Handbook of Internal Combustion Engines
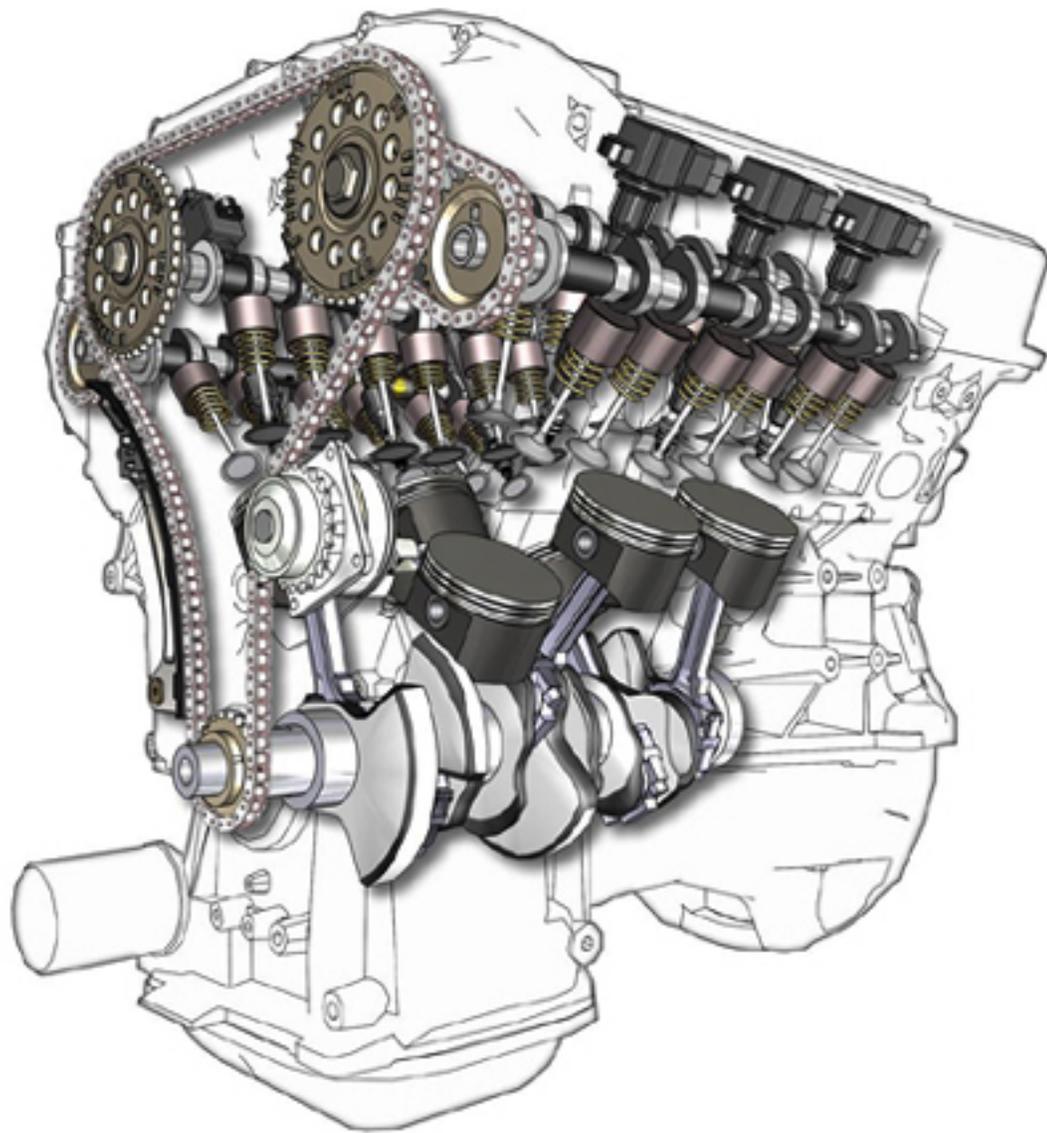
Gigi Leboeuf

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Chapter 1

Internal Combustion Engine

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

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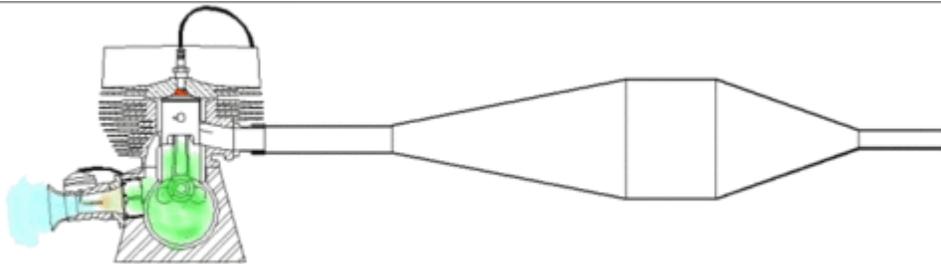
Two stroke engine in operation

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

A large number of different designs for ICEs have been developed and built, with a variety of different strengths and weaknesses. Powered by an energy-dense fuel (which is

very frequently gasoline, a liquid derived from fossil fuels). While there have been and still are many stationary applications, the real strength of internal combustion engines is in mobile applications and they dominate as a power supply for cars, aircraft, and boats, from the smallest to the largest.

An automobile engine partly opened and colored to show components.

Applications

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

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

History

Types of internal combustion engine

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

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

Principles of operation

Reciprocating:

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

Rotary:

- Wankel engine
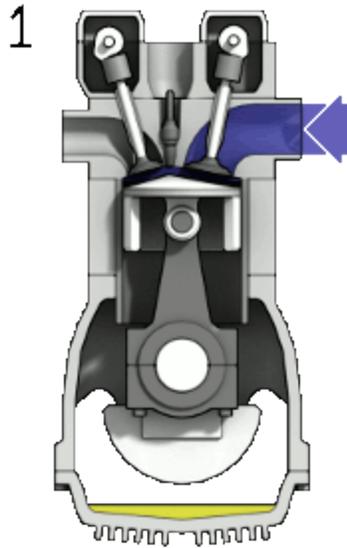
Continuous combustion:
Brayton cycle:

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

Engine configurations

Internal combustion engines can be classified by their configuration.

Four stroke configuration

Operation

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

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

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

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

Combustion

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

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

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

Gasoline Ignition Process

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

Diesel Ignition Process

Diesel engines and HCCI (Homogeneous charge compression ignition) engines, rely solely on heat and pressure created by the engine in its compression process for ignition. The compression level that occurs is usually twice or more than a gasoline engine. Diesel engines will take in air only, and shortly before peak compression, a small quantity of diesel fuel is sprayed into the cylinder via a fuel injector that allows the fuel to instantly ignite. HCCI type engines will take in both air and fuel but continue to rely on an unaided auto-combustion process, due to higher pressures and heat. This is also why diesel and HCCI engines are more susceptible to cold-starting issues, although they will run just as well in cold weather once started. Light duty diesel engines with indirect injection in

automobiles and light trucks employ glowplugs that pre-heat the combustion chamber just before starting to reduce no-start conditions in cold weather. Most diesels also have a battery and charging system; nevertheless, this system is secondary and is added by manufacturers as a luxury for the ease of starting, turning fuel on and off (which can also be done via a switch or mechanical apparatus), and for running auxiliary electrical components and accessories. Most new engines rely on electrical and electronic engine control units (ECU) that also adjust the combustion process to increase efficiency and reduce emissions.

Two stroke configuration

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

Spark-ignition two-strokes are small and light for their power output and mechanically very simple; however, they are also generally less efficient and more polluting than their four-stroke counterparts. In terms of power per cm³, a two-stroke engine produces comparable power to an equivalent four-stroke engine. The advantage of having one power stroke for every 360° of crankshaft rotation (compared to 720° in a 4 stroke motor) is balanced by the less complete intake and exhaust and the shorter effective compression and power strokes. It may be possible for a two stroke to produce more power than an equivalent four stroke, over a narrow range of engine speeds, at the expense of less power at other speeds.

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

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

The largest internal combustion engines in the world are two-stroke diesels, used in some locomotives and large ships. They use forced induction (similar to super-charging, or turbocharging) to scavenge the cylinders; an example of this type of motor is the Wartsila-Sulzer turbocharged two-stroke diesel as used in large container ships. It is the

most efficient and powerful internal combustion engine in the world with over 50% thermal efficiency. For comparison, the most efficient small four-stroke motors are around 43% thermal efficiency (SAE 900648); size is an advantage for efficiency due to the increase in the ratio of volume to surface area.

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

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

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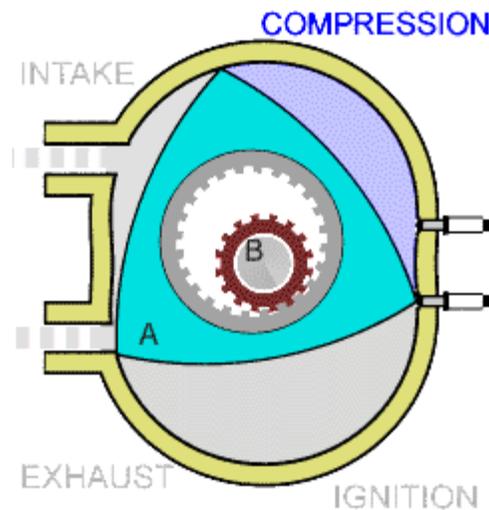
The Wankel cycle. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

The Wankel engine (rotary engine) does not have piston strokes. It operates with the same separation of phases as the four-stroke engine with the phases taking place in

separate locations in the engine. In thermodynamic terms it follows the Otto engine cycle, so may be thought of as a "four-phase" engine. While it is true that three power strokes typically occur per rotor revolution due to the 3:1 revolution ratio of the rotor to the eccentric shaft, only one power stroke per shaft revolution actually occurs; this engine provides three power 'strokes' per revolution per rotor giving it a greater power-to-weight ratio than piston engines. This type of engine is most notably used in the current Mazda RX-8, the earlier RX-7, and other models.

