further reduce intake charge temperature through evaporative cooling.

Intercoolers that exchange their heat directly with the atmosphere are designed to be mounted in areas of an automobile with maximum air flow. These types are mainly mounted in front mounted systems (FMIC). Cars such as the Nissan Skyline, Saab, Volvo 200 Series Turbo, Volvo 700 Series (and 900 series) turbo, Dodge SRT-4, 1st gen Mazda MX-6, Mitsubishi Lancer Evolution and Chevrolet Cobalt SS all use front mounted intercooler(s) mounted near the front bumper, in line with the car's radiator.

Many other turbo-charged cars, particularly where the aesthetics of the car are not to be compromised by unattractive top mount scoops, such as the Toyota Supra (JZA80 only), Nissan 300ZX Twin Turbo, Nissan 200SX (S13/14/14a/15), Mitsubishi 3000gt, Saab 900, Volkswagen, Audi TT, and Turbo Mitsubishi Eclipse use side-mounted air-to-air intercoolers (SMIC), which are mounted in the front corner of the bumper or in front of one of the wheels. Side-mounted intercoolers are generally smaller, mainly due to space constraints, and sometimes two are used to gain the performance of a larger, single intercooler. Cars such as the Subaru Impreza WRX, MINI Cooper S, Toyota Celica GT-Four, Nissan Pulsar GTI-R, Mazdaspeed3, Mazdaspeed6, and the PSA Peugeot Citroën turbo diesels, use air-to-air top mounted intercoolers (TMIC) located on top of the engine. Air is directed through the intercooler through the use of a hood scoop. In the case of the PSA cars the air flows through the grille above the front bumper, then through under-hood ducting. Top mounted intercoolers sometimes suffer from heat diffusion due to proximity with the engine, warming them and reducing their overall efficiency. Some World Rally Championship cars use a reverse-induction system design whereby air is forced through ducts in the front bumper to a horizontally-mounted intercooler.



Fitting an after market front mount intercooler to a car with a factory installed top mount.

Because FMIC systems require open bumper design for optimal performance, the entire system is vulnerable to debris. Some engineers choose other mount locations due to this reliability concern. FMICs can be located in front of or behind the radiator, depending on the heat dissipation needs of the engine.

As well as allowing a greater mass of air to be admitted to an engine, intercoolers have a key role in controlling the internal temperatures in a turbocharged engine. When fitted with a turbo (as with any form of supercharging), the engine's specific power is increased, leading to higher combustion and exhaust temperatures. The exhaust gases passing through the turbine section of the turbocharger are usually around 450 °C (840 °F), but can be as high as 1000 °C (1830 °F) under extreme conditions. This heat passes through the turbocharger unit and contributes to the heating of the air being compressed in the compressor section of the turbo. If left uncooled this hot air enters the engine, further increasing internal temperatures. This leads to a build up of heat that will eventually stabilise, but this may be at temperatures in excess of the engine's design limits- 'hot spots' at the piston crown or exhaust valve can cause warping or cracking of these components. This effect is especially found in modified or tuned engines running at very high specific power outputs. An efficient intercooler removes heat from the air in the induction system, preventing the cyclic heat build-up via the turbocharger, allowing higher power outputs to be achieved without damage.

Compression by the turbocharger causes the intake air to heat up; rather than the air being heated by contact with the hot turbocharger itself, the vast majority is through the act of compression (ideal gas law) plus added heat due to compressor inefficiencies (adiabatic efficiency). The extra power obtained from forced induction is due to the extra air available to burn more fuel in each cylinder. This sometimes requires a lower compression ratio be used, to allow a wider mapping of ignition timing advance before detonation occurs (for a given fuel's octane rating). On the other hand, a lower compression ratio generally lowers combustion efficiency and costs power.

### ***Air-to-liquid intercoolers***

Air-to-liquid intercoolers (aka Charge-Air-Coolers) are heat exchangers that transfer intake charge heat to an intermediate fluid, usually water, which finally rejects heat to the air. These systems use radiators in other locations, usually due to space constraints, to reject unwanted heat, similar to an automotive radiator cooling system. Air-to-liquid intercoolers are usually heavier than their air-to-air counterparts due to additional components making up the system (water circulation pump, radiator, fluid, and plumbing). The Toyota Celica GT-Four had this system from 1988 to 1989, 1994 to 1999, also in the Carlos Sainz Rally Championship Version from 1990 to 1993.

A big advantage of the air-to-liquid setup is the lower overall pipe and intercooler length, which offers faster response (lowers turbo lag), giving peak boost faster than most front-mount intercooler setups. Some setups can use reservoirs that can have ice put into it for intake temperatures lower than ambient air, giving a big advantage (but of course, ice would need constant replacement).

Ford had adopted the technology when they decided to use forced induction (via Supercharger) on their Mustang Cobra and Ford Lightning truck platforms. It uses a water/glycol mixture intercooler inside the intake manifold, just under the supercharger, and has a long heat exchanger front mounted, all powered by a Bosch pump made for Ford. Ford still uses this technology today with their Shelby GT500. The 2005-2007 Chevrolet Cobalt SS Supercharged also utilizes a similar setup.

Air-to-liquid intercoolers are by far the most common form of intercooler found on marine engines, given that a limitless supply of cooling water is available and most engines are located in closed compartments where obtaining a good flow of cooling air for an air-to-air unit would be difficult. Marine intercoolers take the form of a tubular heat exchanger with the air passing through a series of tubes and cooling water circulating around the tubes within the unit's casing. The source of water for the intercooler depends on the exact cooling system fitted to the engine. Most marine engine have fresh water circulating within them which is passed through a heat exchanger cooled by sea water. In such a system the intercooler will be attached to the sea water circuit and placed before the engine's own heat exchanger to ensure a supply of cool water.

## Chapter 12

# Oil Pump (Internal Combustion Engine)



Gerotor type oil pump from a scooter engine

The **oil pump** in an internal combustion engine is usually a gear type (gear pump), driven by the crankshaft or camshaft, or a rotor type (rotary pump).

## ***Lubricating System***

The oiling system addresses the need to properly lubricate an engine when it's running. Properly lubricating an engine not only reduces friction between moving parts but is also the main method by which heat is removed from pistons, bearings, and shafts. Failing to properly lubricate an engine will result in engine failure. The oil pump forces the motor oil through the passages in the engine to properly distribute oil to different engine components. In a common oiling system, oil is drawn out of the oil sump (oil pan, in US English) through a wire mesh strainer that removes some of the larger pieces of debris from the oil. The flow made by the oil pump allows the oil to be distributed around the engine. In this system, oil flows through an oil filter and sometimes an oil cooler, before going through the engine's oil passages and being dispersed to lubricate pistons, rings, springs, valve stems, and more.

## ***Oil Pressure***

The oil pressure generated in most engines should be about 10 psi per every 1000 revolutions per minute (rpm), peaking around 55-65 psi.

Local pressure (at the crankshaft journal and bearing) is far higher than the 50, 60 psi &c. set by the pump's relief valve, and will reach hundreds of psi. This higher pressure is developed by the relative speeds in feet per second (not RPM or journal size directly) of the crankshaft journal itself against the bearing, the bearing width (to the closest pressure leak), oil viscosity, and temperature, balanced against the bearing clearance (the leakage rate).

All pump pressure does is "fill in the hole" and refresh the oil in the annular space faster than the leak expels it. This is why low-speed engines have relatively large journals, with only modest pump size and pressure. Low pressure indicates that leakage from the bearings is higher than the pump's delivery rate.

## ***Gauge pressure***

The oil pressure at the pump outlet, which is what opens the pressure relief valve, is simply the resistance to flow caused by the bearing clearances and restrictions.

The oil pressure gauge, or warning lamp, gives only the pressure at the point where its sender enters that part of the pressurized system – not everywhere, not an average, nor a generalized picture of the systemic pressure.

Despite the frequent comparison to hydraulic engineering theory, this is not a "closed system" in which oil pressure is balanced and identical everywhere. All engines are "open systems", because the oil returns to the pan by a series of controlled leaks. The bearings farthest from the pump always have the lowest pressure because of the number of leaks between the pump and that bearing. Excess bearing clearance increases the pressure loss between the first and last bearing in a series.

Depending on condition, an engine may have acceptable gauge pressure, and still only 5 psi pressure at one connecting rod, which will fail under high load.

The pressure is actually created by the resistance to the flow of the oil around the engine. So, the pressure of the oil may vary during operation, with temperature, engine speed, and wear on the engine. Colder oil temperature can cause higher pressure, as the oil is thicker, while higher engine speeds cause the pump to run faster and push more oil through the engine. Because of variances in temperature and normal higher engine speed upon cold engine start up, it's normal to see higher oil pressure upon engine start up than at normal operating temperatures, where normal oil pressure usually falls between 30 and 45 psi. Too much oil pressure can create unnecessary work for the engine and even add air into the system. To ensure that the oil pressure does not exceed the rated maximum, once pressure exceeds a preset limit a spring-loaded pressure relief valve dumps excess pressure either to the suction side of the pump, or directly back to the oil pan or tank. High oil pressure frequently means extremely high pressure on cold start-up, but this is a design flaw rather than an automatic consequence of high pressure. The observation "if you raise the maximum pressure, the cold pressure goes too high" is accurate, but not intentional.

Even the stock pumps (regardless of brand and model) do not have enough relief valve capacity: the relief port is too small to handle the volume of cold oil. This is why there is a significant difference between cold & hot oil, high & low RPM, &c., but it's typically not a problem with stock engines. A correctly designed relief port (which is not found in production engines) will flow any oil volume the gears will pass, regardless of oil viscosity or temperature, and the gauge reading will only vary slightly.

The oil pressure is monitored by an oil pressure sending unit, usually mounted to the block of the engine. This can either be a spring-loaded pressure sensor or an electronic pressure sensor, depending on the type of sending unit. Problems with the oil pressure sending unit or the connections between it and the driver's display can cause abnormal oil pressure readings when oil pressure is perfectly acceptable.