Gas turbines

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

Jet engine

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

Engine cycle
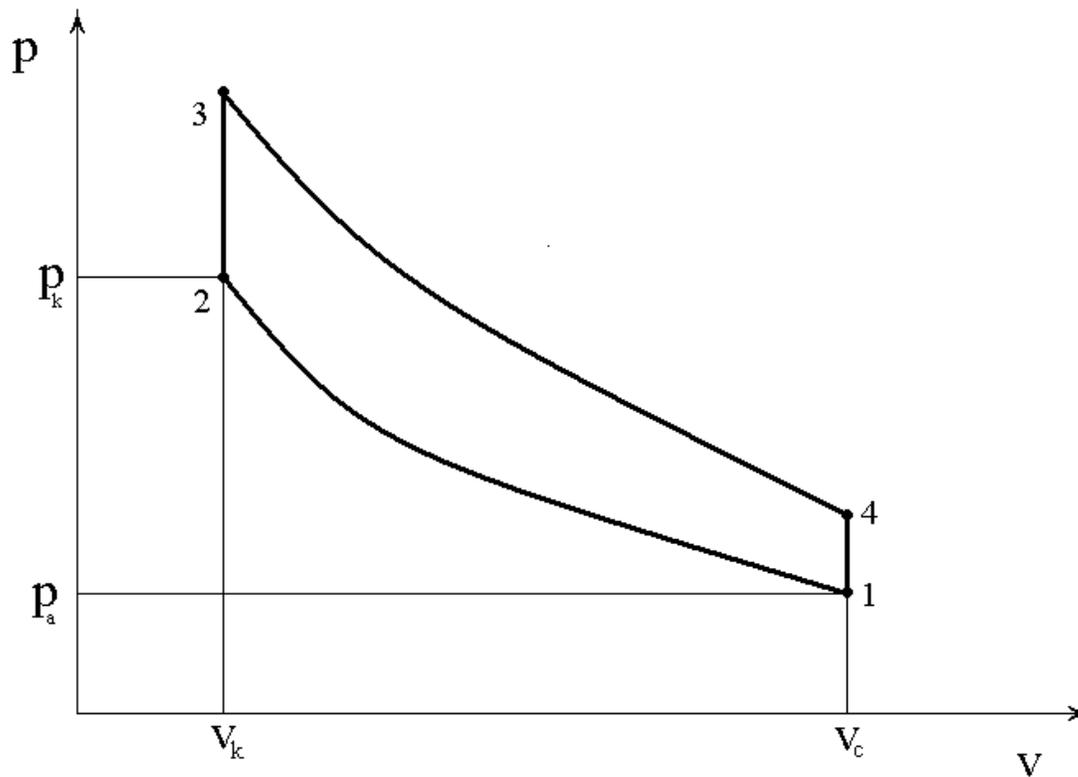
Idealised P/V diagram for two stroke Otto cycle

Two-stroke

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

The steps involved here are:

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

Two Stroke Spark Ignition (SI) engine:

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

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

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

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

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

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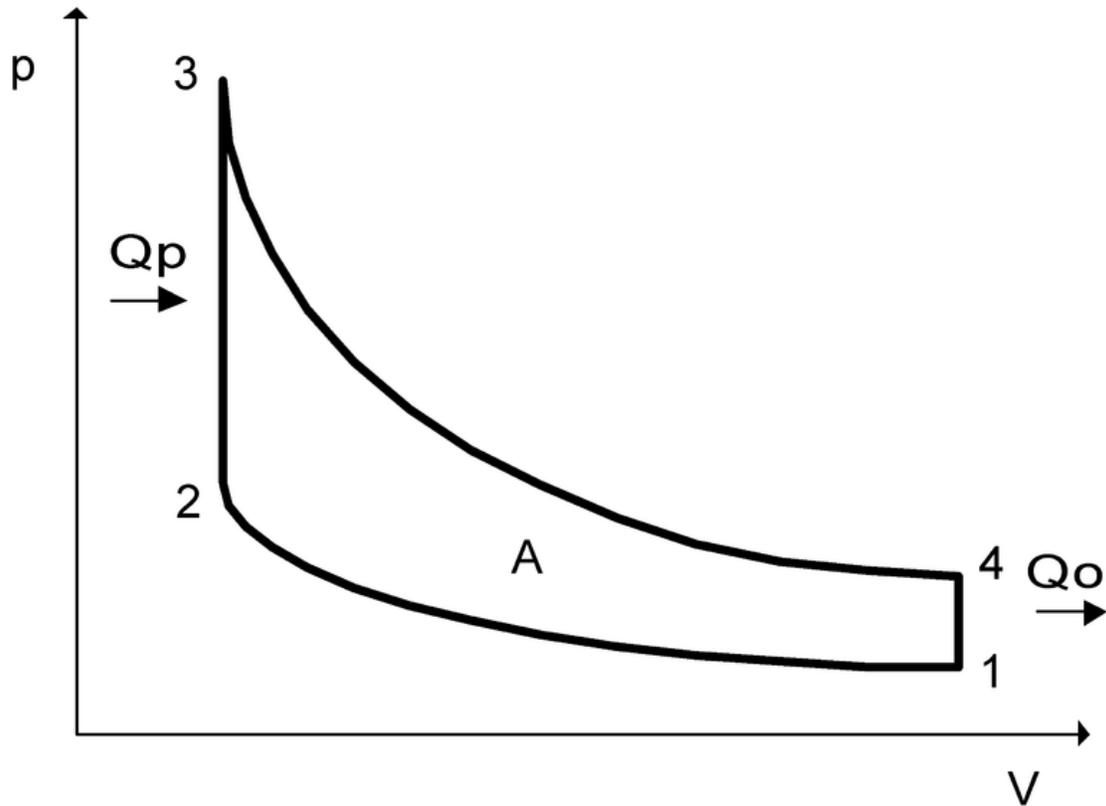
Idealised Pressure/volume diagram of the Otto cycle showing combustion heat input Qp and waste exhaust output Qo, the power stroke is the top curved line, the bottom is the compression stroke

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

The steps involved here are:

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

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

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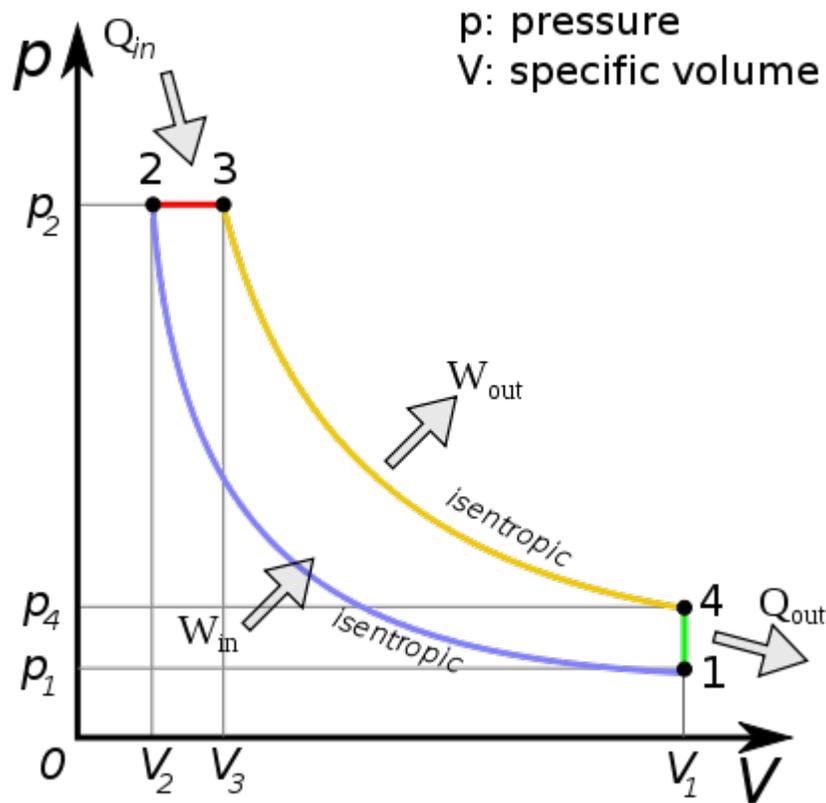
P-v Diagram for the Ideal Diesel cycle. The cycle follows the numbers 1-4 in clockwise direction.

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

Five-stroke

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

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

Six-stroke

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

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

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

Brayton cycle
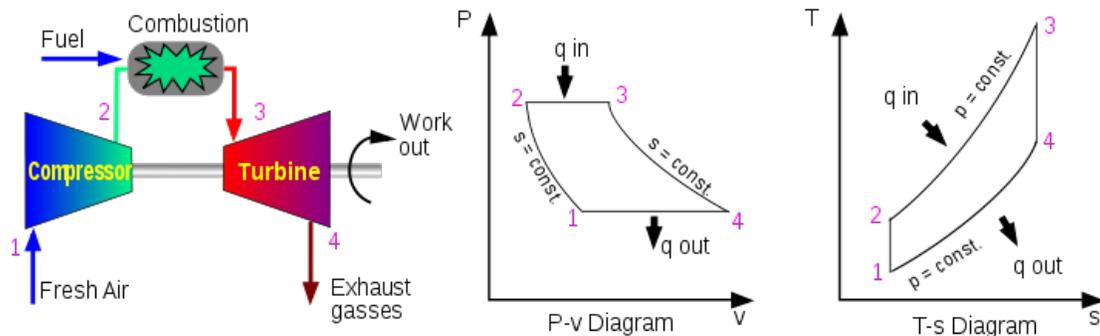
Brayton cycle

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

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

Obsolete

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

Fuels and oxidizers

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

Fuels

Nowadays, fuels used include:

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

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

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

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

Hydrogen

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

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

Oxidizers

One-cylinder gasoline engine (ca. 1910)

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

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

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

Engine starting

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

Measures of engine performance

Engine types vary greatly in a number of different ways:

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

Energy efficiency

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

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

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

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

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

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

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

Measures of fuel/propellant efficiency

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

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

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

Air and noise pollution

Air pollution

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

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

Carbon fuels contain sulfur and impurities that eventually lead to producing sulfur monoxides (SO) and sulfur dioxide (SO_2) in the exhaust which promotes acid rain. One

final element in exhaust pollution is ozone (O_3). This is not emitted directly but made in the air by the action of sunlight on other pollutants to form "ground level ozone", which, unlike the "ozone layer" in the high atmosphere, is regarded as a bad thing if the levels are too high. Ozone is broken down by nitrogen oxides, so one tends to be lower where the other is higher.

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

Noise pollution

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

Idling

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

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

Chapter 2

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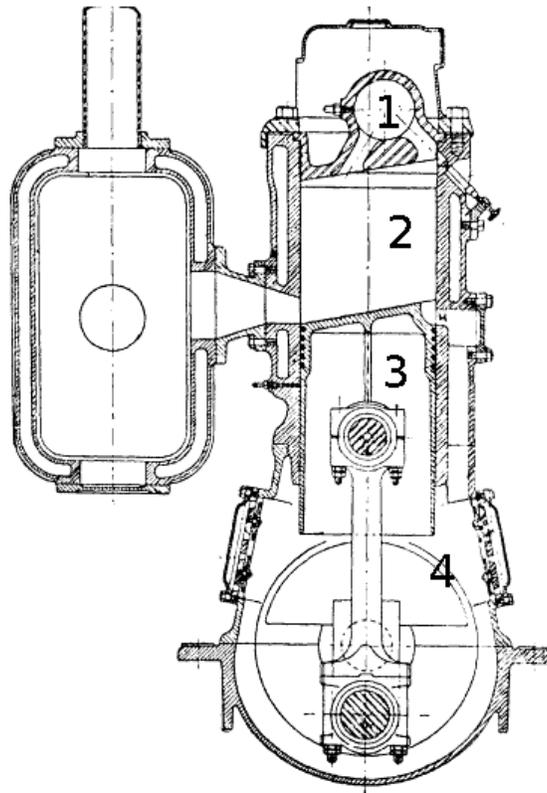
Hot bulb engine (two-stroke).
1. Hot bulb
2. Cylinder
3. Piston
4. Crankcase

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

History

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

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

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

Operation and working cycle

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

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

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

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

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

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

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

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

Four-stroke engines

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

Two-stroke engines

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

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

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

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

the engine, that showed a spinning arrow. The arrow pointed in the direction of normal engine rotation – if the dial spun the other way the engine had reversed itself.