### **Low Oil Pressure**

Low oil pressure, however, can cause engine damage. Low oil pressure can be caused by many things, such as a faulty oil pump, a clogged oil pickup screen, excessive wear on high mileage engines, or simply low oil volume. Indications of low oil pressure may be that the warning light is on, a low pressure reading on the gauge, or clattering/clinking noises from the engine. Low oil pressure is a problem that must be addressed immediately to prevent serious damage.

The leading cause of low oil pressure in an engine is wear on the engine's vital parts. Over time, engine bearings and seals suffer from wear and tear. Wear can cause these parts to eventually lose their original dimensions, and this increased clearance allows for a greater volume of oil to flow over time which can greatly reduce oil pressure. For instance, .001 of an inch worn off of the engine's main bearings can cause up to a 20% loss in oil pressure. Simply replacing worn bearings may fix this problem, but in older

engines with a lot of wear not much can be done besides completely overhauling the engine which is generally not cost effective.

Particles in the oil can also cause serious problems with oil pressure. After oil flows through the engine, it returns to the oil pan, and can carry along a lot of debris. The debris can cause problems with the oil pickup screen and the oil pump itself. The holes in the oil pickup screen measure about 0.04 square inches (0.26 cm<sup>2</sup>). Holes of this size only pick up bigger pieces of debris and allow a lot of smaller pieces to flow through it. The holes in the screen are so big (relative to debris) because at low temperatures and slow engine speed the oil is very viscous and needs large openings to flow freely. Even with these large holes in the screen, it can still become clogged and cause low oil pressure. A .005-inch-thick (0.13 mm) coating on the screen can reduce hole size to about .03 square inches (0.19 cm<sup>2</sup>), which in turn reduces the flow of oil by 44 percent.

Even after passing through the oil pickup screen and the oil filter, debris can remain in the oil. It is very important to change the oil and oil filter to minimize the amount of debris flowing through your engine. This harmful debris along with normal engine wear in high mileage engines causes an increase in clearances between bearings and other moving parts.

Low oil pressure may be simply because there is not enough oil in the sump, due to burning oil (normally caused by piston ring wear or worn valve seals) or leakage. The piston rings serve to seal the combustion chamber, as well as remove oil from the internal walls of the cylinder. However, when they wear, their effectiveness drops, which leaves oil on the cylinder walls during combustion. In some engines, burning a small amount of oil is normal and shouldn't necessarily cause any alarm, where as burning lots of oil is a sign that the engine might be in need of an overhaul.

### **Oil Pumps in High Performance Engines**

Not all engines have the same oiling needs. High performance engines, for example, place higher stress on the lubricating system. In this case, the lubricating system must be especially robust to prevent engine damage. Most engines in cars on the road today don't run much past 5,000–6,000 rpm, but that isn't always the case in performance engines, where engine speeds could reach up to 8000-9000 rpm. In engines like these, it is imperative that the oil circulates quickly enough, or air may become trapped in the oil. Also, to free up power, some engines in performance applications run lower weight oil, which requires less power to run the oil pump. Common oil weights in engines today are usually either 5w30 or 10w30 oil, where as performance engines might use 0w20 oil, which is less viscous.

### ***Wet and Dry Sump Systems***

Conventional wet sump engines have one oil pump. It is generally located inside the lower part of the engine, usually below and/or to one side of the crankshaft. On dry sump engines, at least two oil pumps are required: one to pressurize and distribute the oil

around the engine components, and at least one other 'scavenge pump' to evacuate the oil which has pooled at the bottom of the engine. This scavenge pump is sometimes (but not always) located in the 'sump' of the engine, and crucially, this scavenge pump's flow-rate capacity must exceed that of the pump which pressurizes and distributes oil throughout the engine.

Because of the dry sump's external oil reservoir, excess air can escape the oil before the oil is pumped back through the engine. Dry sumps also allow for more power because it reduces the amount of windage, oil sloshing up into the rotating assembly, and the vacuum from the scavenge pump improves ring seal. Dry sumps are more popular in racing applications because of the improved power and reduced oil sloshing that would otherwise reduce oil pressure. Disadvantages of dry sumps are increased weight, additional parts, and more chances for leaks and problems to occur.

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## Chapter 13

# 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

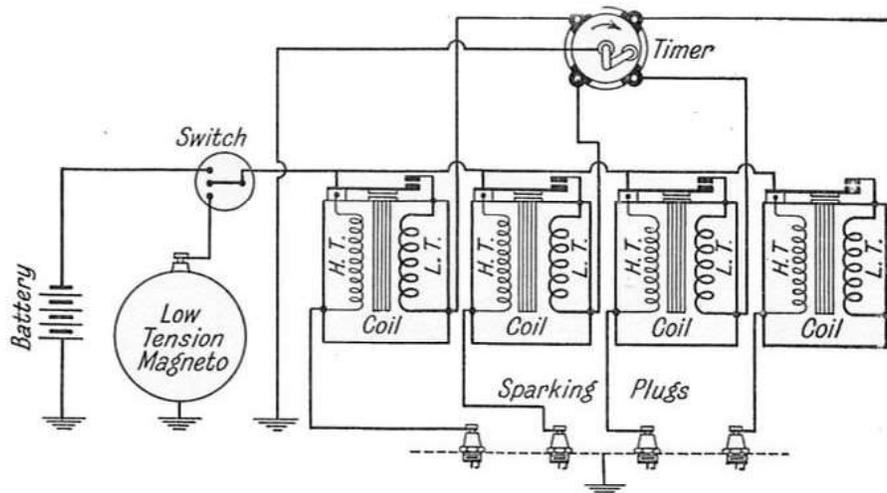
The simplest form of spark ignition is that using a magnet. The engine spins a magnet inside a coil, or, in the earlier designs, a coil inside a fixed magnet, and also operates a contact breaker, interrupting the current and causing the voltage to be increased sufficiently to jump a small gap. The spark plugs are connected directly from the magneto output. Early magnetos had one coil, with the contact breaker (spark 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.

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## ***Modern ignition systems***

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

## **Mechanically timed ignition**

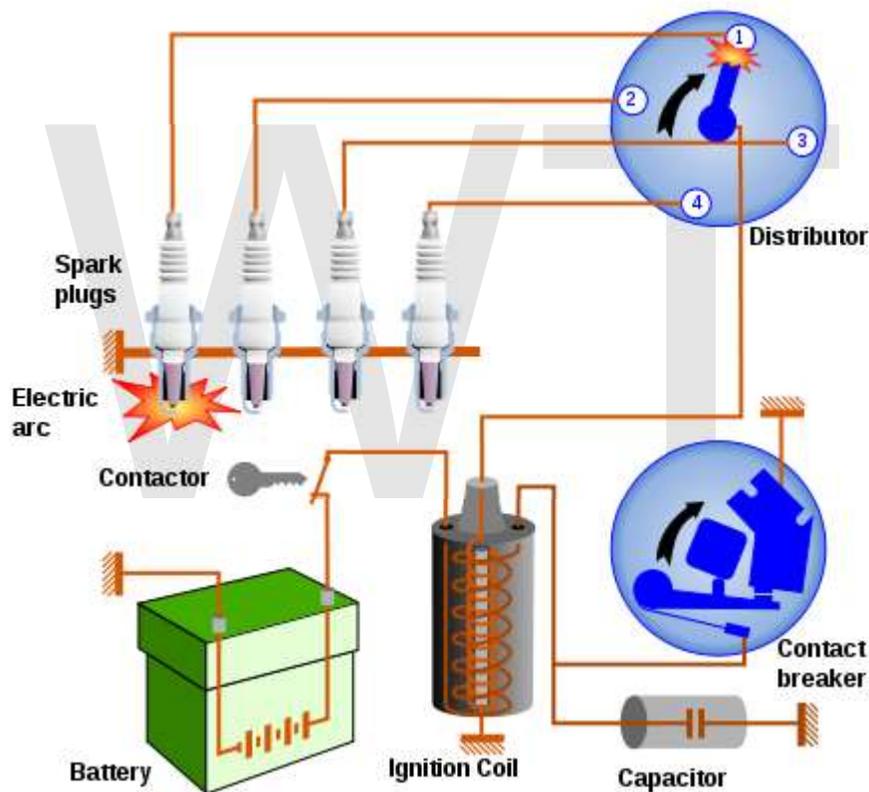


Distributor cap

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 an 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

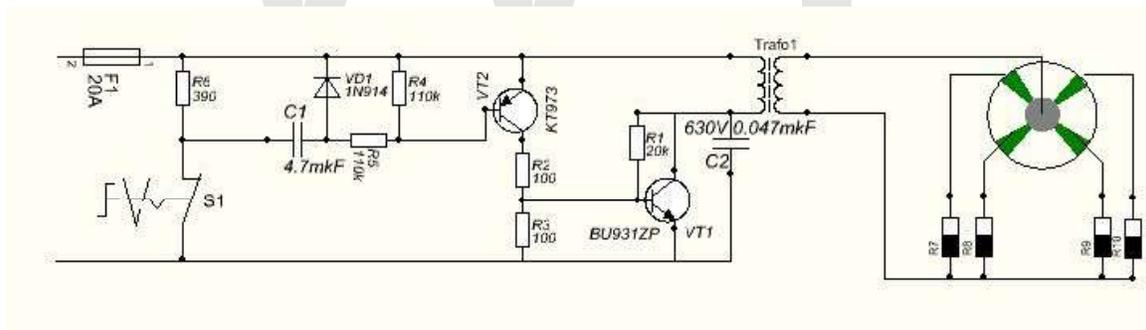
example, the position of the contact breaker points relative to the engine angle can be changed a small amount dynamically, allowing the ignition timing to be automatically advanced with increasing revolutions per minute (RPM) and/or increased manifold vacuum, giving better efficiency and performance.

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 O<sub>2</sub> 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.