Advantages

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

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

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

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

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

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

Uses

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

The reliability of the hot-bulb engine, their ability to run on many fuels and the fact that they can be left running for hours or days at a time made them extremely popular with agricultural, forestry and marine users, where they were used for pumping and for

powering milling, sawing and threshing machinery. Hot-bulb engines were also used on road rollers and tractors.

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

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

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

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

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

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

The hot-bulb engine was invented at the same time that dynamos and electric light systems were perfected, and electricity generation was one of the hot-bulb engines main uses. The engine could achieve higher R.P.M. than a standard reciprocating steam engine (although high-speed steam engines were developed during the 1890s), and its low fuel and maintenance requirements (including the ability to be operated and maintained by only one person) made it ideal for small-scale power supply. Generator sets driven by hot-bulb engines were installed in numerous large houses (especially in rural areas) in Europe, as well as in factories, theatres, lighthouses, radio stations and many other

locations where a centralised electricity grid was not available. Usually the dynamo or alternator would be driven off the engine's flywheel by a flat belt, to allow the necessary 'gearing up'- making the generator turn at a faster speed than the engine. Companies such as Armstrong Whitworth and Boulton Paul manufactured and supplied complete generating sets (both the engine and generator) from the 1900s to the late 1920s, when the formation of national grid systems throughout the world and the replacement of the hot-bulb engine by the diesel engine caused a drop in demand.

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

Compression ignition

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

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

Replacement

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

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

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

much wider speed range, making them more versatile. This made these medium-sized diesels a very popular choice for use in generator sets, replacing the hot-bulb engine as the engine of choice for small-scale power generation.

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

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

Hot bulb pseudo diesel development

1890s–1910

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

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

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

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

ignition. To counteract pre-ignition, water would be dripped into the air intake, providing some flexibility.

- In the diesel engine, fuel is injected into the cylinder, with an adjusted timing relative to the engine speed and load, shortly before the top dead center of the Compression Stroke is reached.

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

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

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

1910–1950s

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

The hot bulbs started to develop cracks and breakups and were gradually replaced by water cooled cylinder heads with a flat hot spot. Over time the compression ratios were increased from $\frac{1}{3}$ to $\frac{1}{14}$.Fuel injection started from 135 degrees before top dead center, with low compression to 20 degrees before top dead center with later higher compression engines increasing the hot air factor for ignition and increasing the fuel efficiency. Glowplugs finally replaced the preheating with a blowtorch methods and engine speeds were increased, resulting in what is now classified as an indirect injection diesel. Hot bulb or prechambered engines are always easier to produce. more reliable and could handle smaller amounts of fuel in smaller engines, than the direct injected "pure" diesels could.

Production

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

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

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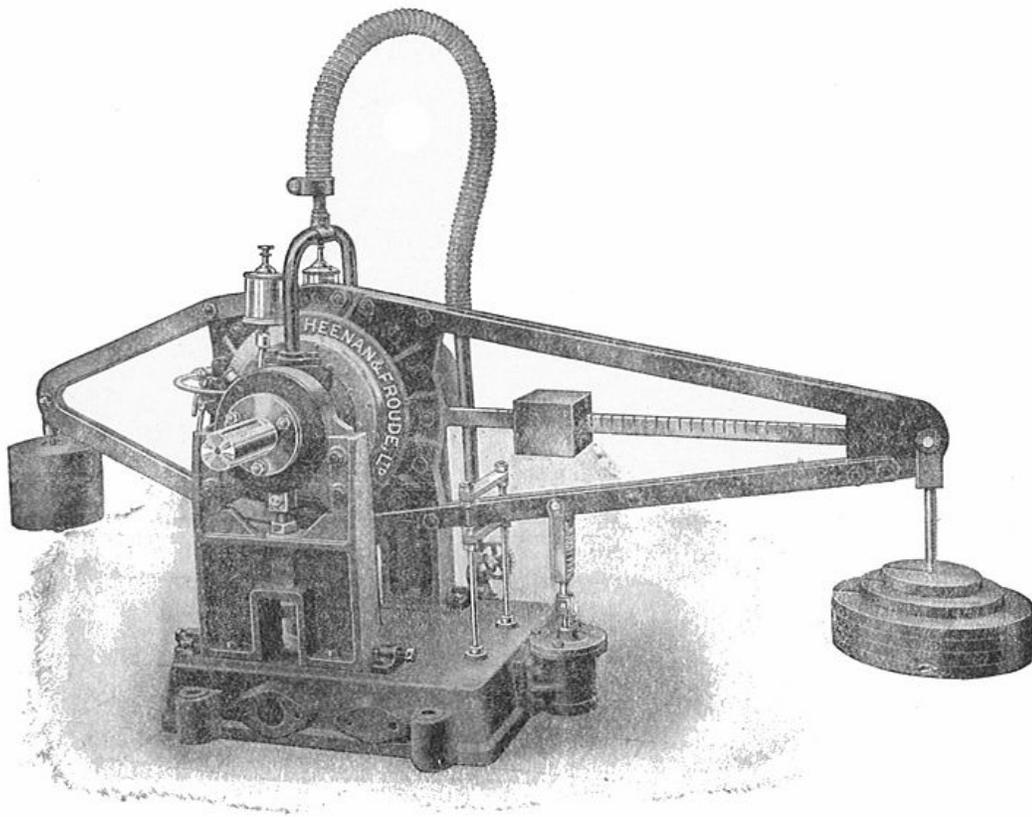
Dynamometer

Early hydraulic dynamometer, with dead-weight torque measurement.

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

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

dynamometer. A dynamometer that can either drive or absorb is called a *universal* or *active* dynamometer.

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

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

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

Principles of operation of torque power (absorbing) dynamometers

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

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

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

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

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

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

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

Power is calculated based on torque x RPM / 5252.

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

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

$$P = \tau \cdot \omega$$
or
$$P = F \cdot v$$
where
P is the power in watts
τ is the torque in newton metres
ω is the angular velocity in radians per second
F is the force in newtons
v is the linear velocity in metres per second

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

For imperial units,

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

where

P_{hp} is the power in horsepower

$\tau_{lb \cdot ft}$ is the torque in pound-feet

ω_{RPM} is the rotational velocity in revolutions per minute

For metric units,

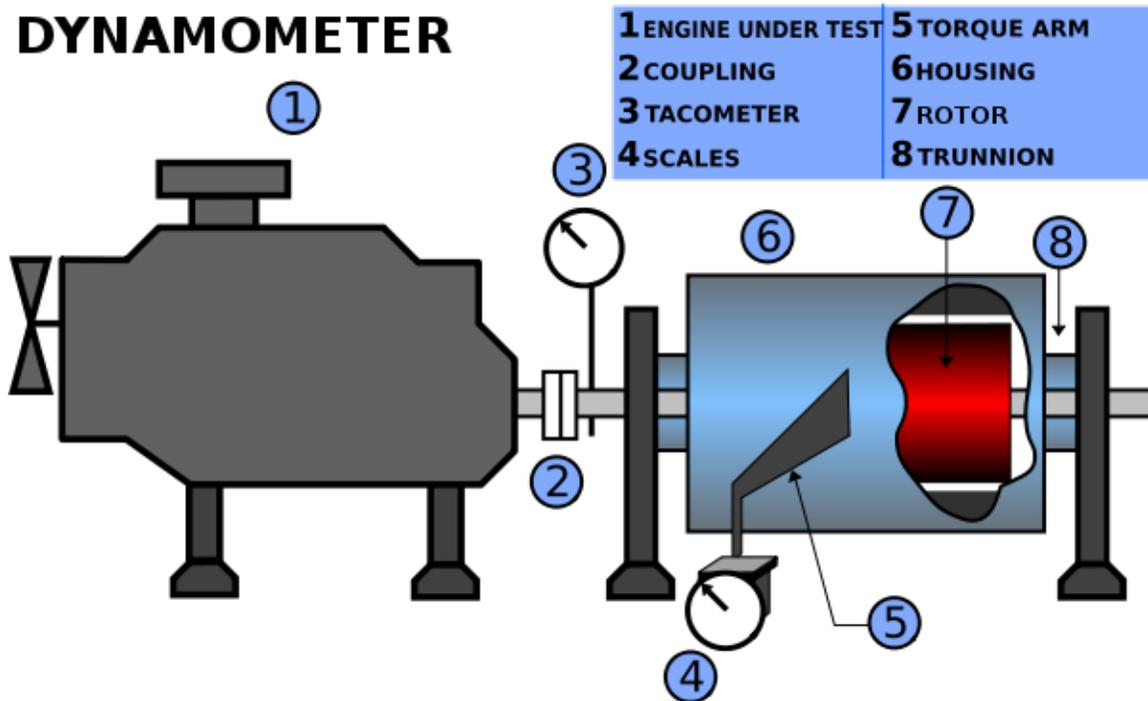$$P_{kW} = \frac{\tau_{N \cdot m} \cdot \omega_{rpm}}{9549}$$

where

P_{kW} is the power in kilowatts

$\tau_{N \cdot m}$ is the torque in newton metres

ω_{rpm} is the rotational velocity in revolutions per minute

Detailed dynamometer description

DYNAMOMETER

1 ENGINE UNDER TEST	5 TORQUE ARM
2 COUPLING	6 HOUSING
3 TACOMETER	7 ROTOR
4 SCALES	8 TRUNNION

Electrical dynamometer setup showing engine, torque measurement arrangement and tachometer

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

means for developing torque can be frictional, hydraulic, electromagnetic etc. according to the type of absorption/driver unit.

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

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

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

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

Types of dynamometers

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

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

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

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

Types of absorption/driver units

- Eddy current or electromagnetic brake (absorption only)
- Magnetic Powder brake (absorption only)

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

Eddy current type absorber

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

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

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

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

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

Powder dynamometer

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

Hysteresis dynamometers

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

potential benefit for the hysteresis absorber is that the diameter can be decreased and operating RPM of the absorber may be increased.