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## Chapter 14

# 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**

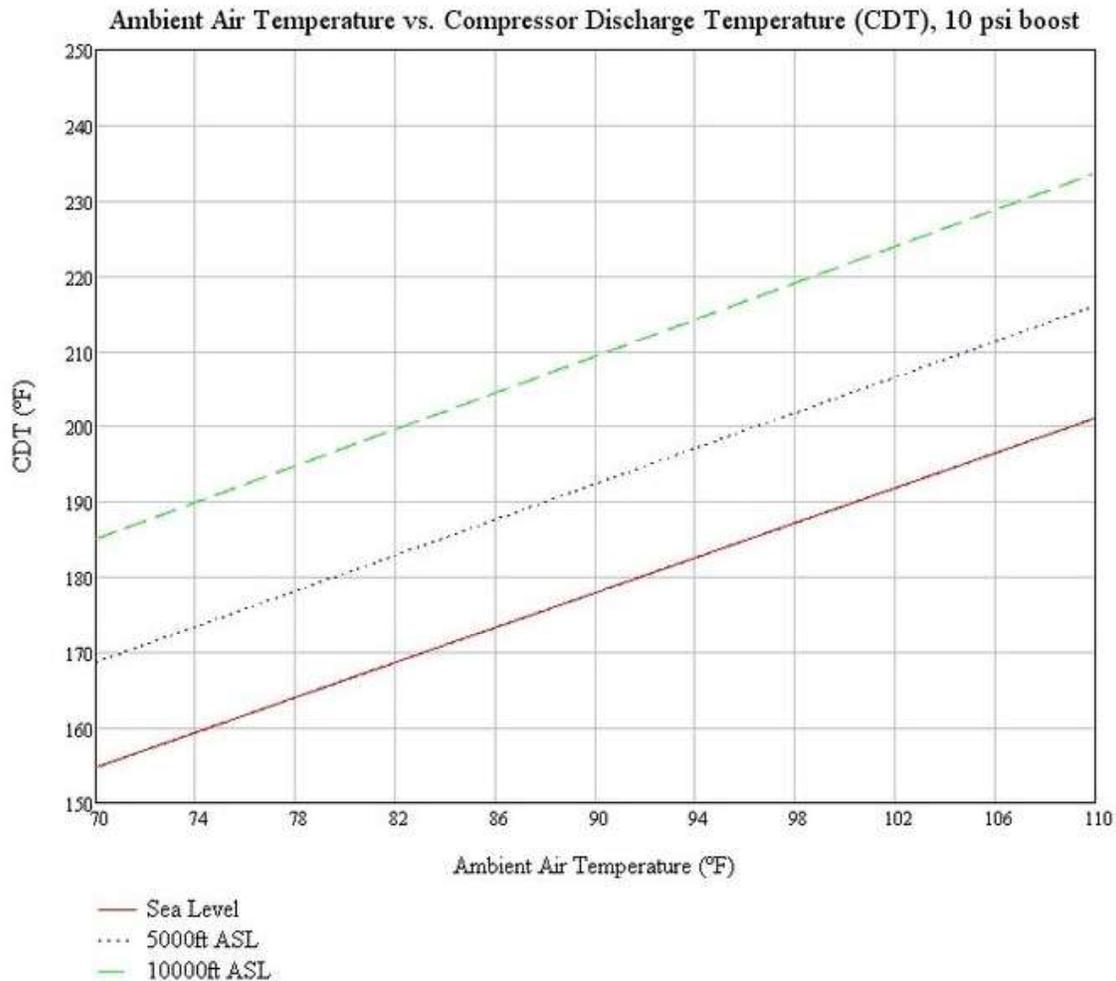
- Axial turbine
- Radial turbine

### **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)

$\gamma$ = Ratio of specific heats for air =  $C_p/C_v$

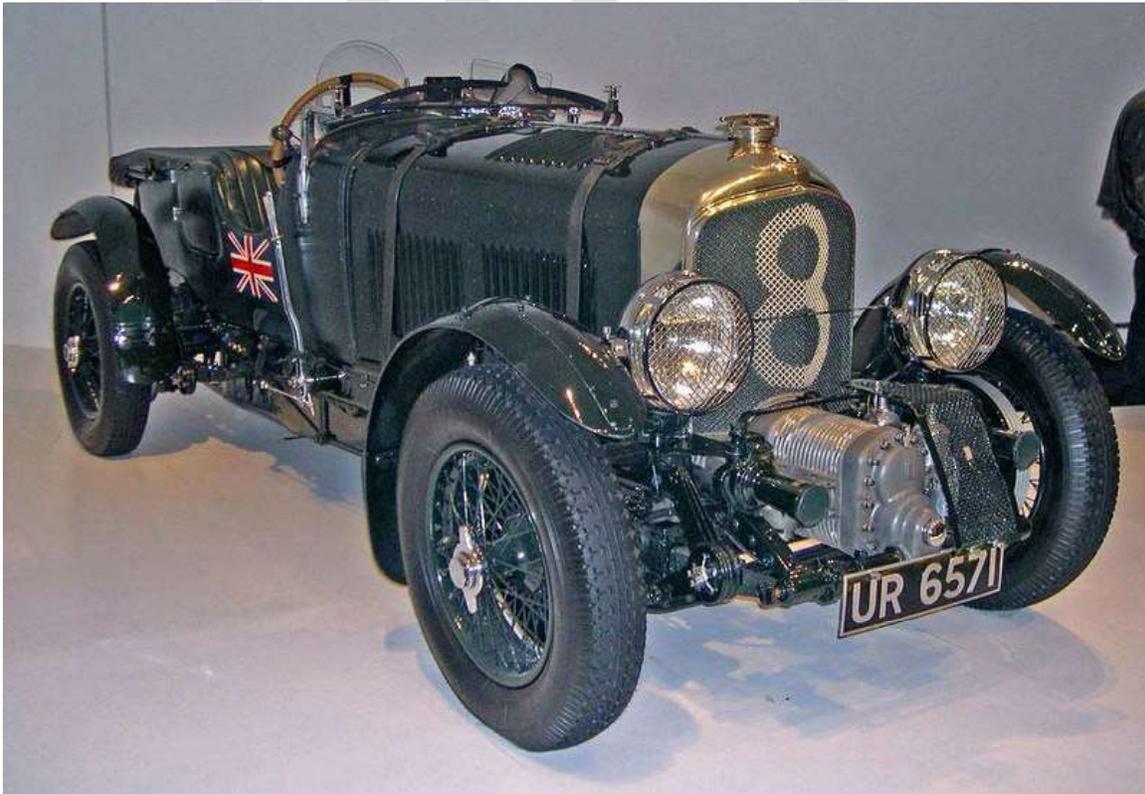
$C_p$ = Specific heat at constant pressure

$C_v$ = 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 ancillaries 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.

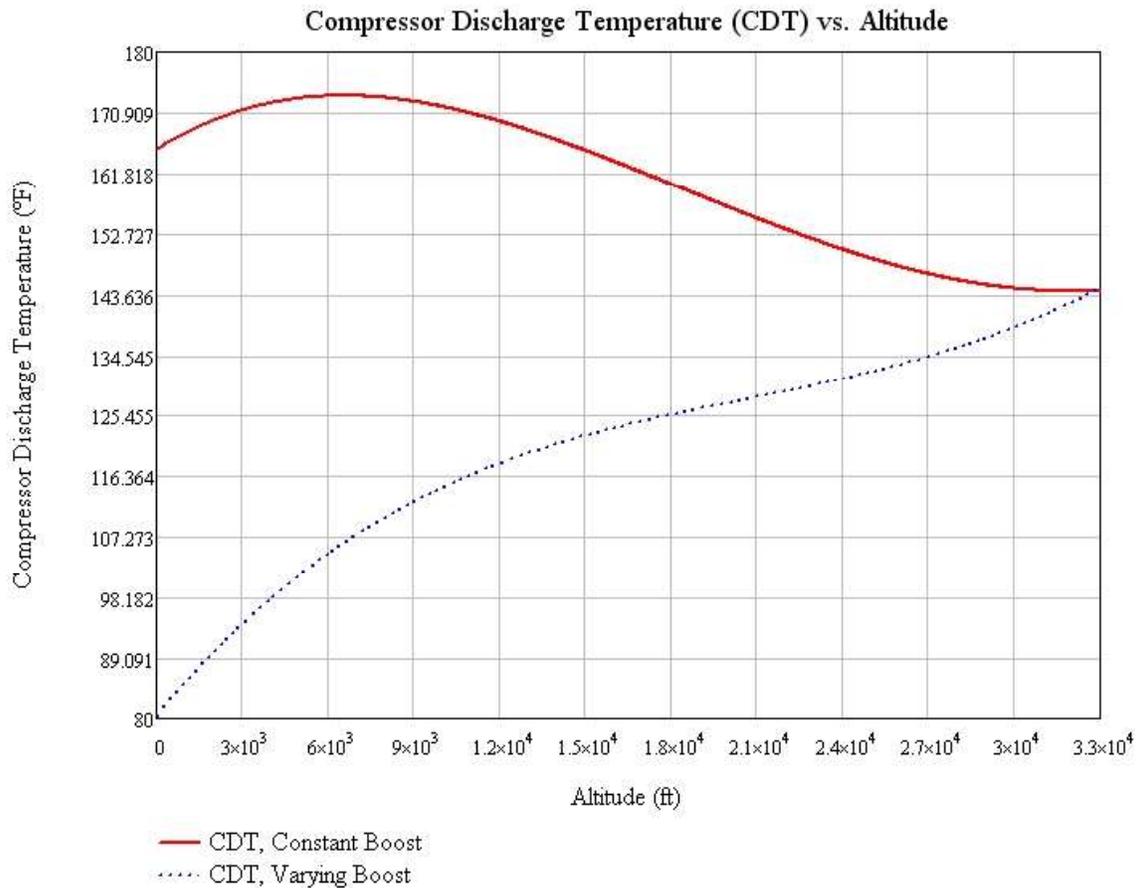
Superchargers are a natural addition to aircraft piston engines which are intended for operation at high altitudes. As an aircraft climbs to higher altitude, air pressure and air density decreases. The output of a piston engine drops because of the reduction in the mass of air that can be drawn into 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  $\frac{1}{3}$  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 oversized 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

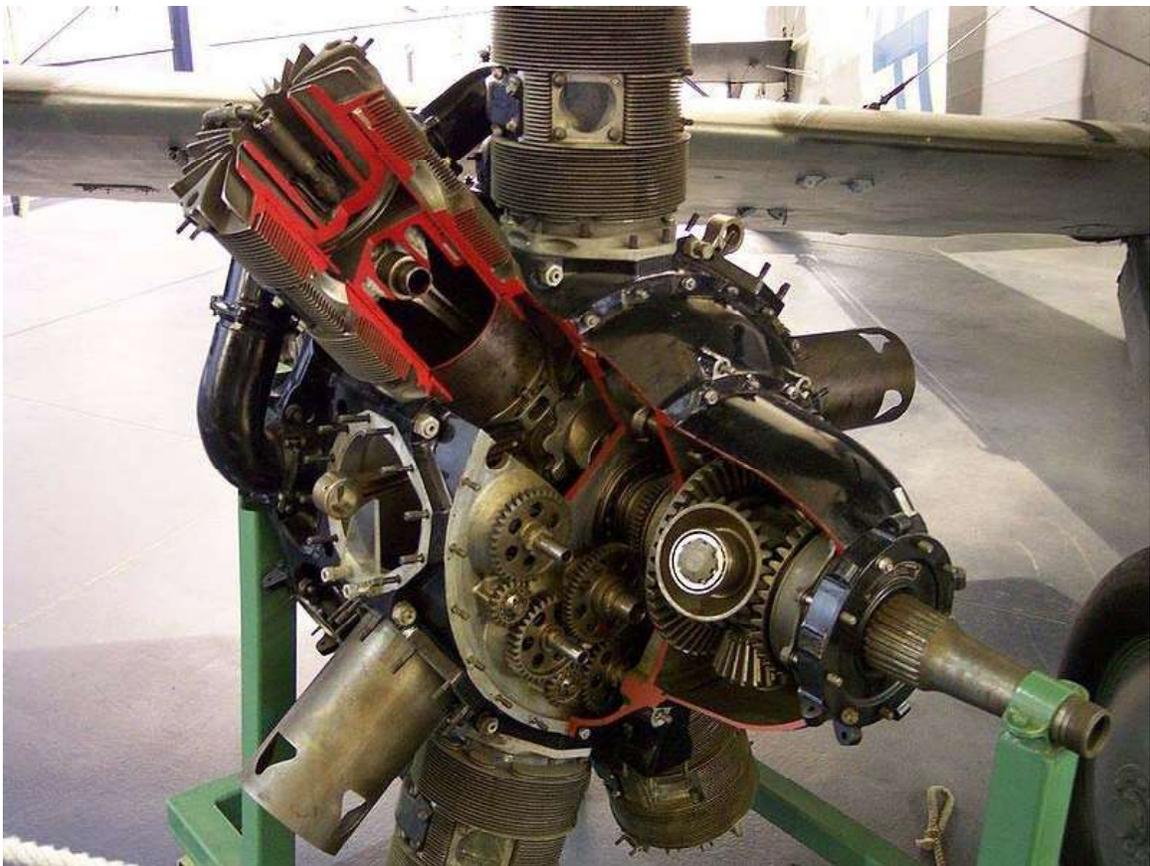
use of the new fuel during World War II began in early 1940 when 100-octane fuel was delivered to the British Royal Air Force from refineries in America and the East Indies. The German *Luftwaffe* also had supplies of a similar fuel.

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).

WWT

## Chapter 15

# Sleeve Valve



*Bristol Perseus*

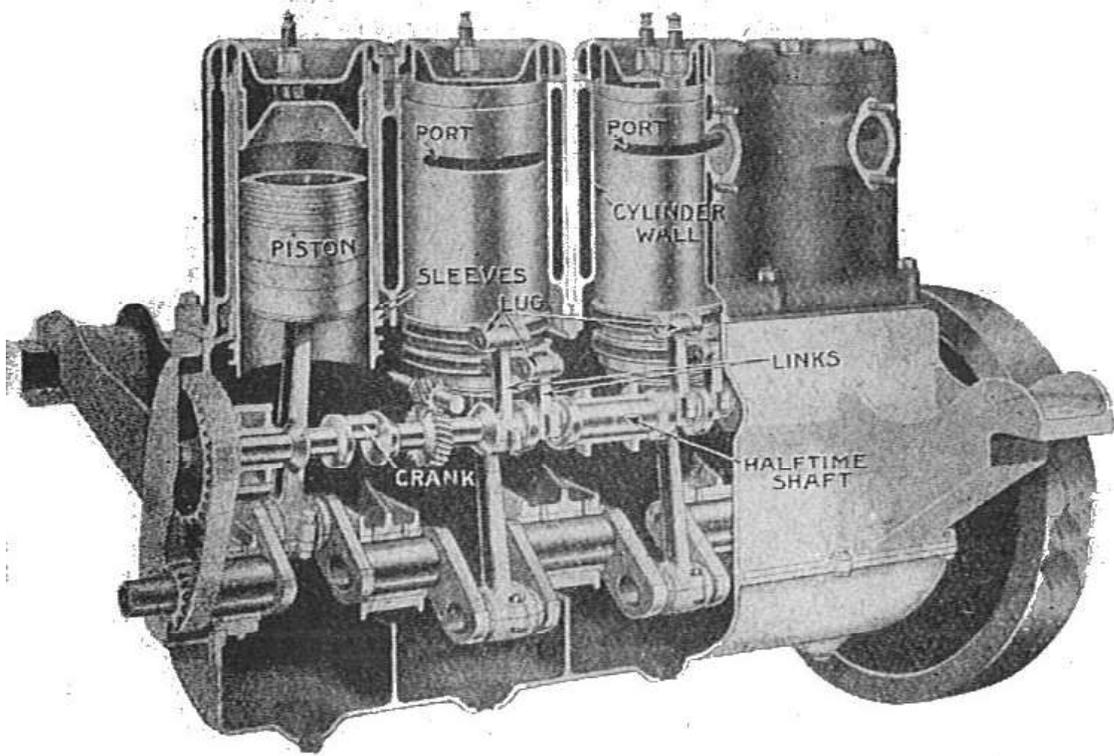
The **sleeve valve** is a type of valve mechanism for piston engines, distinct from the more common poppet valve. Sleeve-valve engines saw use in a number of pre-World War II luxury cars, sports cars, the Willys-Knight car and light truck, the British Daimler and French Avions Voisin luxury cars, also 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**

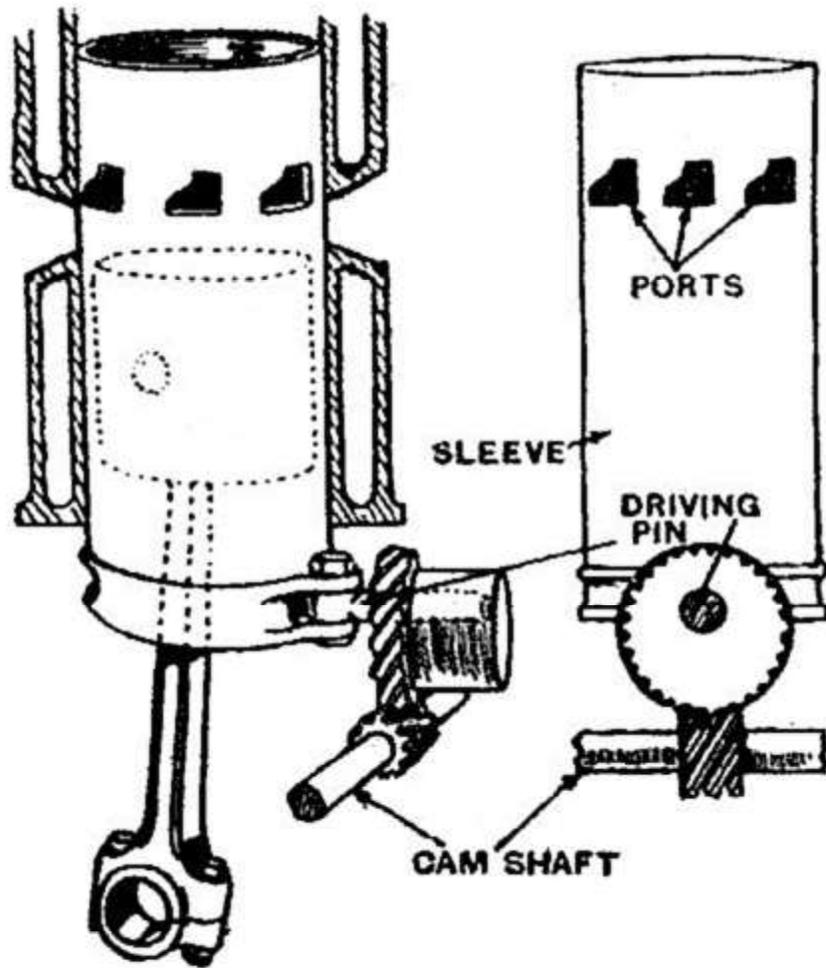
A sleeve valve takes the form of one or more machined sleeves. It fits between the piston and the cylinder wall in the cylinder of an internal combustion engine where it rotates and/or slides, ports (holes) in the side of the valve(s) aligning with the cylinder's inlet and exhaust ports at the appropriate 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 16