Electric motor/generator dynamometer

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

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

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

Fan brake

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

Hydraulic brake

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

Water brake type absorber

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

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

The schematic shows the most common type of water brake, the variable level type. Water is added until the engine is held at a steady RPM against the load. Water is then kept at that level and replaced by constant draining and refilling, which is needed to carry away the heat created by absorbing the horsepower. The housing attempts to rotate in response to the torque produced but is restrained by the scale or torque metering cell that measures the torque.
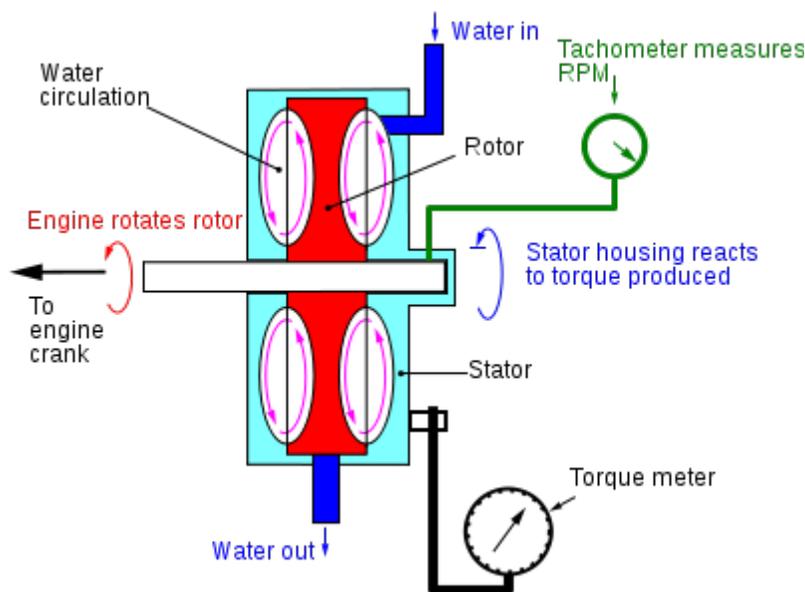
This schematic shows a water brake, which is actually a fluid coupling with a housing restrained from rotating—similar to a water pump with no outlet.

Compound Dynamometers

In most cases, motoring dynamometers are symmetrical; a 300 kW AC dynamometer can absorb 300 kW as well as motor at 300 kW. This is an uncommon requirement in engine testing and development. Sometimes, a more cost-effective solution is to attach a larger absorption dynamometer with a smaller motoring dynamometer; alternatively, a larger

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

How dynamometers are used for engine testing

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

Types of dynamometer systems
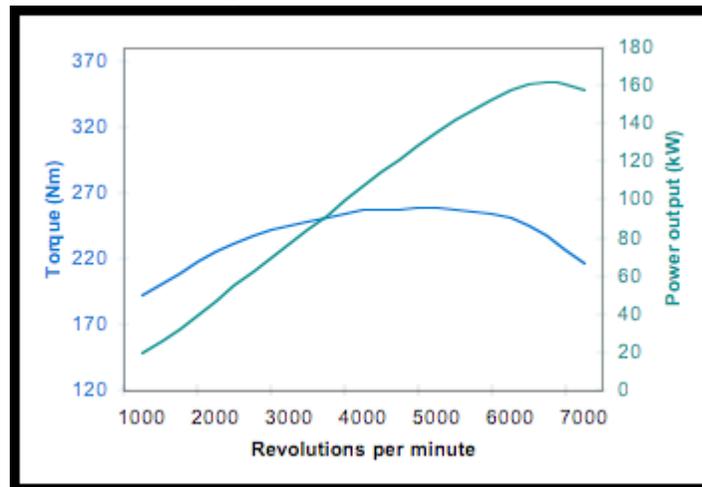
Dyno graph 1
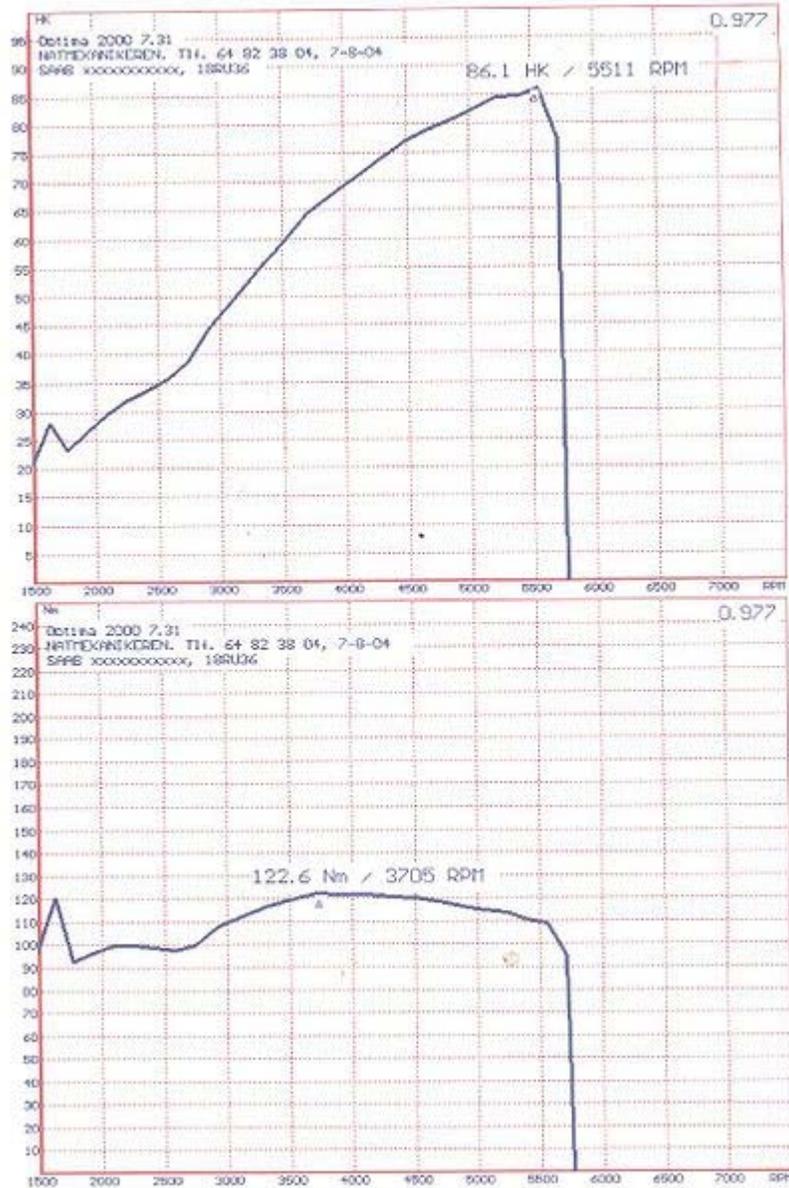
Dyno graph 2

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

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

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

There are essentially 3 types of dynamometer test procedures

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

Types of Sweep Tests:

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

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

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

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

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

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

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

Engine dynamometer

HORIBA engine dynamometer TITAN

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

Chassis dynamometer

Saab 96 on chassis dynamometer

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

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

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

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

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

Chassis dynos can be fixed or portable.

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

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

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

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

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

Because of frictional and mechanical losses in the various drivetrain components, the measured rear wheel brake horsepower is generally 15-20 percent less than the brake

horsepower measured at the crankshaft or flywheel on an engine dynamometer. Other sources, after researching several different "engine" dyno software packages, found that the engine dyno user can integrally add "frictional loss" channel factors of +10% to +15% to the flywheel power, raising the claim that 20% to 25% or even more power is actually lost between the crankshaft at high power outputs.

Common misconceptions about dynos

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

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

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

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

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

Engine damage: Can dyno testing damage engines?

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

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

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

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

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

History

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

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

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

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

Air-Fuel Ratio Meter & Air Flow Bench

Air-Fuel Ratio Meter

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

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

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

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

Benefits of air-fuel ratio metering

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

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

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

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

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

Oxygen sensor types

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

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

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

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

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

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

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

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

Which type of air-fuel ratio meter to be used

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

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

Air Flow Bench
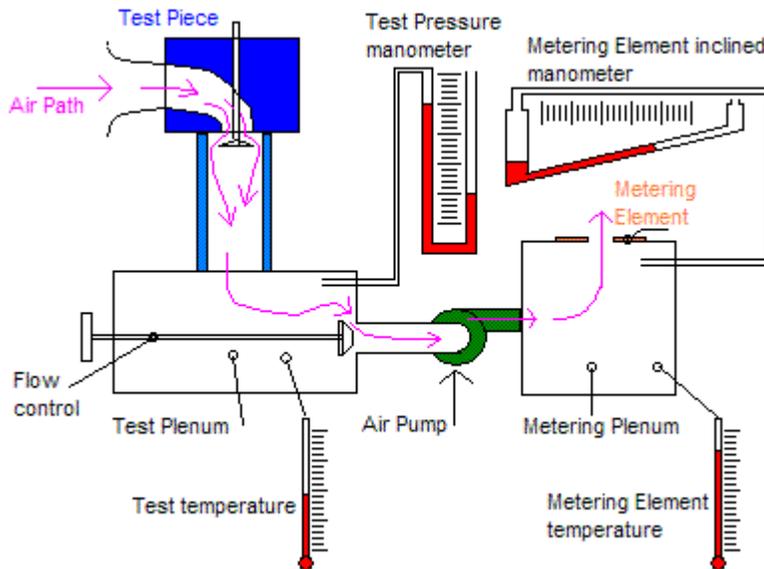
Typical Flow Bench schematic

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

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

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

Air pump

The air pump used must be able to deliver the volume required at the pressure required. Most flow testing is done at 10 and 28 inches of water pressure (2.5 to 7 kilopascals). Although other test pressures will work, the results would have to be converted for comparison to the work of others. The pressure developed must account for the test pressure plus the loss across the metering element plus all other system losses. The greater the accuracy of the metering element the greater is the loss. Flow volume of

between 100 and 600 cubic feet per minute (0.05 to 0.28 m³/s) would serve almost all applications depending on the size of the engine under test.

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

Metering element

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

Instrumentation

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

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

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

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

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

Flow bench data

The air flow bench can give a wealth of data about the characteristics of a cylinder head or whatever part is tested. The result of main interest is bulk flow. It is the volume of air

that flows through the port in a given time. Expressed in cubic feet per minute or cubic meters per second/minute.