# Thermodynamic Cycle

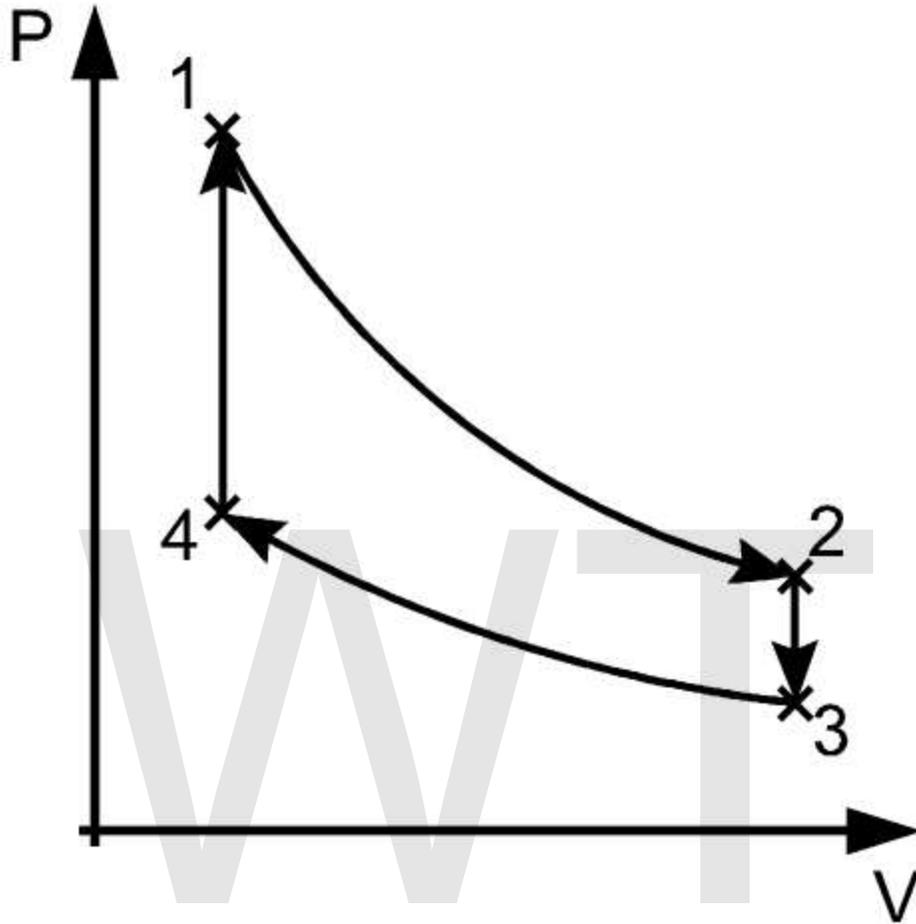
A **thermodynamic cycle** consists of a series of thermodynamic processes transferring heat and work, while varying pressure, temperature, and other state variables, eventually returning a system to its initial state. In the process of going through this cycle, the system may perform work on its surroundings,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

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

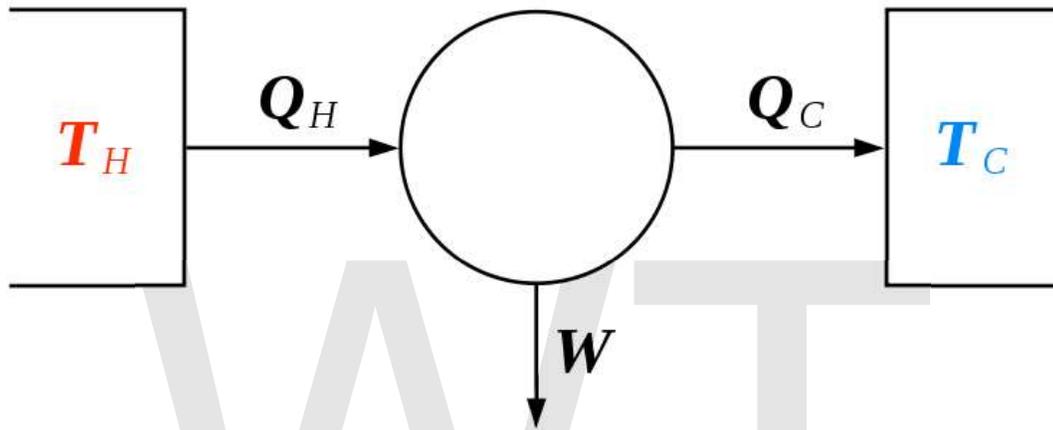
This work is equal to the balance of heat ( $Q$ ) transferred into the system:

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

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.

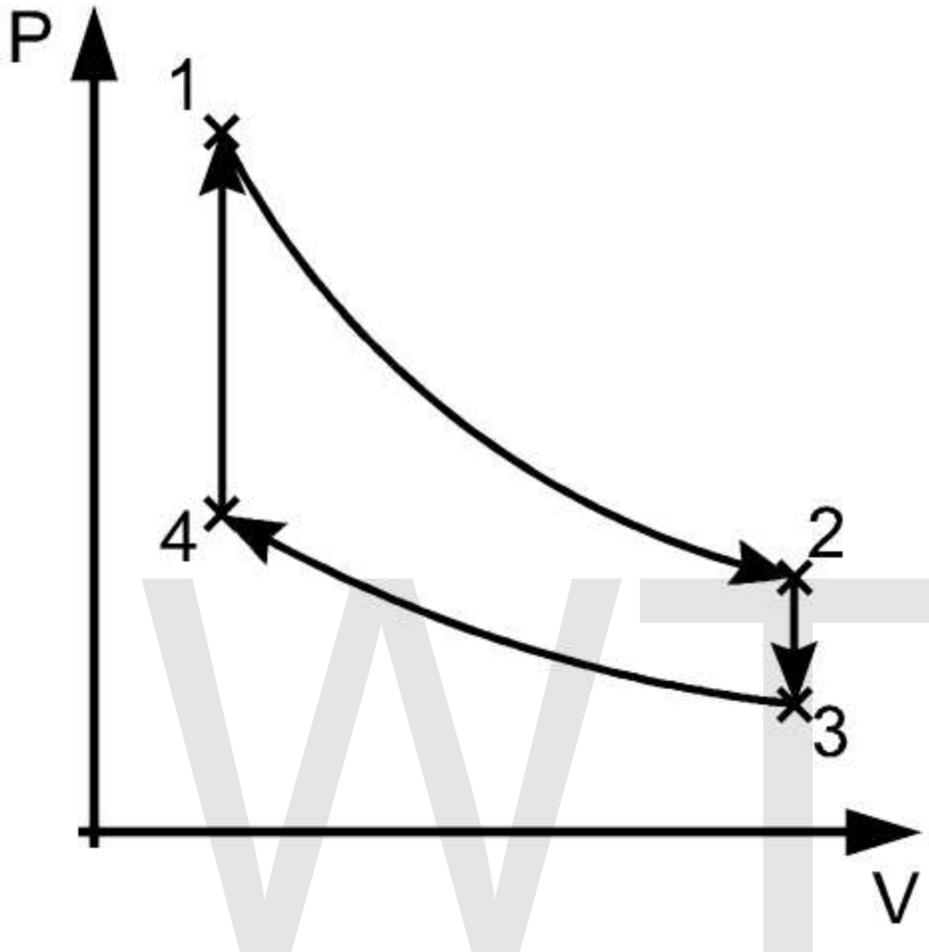
If the cyclic process moves clockwise around the loop, then  $W$  will be positive, and it represents a heat engine. If it moves counterclockwise, then  $W$  will be negative, and it represents a heat pump.

### 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:

$$(3) \quad W = W_{1 \rightarrow 2} + W_{2 \rightarrow 3} + W_{3 \rightarrow 4} + W_{4 \rightarrow 1}$$

$$W_{1 \rightarrow 2} = \int_{V_1}^{V_2} P dV, \text{ negative, work done by system}$$

$$W_{2 \rightarrow 3} = \int_{V_2}^{V_3} P dV, \text{ zero work if } V_2 \text{ equal } V_3$$

$$W_{3 \rightarrow 4} = \int_{V_3}^{V_4} P dV, \text{ positive, work done on system}$$

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

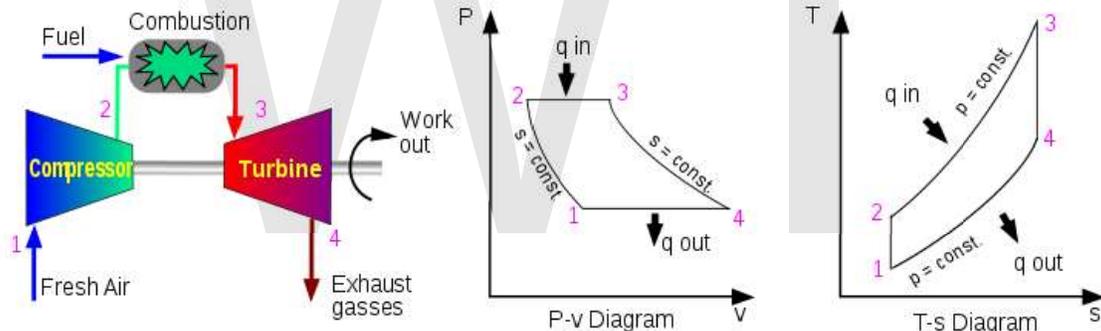
If no volume change happens in process 4->1 and 2->3, equation (3) simplifies to:

$$(4) \quad W = W_{1 \rightarrow 2} + W_{3 \rightarrow 4}$$

## 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.

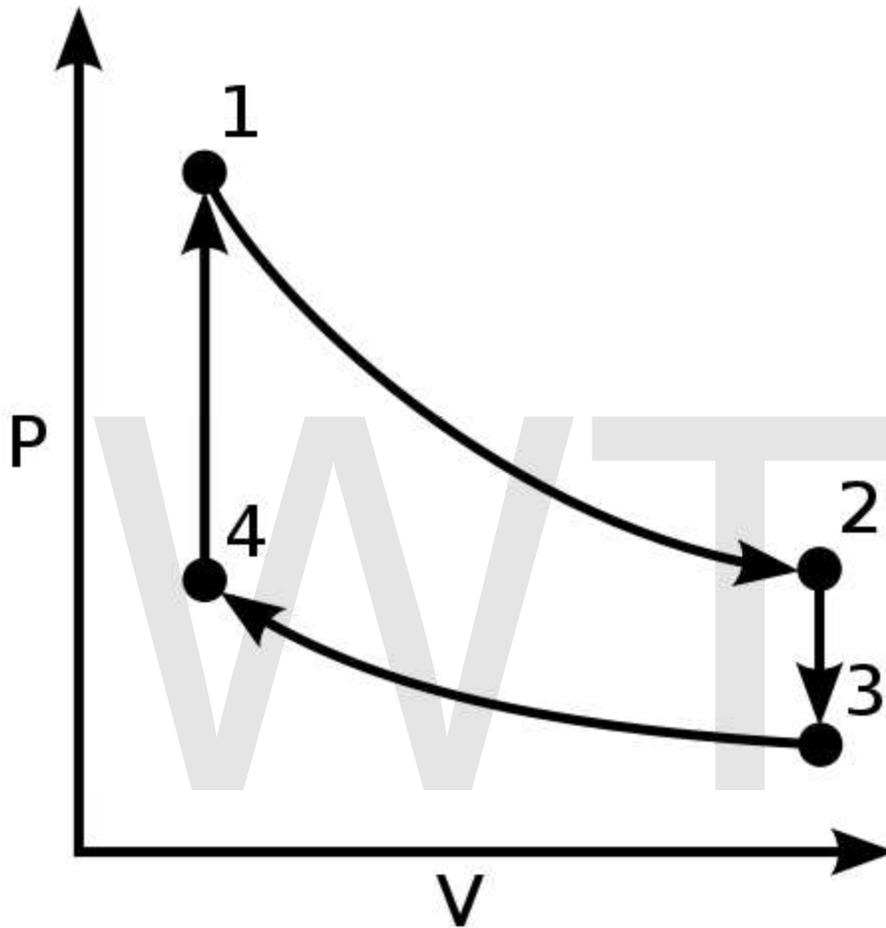
## Modelling real systems



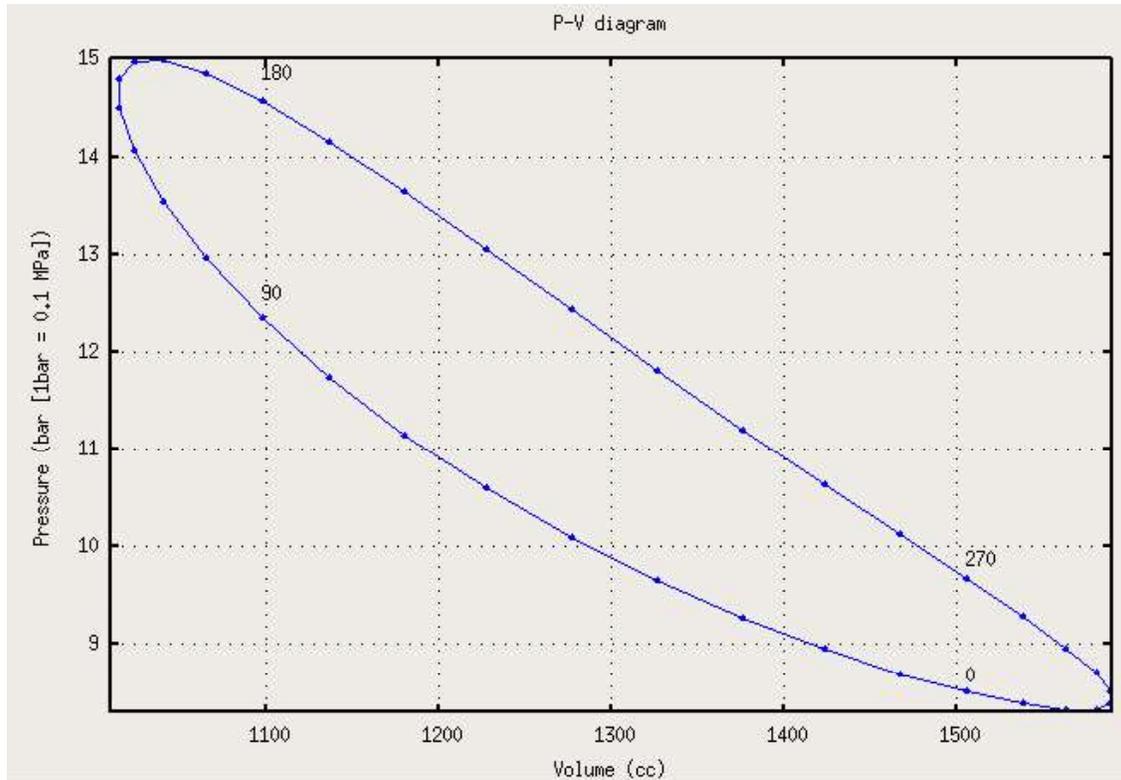
Example of a real system modelled by an idealized process: PV and TS diagrams of a Brayton cycle mapped to actual processes of a gas turbine engine

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 as 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.

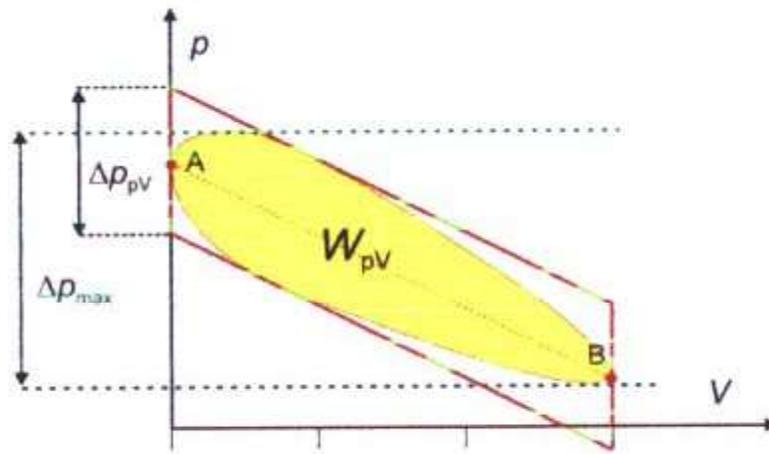
The difference between an idealized cycle and actual performance may be significant. For example, the following images illustrate the differences in work output predicted by an ideal Stirling cycle and the actual performance of a Stirling engine:



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:

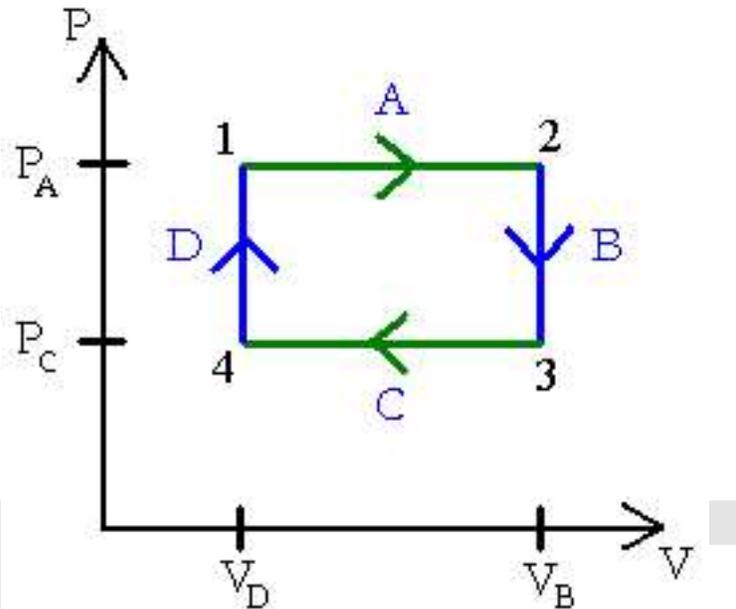
Cycle	Process 1-2 (Compression)	Process 2-3 (Heat Addition)	Process 3-4 (Expansion)	Process 4-1 (Heat Rejection)	Notes
Power cycles normally with external combustion - or heat pump cycles:					
<b>Bell Coleman</b>	adiabatic	isobaric	adiabatic	isobaric	A reversed Brayton cycle
<b>Brayton</b>	adiabatic	isobaric	adiabatic	isobaric	Jet engines aka first Ericsson cycle from 1833
<b>Carnot</b>	isentropic	isothermal	isentropic	isothermal	the second
<b>Ericsson</b>	isothermal	isobaric	isothermal	isobaric	Ericsson cycle from 1853
<b>Scuderi</b>	adiabatic	variable pressure and volume	adiabatic	isochoric	
<b>Stirling</b>	isothermal	isochoric	isothermal	isochoric	
<b>Stoddard</b>	adiabatic	isobaric	adiabatic	isobaric	

Power cycles normally with internal combustion:

<b>Diesel</b>	adiabatic	isobaric	adiabatic	isochoric	
<b>Lenoir</b>	isobaric	isochoric	adiabatic	isobaric	Pulse jets (Note: 3 of the 4 processes are different)
<b>Otto</b>	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,

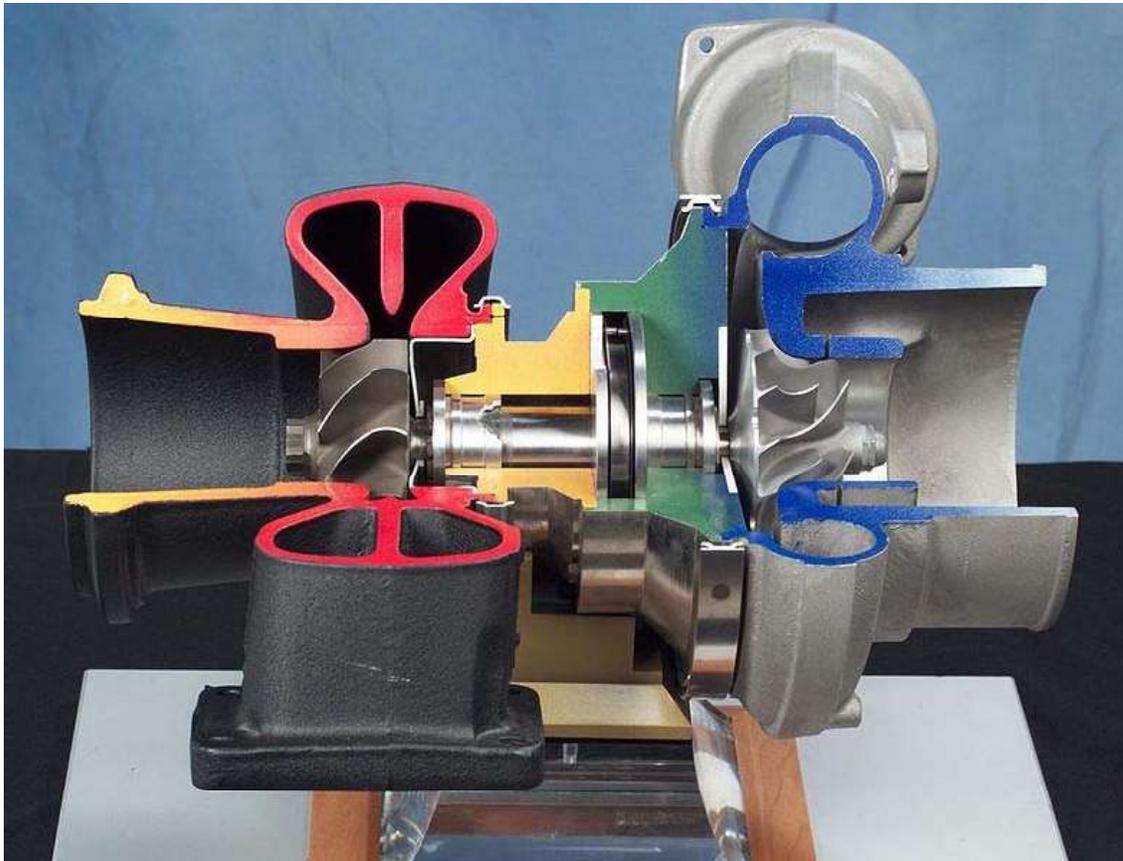
$$\oint dS = \oint \frac{dQ}{T} = 0$$

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

WWT

## Chapter 17

# 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 turbochargers 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.

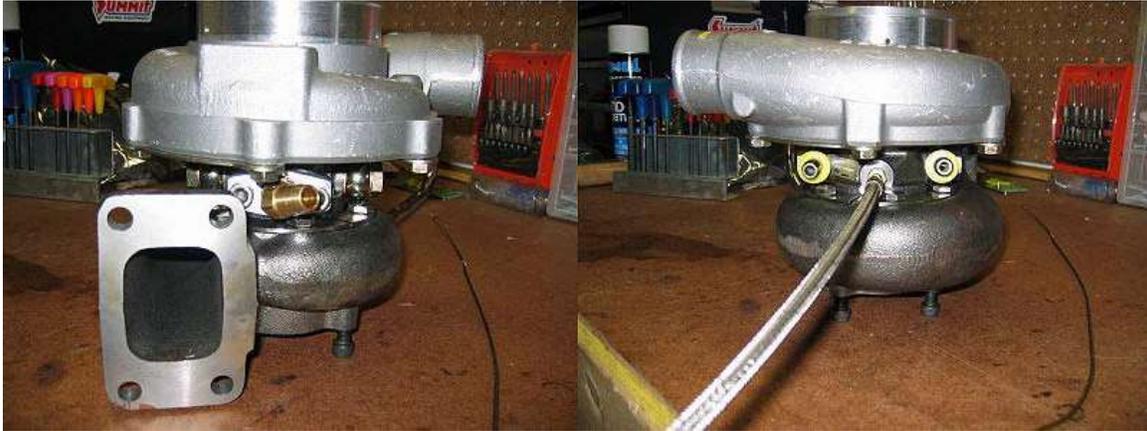
In drag racing, an 1,800 hp (1,340 kW) twin-turbocharged Pontiac GTA developed by Gale Banks of Southern California, set a land speed record for the "World's Fastest Passenger Car" of 277 mph (446 km/h). This event was chronicled at the time in a 1987 cover story published by *Autoweek* magazine. Gale 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 bodysells 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**

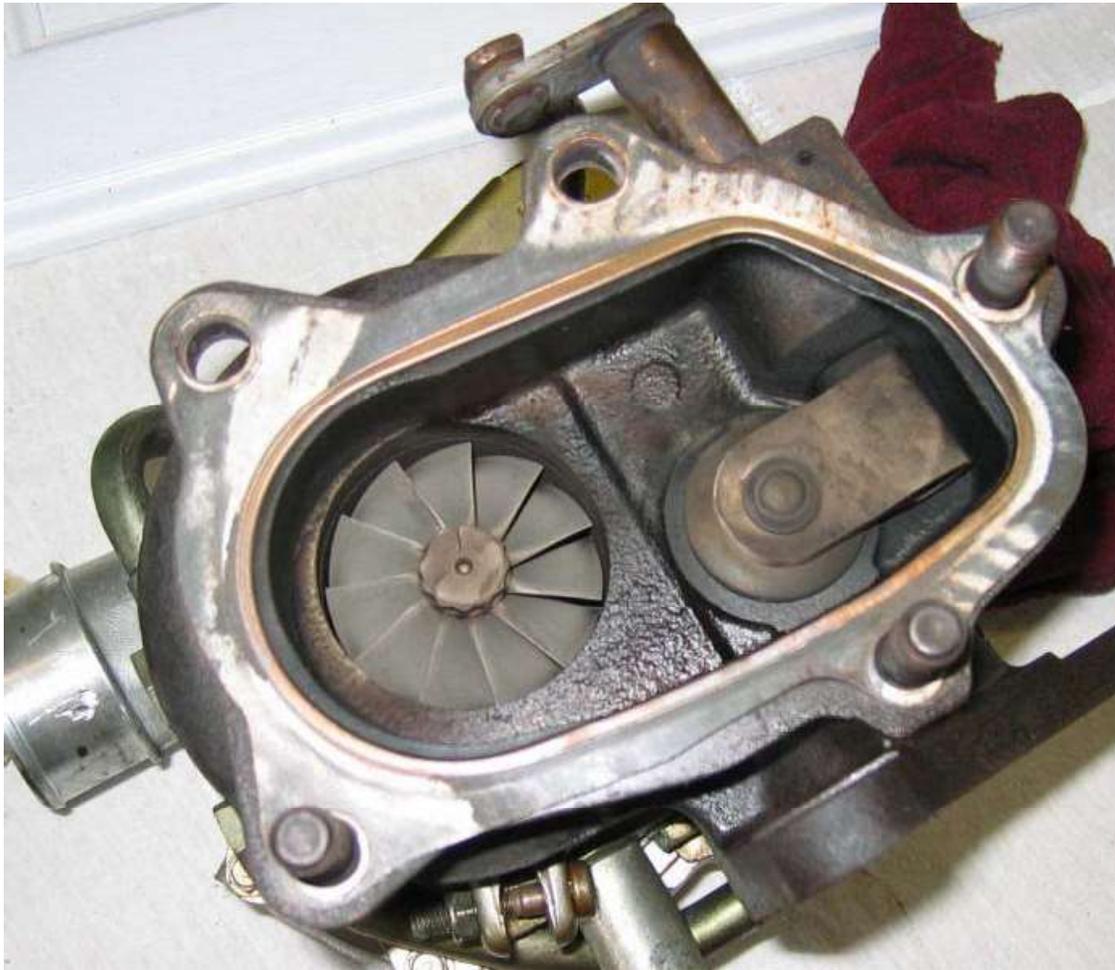
In the automotive world, boost refers to the increase in pressure that is generated by the turbocharger in the intake manifold that exceeds normal atmospheric pressure. Atmospheric pressure is approximately 14.7 psi or 1.0 bar, and anything above this level is considered to be boost. The level of boost 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, turbochargers 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**

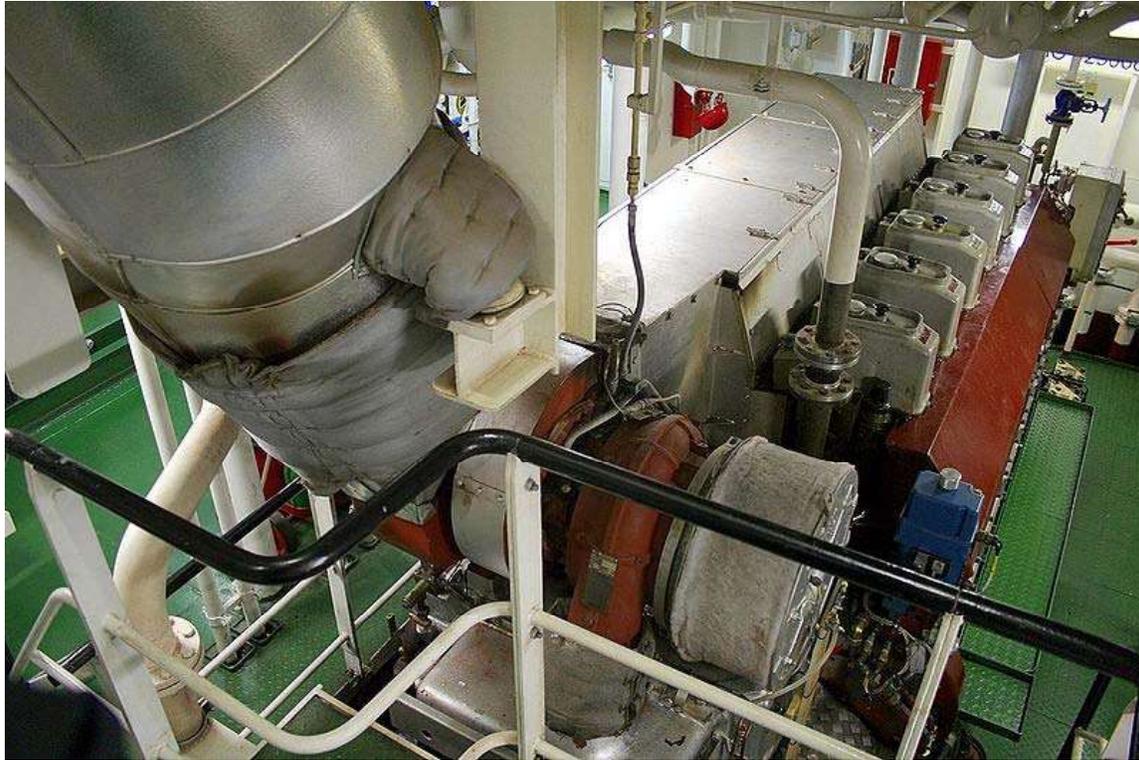
Some car makers combat lag by using two small turbos. A typical arrangement for this is to have one turbo active across the entire rev range of the engine and one coming on-line at higher RPM. Below this RPM, both exhaust and air inlet of the secondary turbo are closed. Being individually smaller they 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.