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

Flow coefficients are determined by comparing the actual flow of a test piece to the theoretical flow of a perfect orifice of equal area. Thus the flow coefficient should be a close measure of efficiency. It cannot be exact because the *L/D* does not indicate the actual minimum size of the duct.
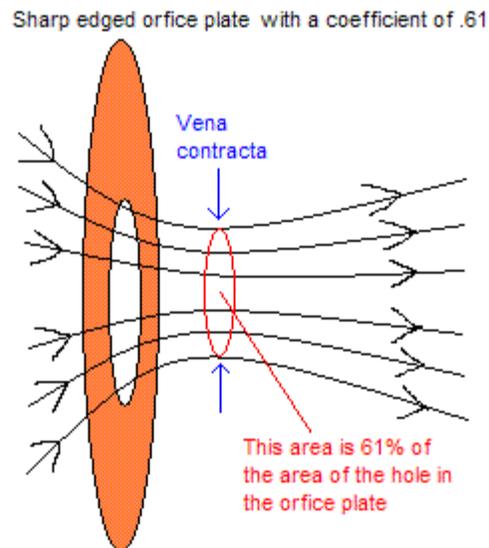
A real orifice plate showing how the fluid would actually flow
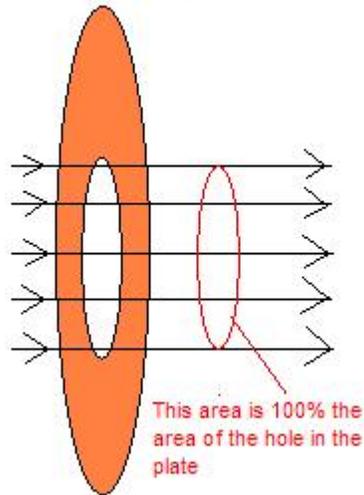
A theoretical orifice plate showing perfect flow which is used as a standard for comparing the efficiencies of real flows

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

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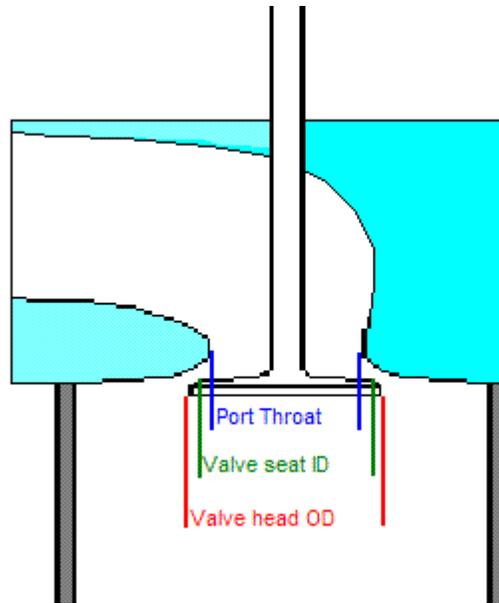
Various characteristic measurements used to determine flow coefficients

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

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

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

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

For one set of English units

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

Where:

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

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

For SI units

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

Where:

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

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

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

Limitations

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

Steady state flow vs dynamic flow

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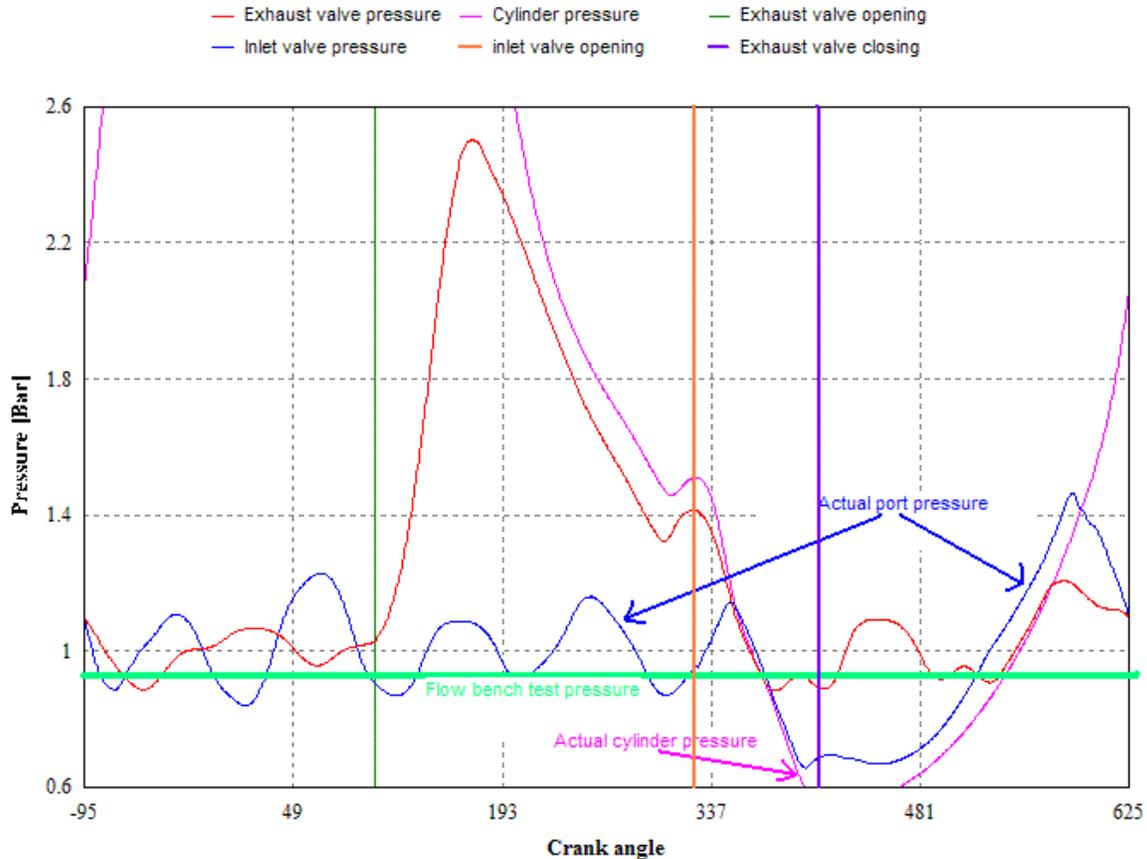
Comparison of flow bench test pressure to actual engine pressures predicted by an engine simulation program

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

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

Pressure differential

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

Air only vs mixed gas/fuel mist flow

The flow bench tests using only air while a real engine usually uses air mixed with fuel droplets and fuel vapor, which is significantly different. Evaporating fuel passing through

the port-runner has the effect of adding gas to and lowering the temperature of the air stream along the runner and giving the outlet flow rate slightly higher than the flow rate entering the port-runner. A port which flows dry air well might cause fuel droplets to fall out of suspension causing a loss of power not indicated by flow figures alone.

Bulk flow vs flow velocity

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

Even room temperature vs. uneven high temperature

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

Physical and mechanical differences

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

Exhaust port conditions

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

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

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

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

In a given 2-Valve push-rod engine, it's common to see exhaust port sizes roughly 60% the size of the intake. 2-Valve push-rod engines, regardless of how well tuned, don't flow well nor are capable of 100% volumetric efficiency with out extreme amounts of work

done, which would make them unsuitable for daily driven applications. Due to the poor flowing characteristics, these styles of engines typically make more torque than horsepower. In that regard, it's often held that complimenting the engine's strengths will offer the best gains. Thusly, exhaust ports and valves are sized much smaller as to facilitate the production of torque.

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

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

Chapter 5

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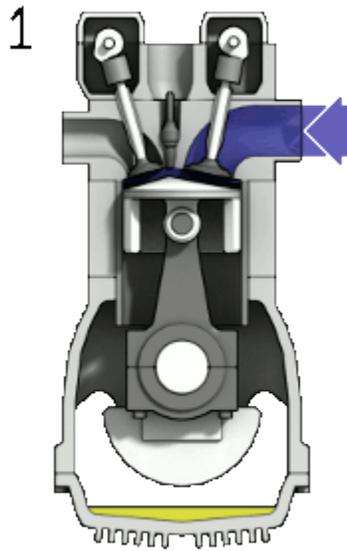
Four-stroke cycle used in gasoline/petrol engines. The right blue side is the intake and the left yellow side is the exhaust. The cylinder wall is a thin sleeve surrounded by cooling water.

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

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

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

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

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

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

History

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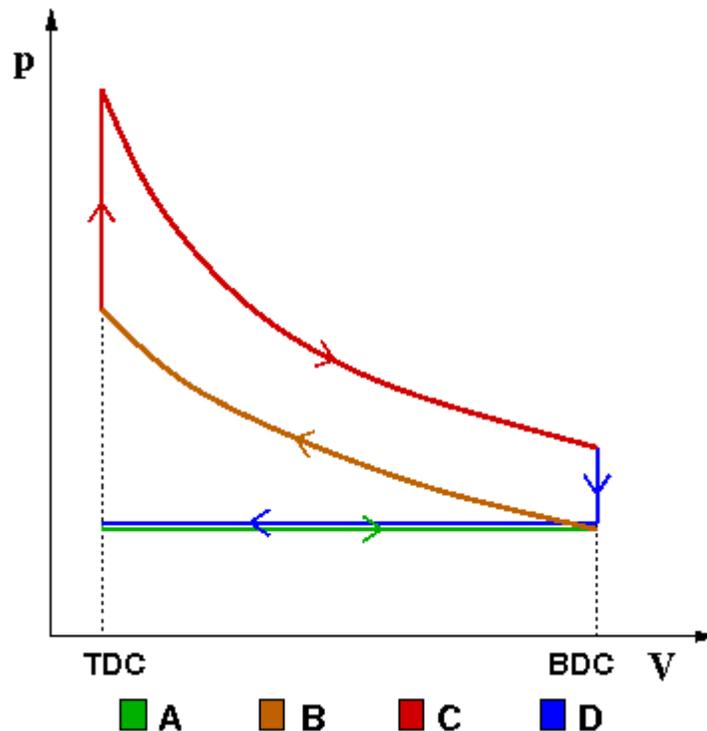
The idealized four-stroke Otto cycle p-V diagram: the intake (A) stroke is performed by an isobaric expansion, followed by the compression (B) stroke, performed by an adiabatic compression. Through the combustion of fuel an isochoric process is produced, followed by an adiabatic expansion, characterizing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

closed by an isochoric process and an isobaric compression, characterizing the exhaust (D) stroke.

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

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

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

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

## *Design and engineering principles*

Fuel octane rating

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

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

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

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

Power output limit
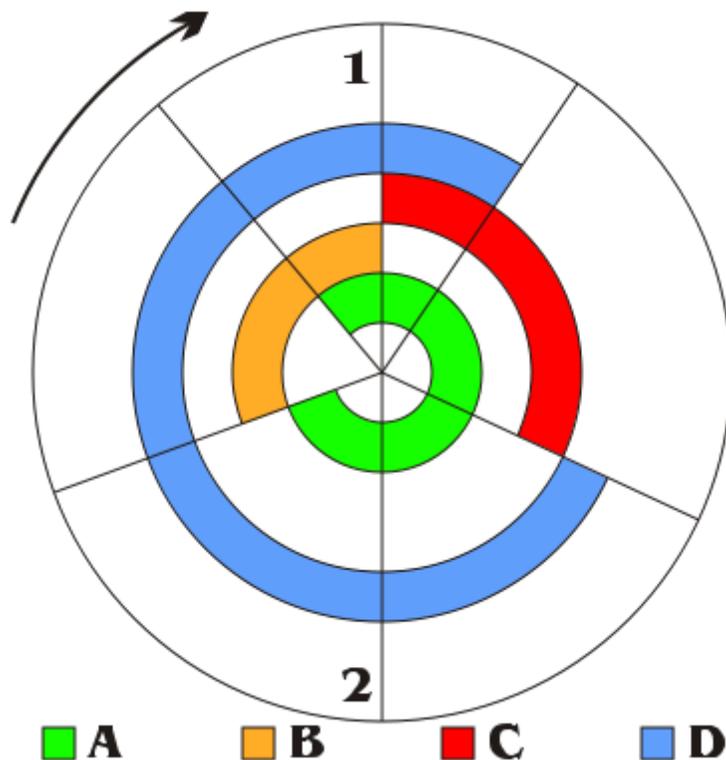
The four-stroke cycle
1=TDC
2=BDC
A: Intake