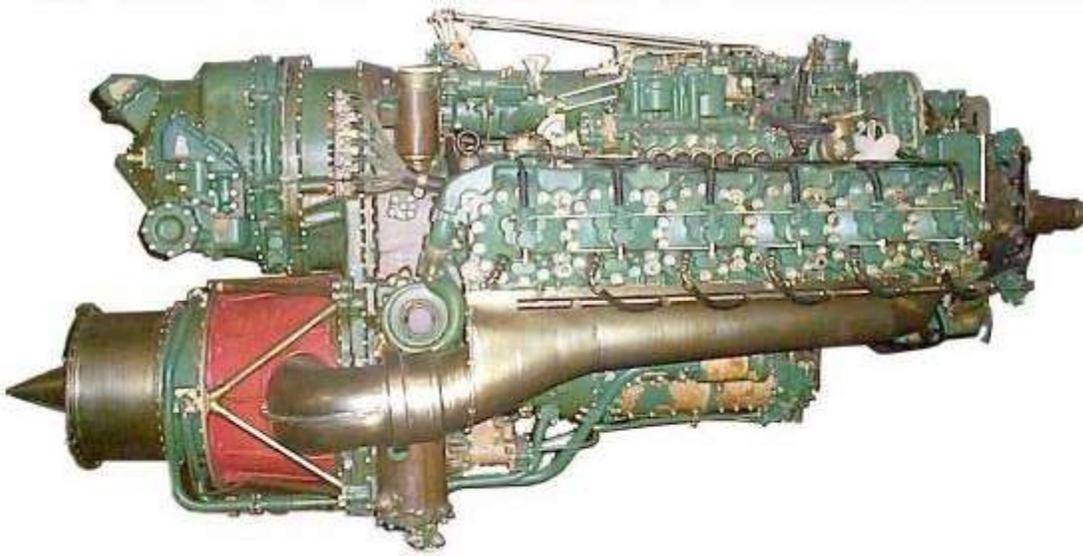
### **Boost threshold**

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 18

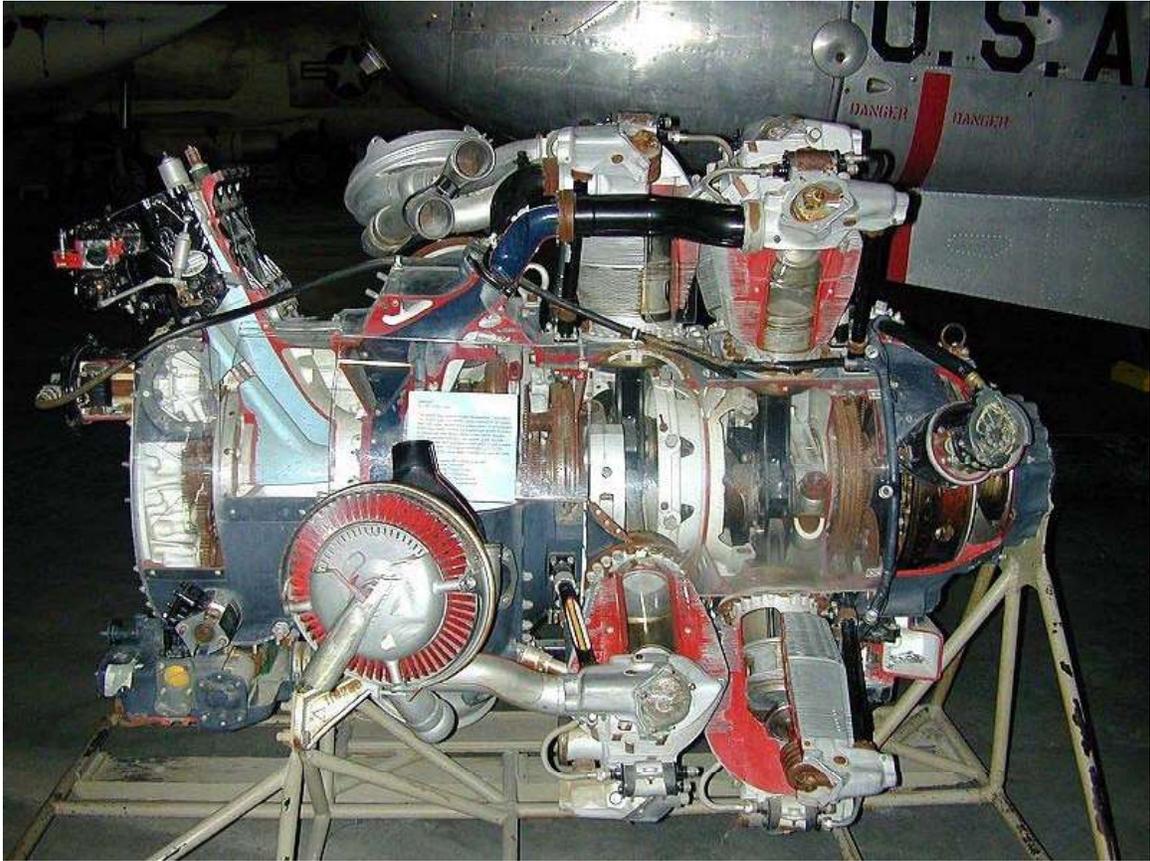
# Turbo-Compound Engine & Opposed-Piston Engine

## 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

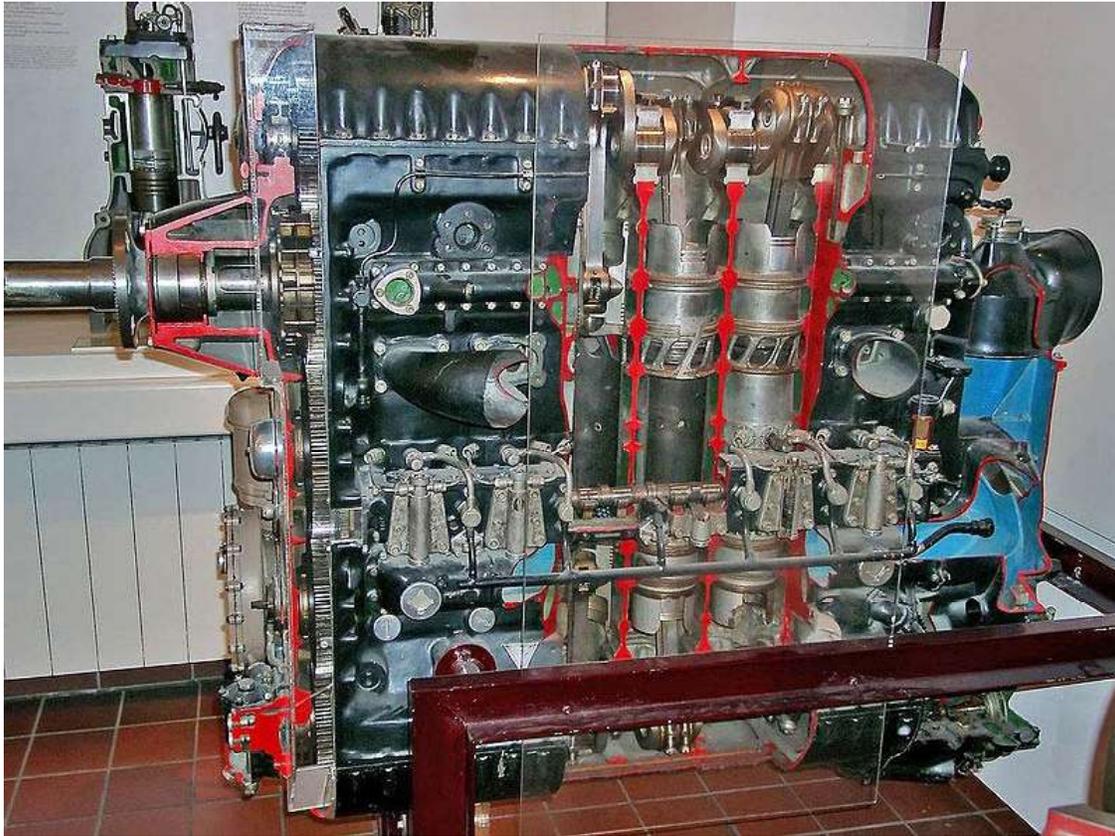
# Opposed-Piston Engine



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.

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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-

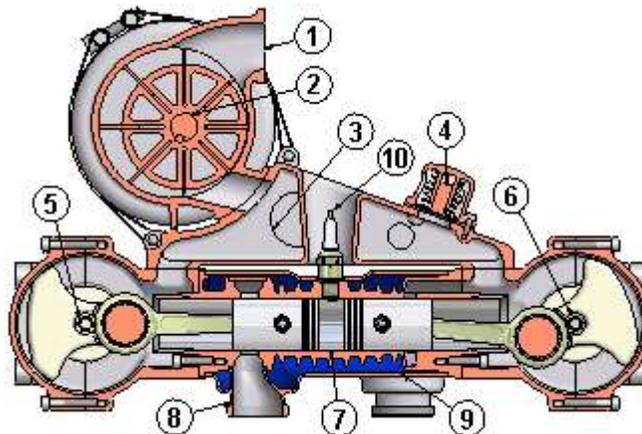
piston diesel aircraft engine with twin geared crankshafts for General aviation applications, by both Dair and PowerPlant Developments in the UK.

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<sup>3</sup> (15 cu in), and one with 350 cm<sup>3</sup> (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 thermally 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.