B: Compression
C: Power
D: Exhaust

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

Intake/exhaust port flow

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

Supercharging

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

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

Turbocharging

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

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

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

Rod and piston-to-stroke ratio

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

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

Valvetrain

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

Valve clearance

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

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

Energy balance

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

Modern engines are often intentionally built to be slightly less efficient than they could otherwise be. This is necessary for emission controls such as exhaust gas recirculation and catalytic converters that reduce smog and other atmospheric pollutants. Reductions in efficiency may be counteracted with an engine control unit using lean burn techniques.
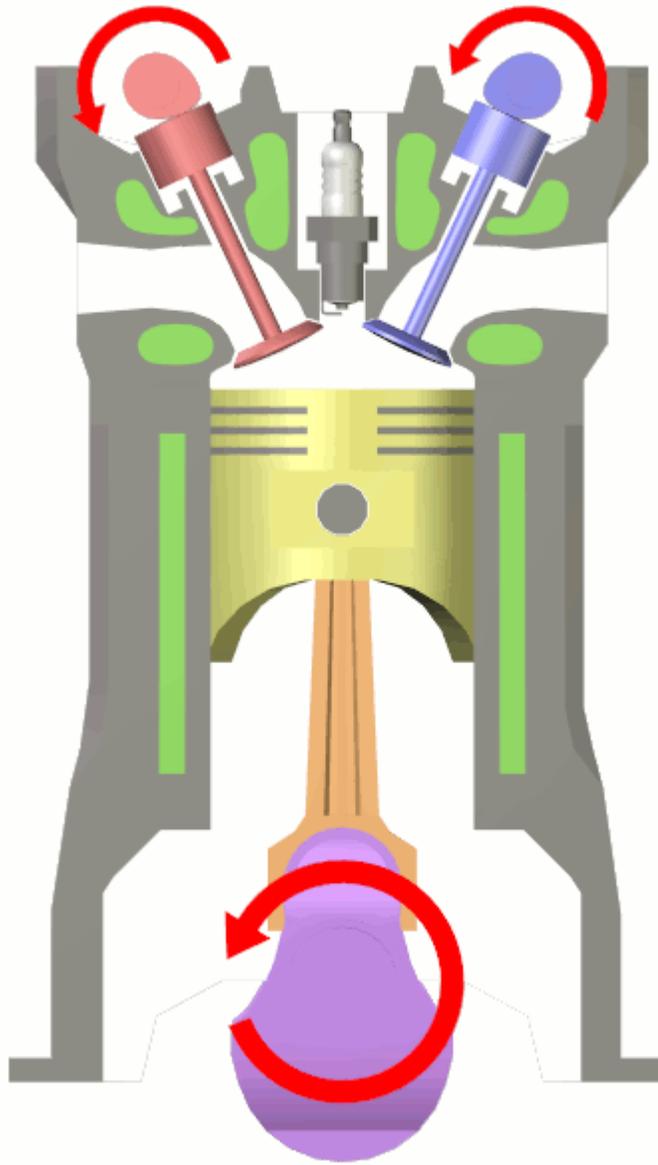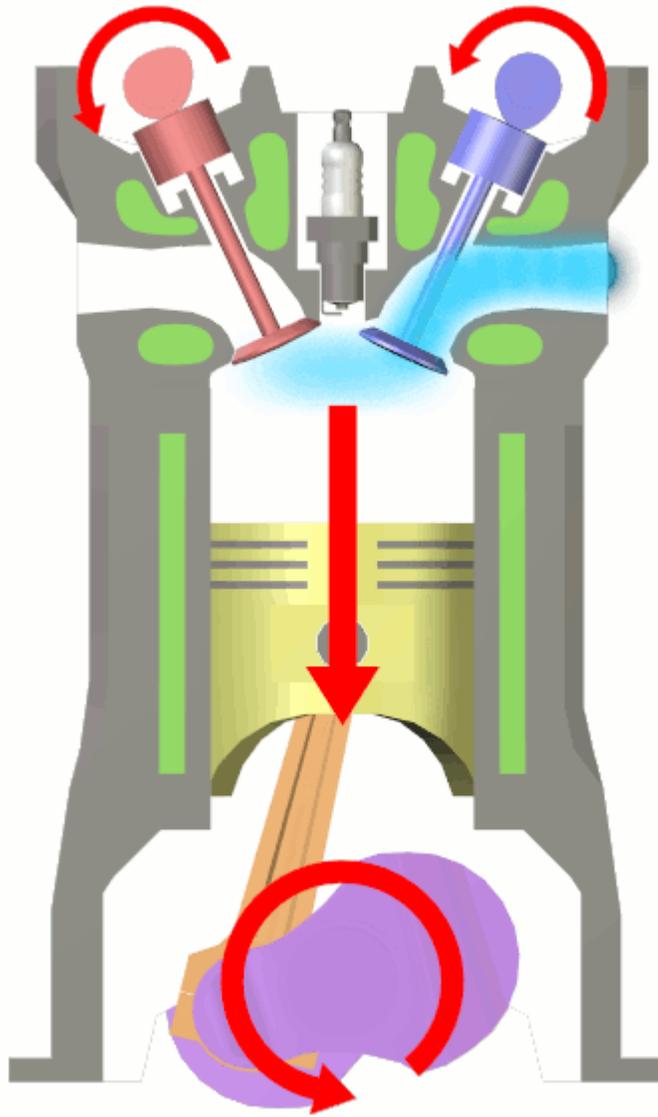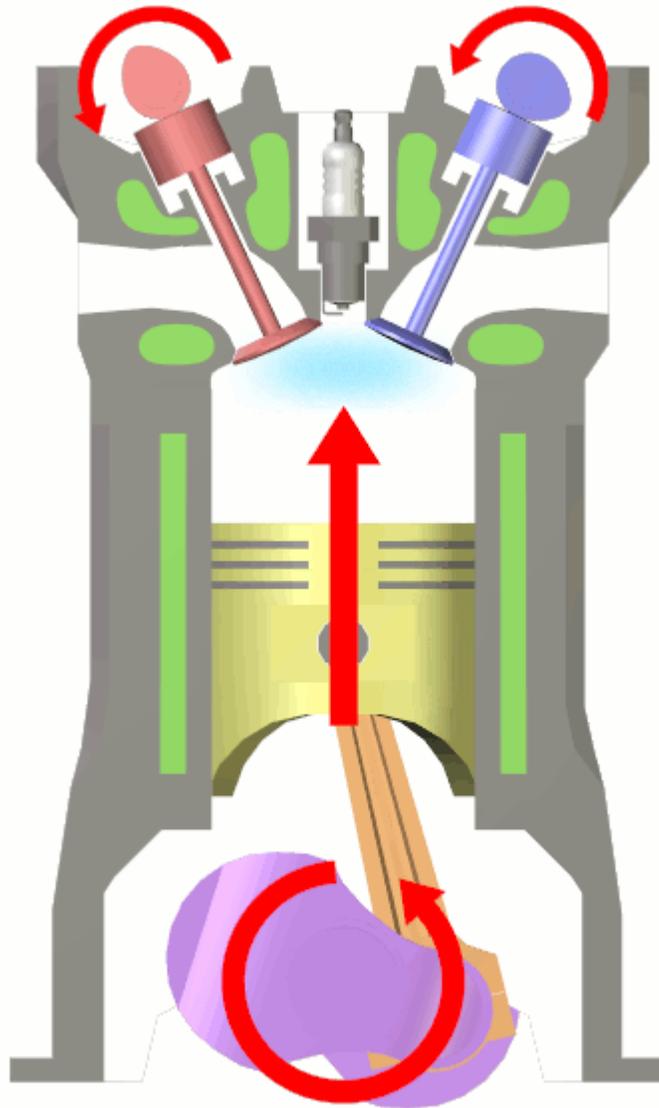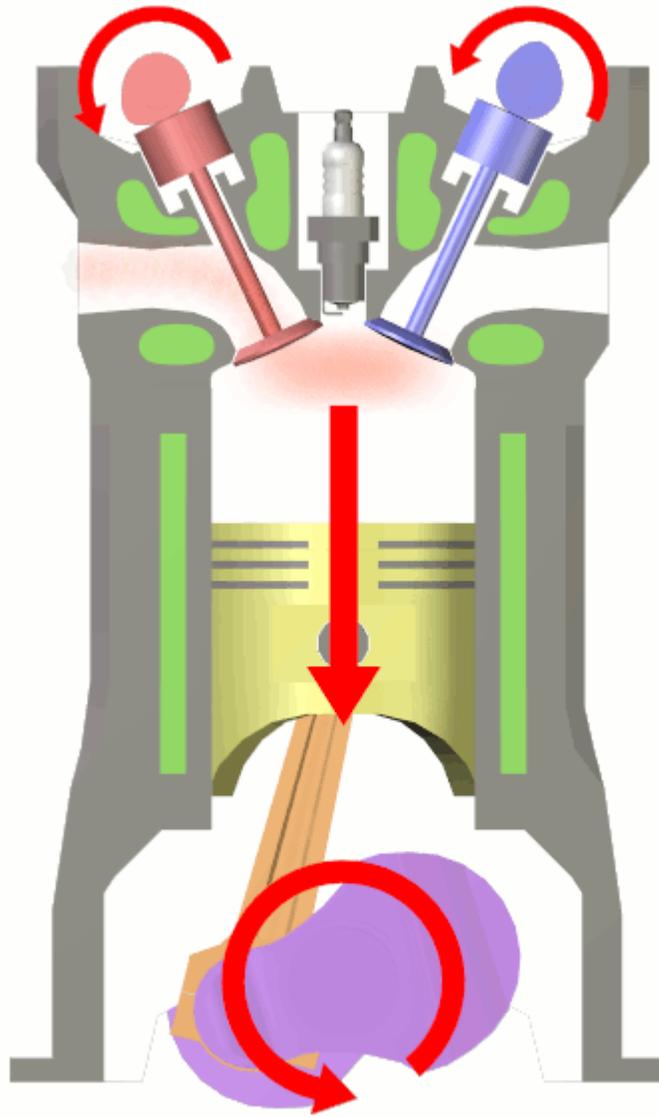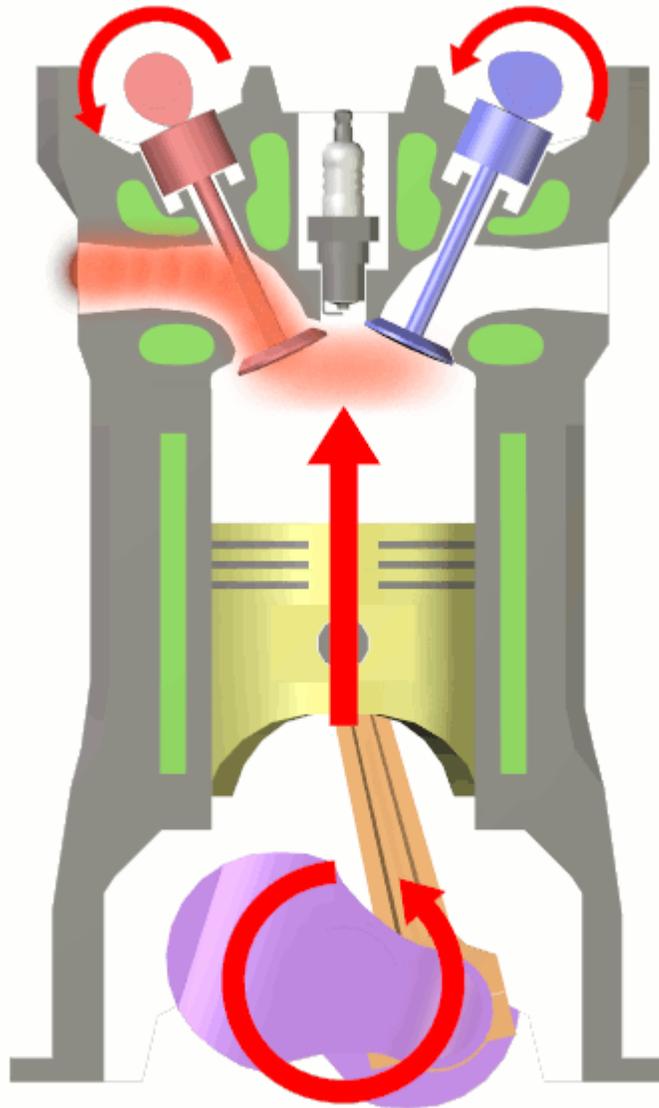
Starting position, intake stroke, and compression stroke.
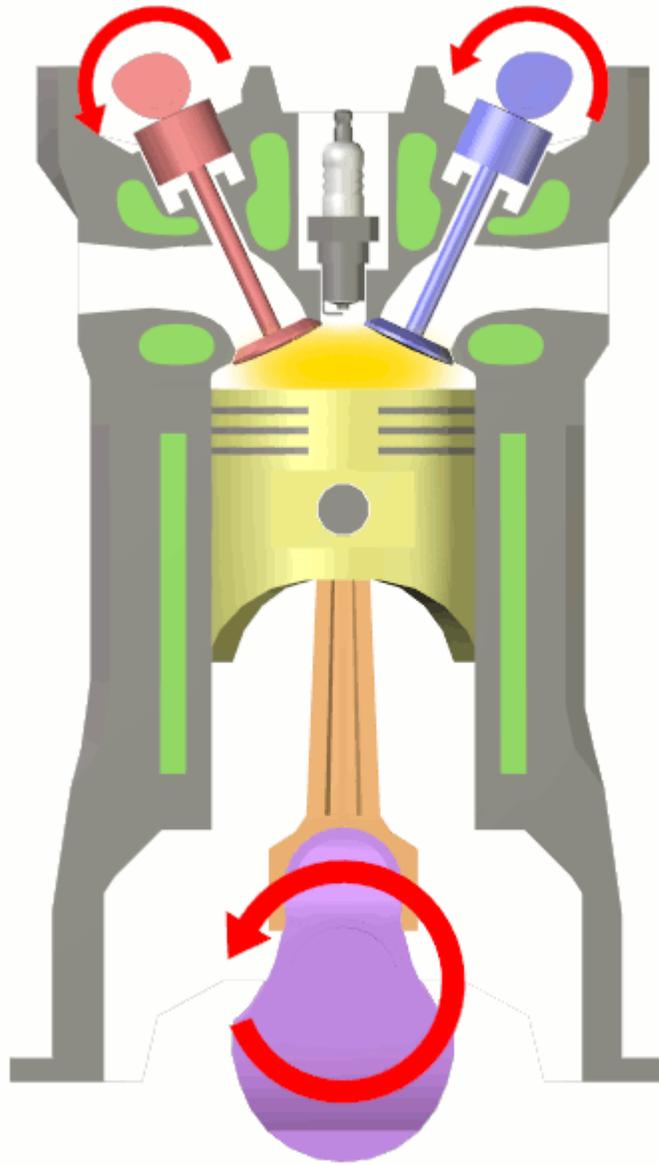
Chapter 6

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 7

Two- and four-Stroke Engines

M4+2 engine

The M4+2 engine , also known as the double piston internal combustion engine, is a new type of combustion engine invented by a Polish patent holder Piotr Mężyk.

The M4+2 engine took its name from a combination of the two working modes of the known engines, that is from the Two-stroke engine and Four-stroke engine. In the M4+2 the advantages of both engines being connected are obvious; the pistons of the engine working in one combustion cylinder are set oppositely to each other, but in different modes. Although the projects of connecting two stroke modes in one cylinder were tried already a long time ago - Opposed piston engine, the combination of the two different cycles had never been tried before. It turned out that the engine is not only able to work, but that the effects are very promising. The engine has a far greater efficiency over the break-even value known to combustion engines (ca 35%) and closer to the one associated with steam turbines or electric engines (ca 70%).

The M4+2 prototype constructed at the Silesian University of Technology, Poland

The other advantages are as follows:

- more efficient power production (150 Horsepower from 1000 cc of volume in the basic version)
- ability to differentiate fuel types (natural plant oils as well as the traditional ones)

- much better ecological effects – a huge reduction of carbon dioxide and other gas emission
- smaller fuel consumption
- prolonged strokes expansion
- possibility to change the compression parameters without having to stop the engine
- simplicity of construction

The idea was developed at the Silesian University of Technology, Poland, under the leadership of dr Adam Ciesiołkiewicz. It was granted a patent nr 195052 by the Polish Patent Office.

The M4+2 engine working cycle
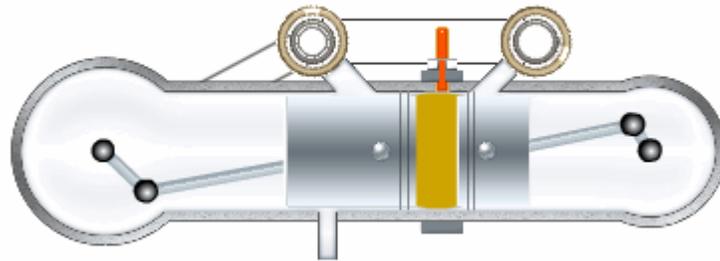
The M4+2 engine working cycle

The stages of the working cycle:

- Gas exhaust
- Fresh air inlet (two stages)
- Medium compression
- Two stage combustion
- Gas expansion

The filling process takes place at the overpressure phase, using a mechanical gas compressor and a throttle for the purpose of regulation.
The load change is assisted by a four stroke piston, working as a dynamic boosting system and allowing the good scavenging of working space.
There is a possibility of changing relative piston's position during the engine work what gives the possibility of changing the compression ratio depending on the temporary sort of the load, what forecast the possibility of different fuels combustion (low octane petrol, bio-fuels with high stage of vegetable components)

The working cycle is characterised by an almost constant combustion characeristic of the workings space volume increasing during the expansion stage.

Ricardo 2x4 engine

Two modes of cycles are currently researched at Ricardo Consulting Engineers in UK. The concept consists in switching from one mode to the other depending on rpm value. Four stroke engine is more efficient when running at full throttle, while the opposite is valid for the two stroke engine. When small car carrying heavy load runs at half speed, the engine automatically switches to the two cycle mode which is then more efficient. The research on this one showed 27% reduction in fuel consumption.

Since the shaft of the four stroke piston in the M4+2 engine revolves always twice faster than the shaft of the two stroke piston, meaning the two stroke part runs always at half speed, both parts work in optimal conditions regarding fuel consumption at all times. Same principle, just the design of the M4+2 is much simpler.

Chapter 8

Wankel Engine
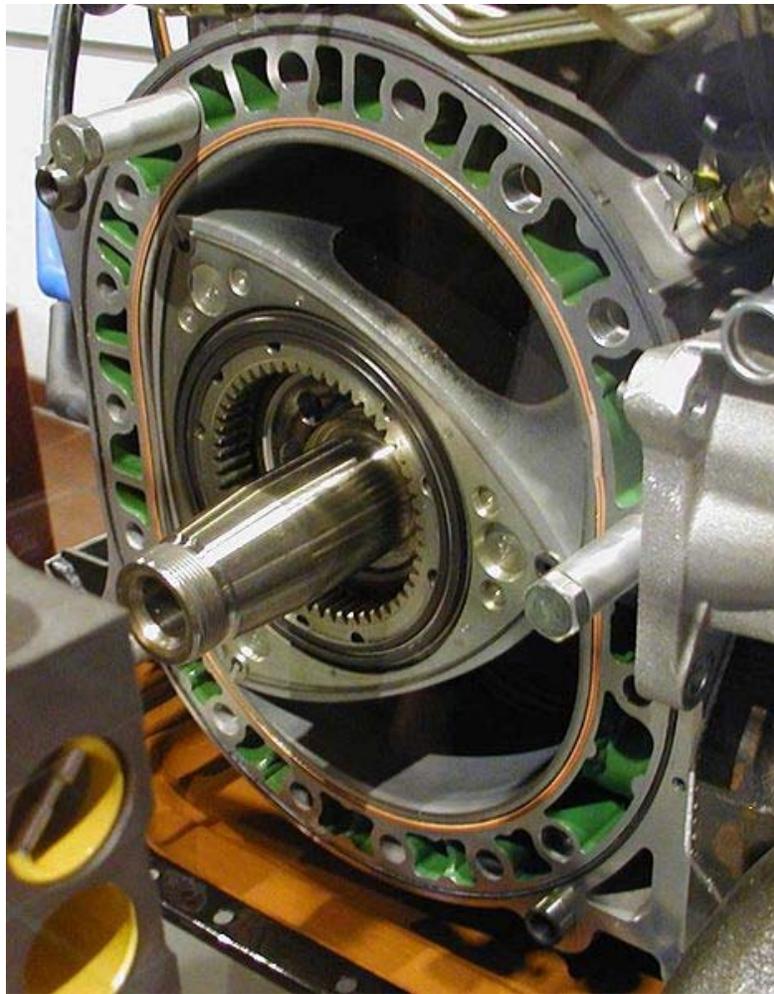
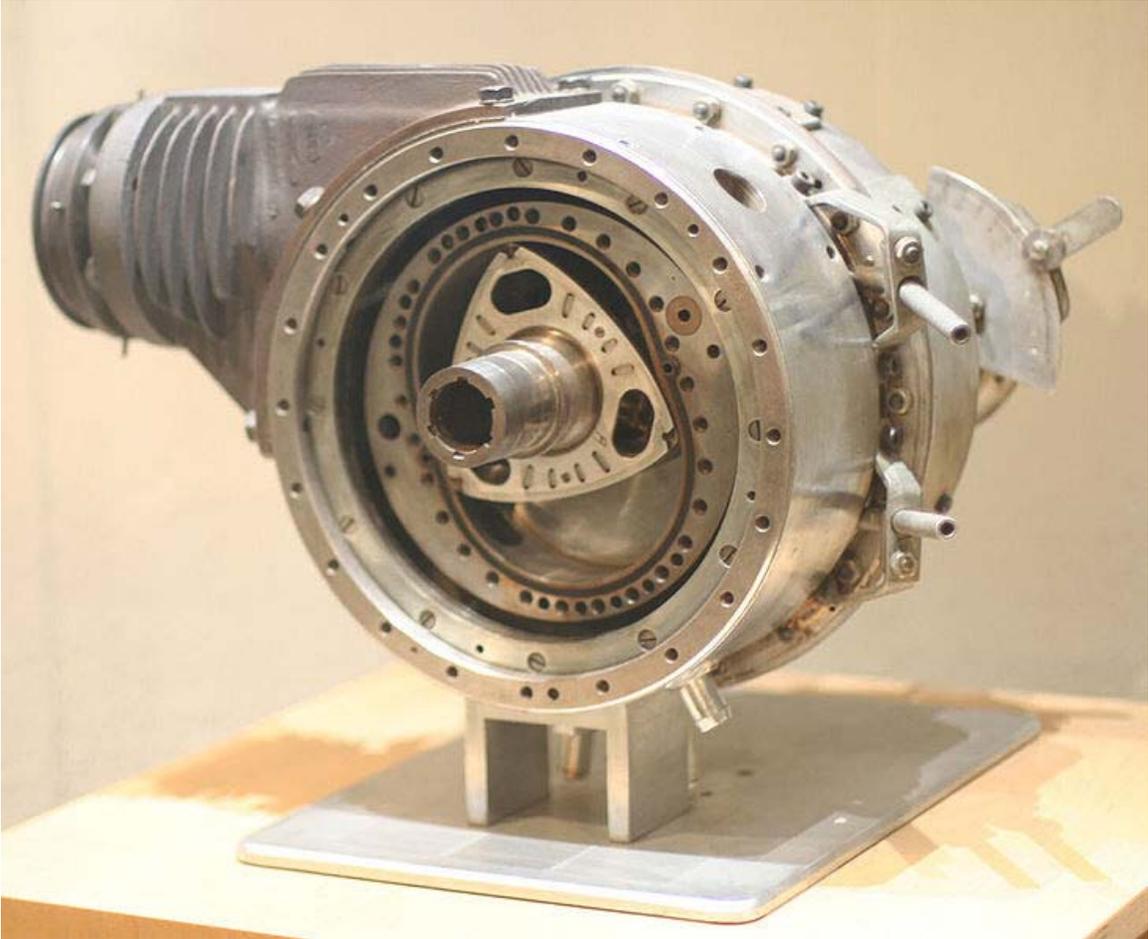A Wankel engine in Deutsches Museum in Munich, Germany

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

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

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

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

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

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

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

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

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

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

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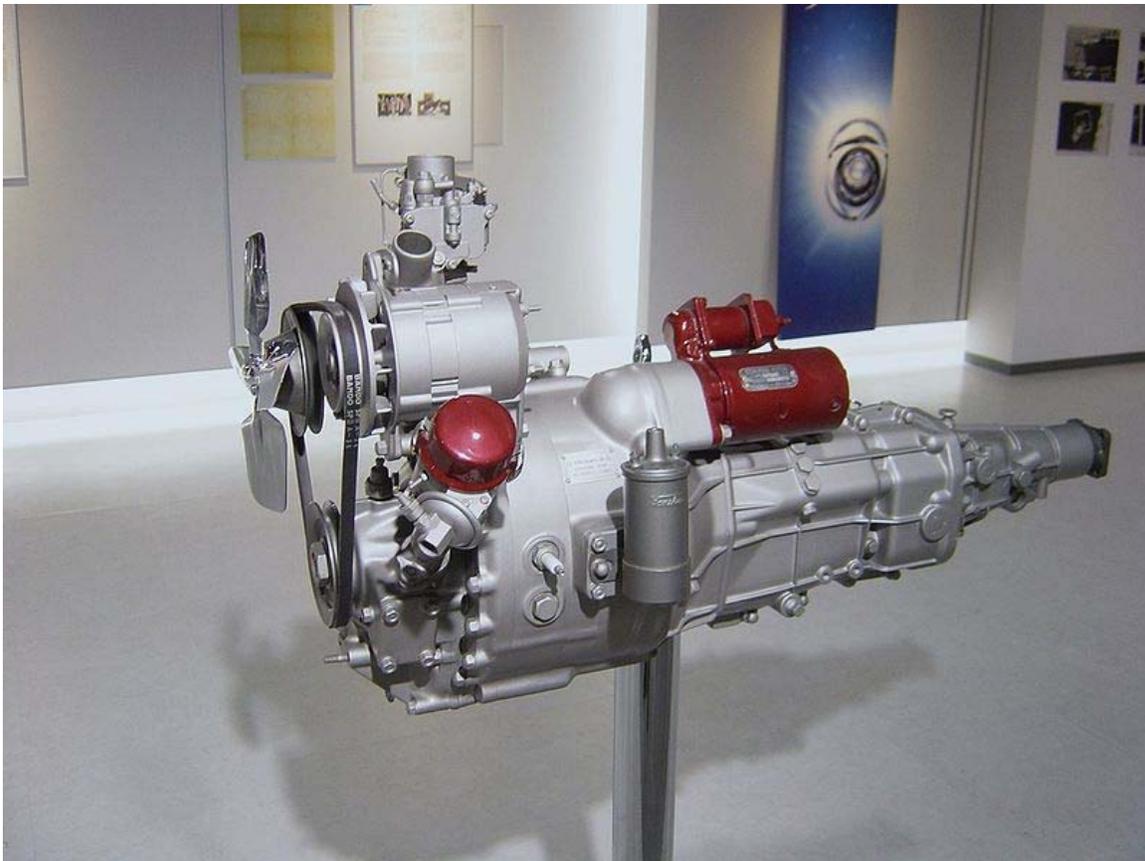
Mazda's first Wankel engine, at the Mazda Museum in Hiroshima, Japan

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

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

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

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

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

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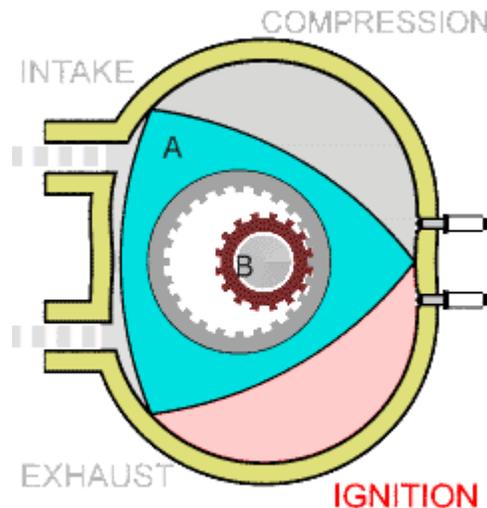
The Wankel cycle. The "A" marks one of the three apexes of the rotor. The "B" marks the eccentric shaft and the white portion is the lobe of the eccentric shaft. The shaft turns three times for each rotation of the rotor around the lobe and once for each orbital revolution around the eccentric shaft.

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

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

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

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

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

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

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

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

Engineering

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

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

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

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

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

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

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

Materials

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

Sealing

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

Fuel consumption and emissions

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

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

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

Advantages

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

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

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

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

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

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

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

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

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

Disagvantages

Rolls Royce R6 two stage Wankel Diesel engine

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

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

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

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

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

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

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

Applications

Automobile racing

Mazda 787B

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

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

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

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

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

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

Motorcycle engines

Norton Interpol2 prototype

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

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

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

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

Aircraft engines

Diamond DA20 with Diamond Engines Wankel

Sikorsky Cypher UAV powered with a UEL AR801 Wankel engine

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

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

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

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

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

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

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

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

Other uses
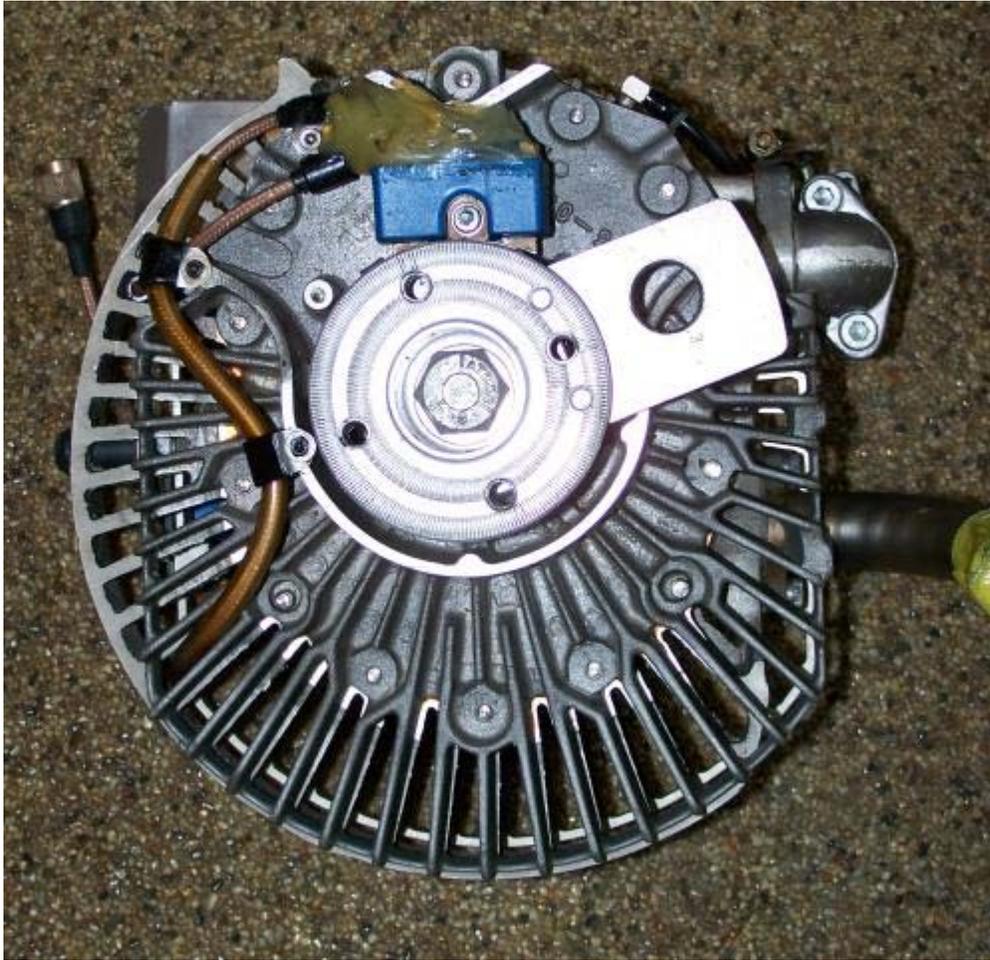
UEL UAV-741 Wankel engine for a UAV

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

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

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

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

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

Non-internal combustion

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

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