

Diesel engine

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The **diesel engine** (correctly known as a **compression-ignition** or **CI engine**) is an internal combustion engine in which ignition of the fuel that has been injected into the combustion chamber is caused by the high temperature which a gas achieves (i.e. the air) when greatly compressed (adiabatic compression). Diesel engines work by compressing only the air. This increases the air temperature inside the cylinder to such a high degree that it ignites atomised diesel fuel that is injected into the combustion chamber. This contrasts with spark-ignition engines such as a petrol engine (gasoline engine) or gas engine (using a gaseous fuel as opposed to petrol), which use a spark plug to ignite an air-fuel mixture. In compression-ignition engines, glow plugs (combustion chamber pre-warmers) may be used to aid starting in cold weather, or when the engine uses a lower compression-ratio, or both. The original compression-ignition engine operates on the "constant pressure" cycle of gradual combustion and produces no audible knock.

The compression-ignition engine has the highest thermal efficiency (engine efficiency) of any practical internal or external combustion engine due to its very high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. A small efficiency loss is also avoided compared to two-stroke non-direct-injection gasoline engines since unburnt fuel is not present at valve overlap and therefore no fuel goes directly from the intake/injection to the exhaust. Low-speed compression-ignition engines (as used in ships and other applications where overall engine weight is relatively unimportant) can have a thermal efficiency that exceeds 50%.^{[1][2]}

Compression-ignition engines are manufactured in two-stroke and four-stroke versions. They were originally used as a more efficient replacement for stationary steam engines. Since the 1910s they have been used in submarines and ships. Use in locomotives, trucks, heavy equipment and electricity generation plants followed later. In the 1930s, they slowly began to be used in a few automobiles. Since the 1970s, the use of compression-ignition engines in larger on-road and off-road vehicles in the US increased. According to the British Society of Motor Manufacturing and Traders, the EU average for compression-ignition cars accounts for 50% of the total sold, including 70% in France and 38% in the UK.^[3]

The world's largest compression-ignition engine is currently a Wärtsilä-Sulzer RTA96-C Common Rail marine compression-ignition, which produces a peak power output of 84.42 MW (113,210 hp) at 102 rpm.^{[4][5]}



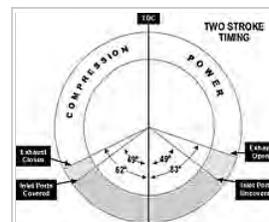
Diesel generator on an oil tanker



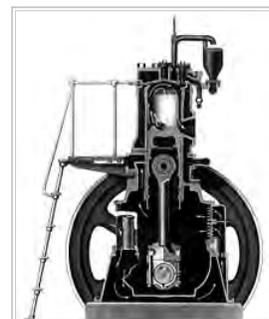
A diesel engine built by MAN AG in 1906

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Detroit Diesel timing



Fairbanks Morse model 32

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History

The definition of a "Diesel" engine to many has become an engine that uses compression ignition. To some it may be an engine that uses heavy fuel oil. To others an engine that does not use spark ignition. However the original cycle proposed by Rudolph Diesel in 1892 was a constant temperature cycle (a cycle based on the Carnot theory) which would require much higher compression than what is needed for compression ignition. Diesel's idea was to compress the air so tightly that the temperature of the air would exceed that of combustion. In his 1892 US patent (granted in 1895) #542846 Diesel describes the compression required for his cycle:

"pure atmospheric air is compressed, according to curve 1 2, to such a degree that, before ignition or combustion takes place, the highest pressure of the diagram and the highest temperature are obtained—that is to say, the temperature at which the subsequent combustion has to take place, not the burning or igniting point. To make this more clear, let it be assumed that the subsequent combustion shall take place at a temperature of 700°. Then in that case the initial pressure must be sixty-four atmospheres, or for 800° centigrade the pressure must be ninety atmospheres, and so on. Into the air thus compressed is then gradually introduced from the exterior finely divided fuel, which ignites on introduction, since the air is at a temperature far above the igniting-point of the fuel. The characteristic features of the cycle according to my present invention are therefore, increase of pressure and temperature up to the maximum, not by combustion, but prior to combustion by mechanical compression of air, and there upon the subsequent performance of work without increase of pressure and temperature by gradual combustion during a prescribed part of the stroke determined by the cut-oil".^[6]

In later years Diesel realized his original cycle would not work and he adopted the constant pressure cycle. Diesel describes the cycle in his 1895 patent application. Notice that there is no longer a mention of compression temperatures exceeding the temperature of combustion. Now all that is mentioned is the compression must be high enough for ignition.

"1. In an internal-combustion engine, the combination of a cylinder and piston constructed and arranged to compress air to a degree producing a temperature above the igniting-point of the fuel, a supply for compressed air or gas; a fuel-supply; a distributing-valve for fuel, a passage from the air supply to the cylinder in communication with the fuel-distributing valve, an inlet to the cylinder in communication with the air-supply and with the fuel-valve, and a cut-oil, substantially as described." See US patent # 608845 filed 1895 / granted 1898^{[7][8][9]}

History shows that the invention of the Diesel engine was not based solely on one man's idea but it was the culmination of many different ideas that would be developed over time.

In 1806 Claude and Nicéphore Niépce (brothers) developed the first known internal combustion engine and the first fuel injection system. The Pyrèolophore fuel system used a blast of air provided by a bellows to atomize Lycopodium (a highly combustible fuel made from broad moss). Later coal dust mixed with resin became the fuel. Finally in 1816 they experimented with alcohol and white oil of petroleum (a fuel similar to kerosene). They discovered that the kerosene type fuel could be finely vaporized by passing it through a reed type device, this made the fuel highly combustible.

In 1874 George Brayton developed and patented a 2 stroke, oil fueled constant pressure engine "The Ready Motor". This engine used a metered pump to supply fuel to an injection device in which the oil was vaporized by air and burned as it entered the cylinder.^[10] These were some of the first practical internal combustion engines to supply motive power. Brayton's engines were installed in several boats, a rail car, 2 submarines and a bus.^[11] Early Diesel engines use a similar cycle.^{[12][13]}

Throughout the 1880s Brayton continued trying to improve his engines. In 1887 Brayton developed and patented a 4 stroke direct injection oil engine (US patent #432,114 of 1890, application filed in 1887) The fuel system used a variable quantity pump and liquid fuel high pressure spray type injection. The liquid was forced through a spring loaded relief type valve (injector) which caused the fuel to become divided into small droplets (vaporized). Injection was timed to occur at or near the peak of the compression stroke. A platinum igniter or ignitor provided the source of ignition. Brayton describes the invention as follows: "I have discovered that heavy oils can be mechanically converted into a finely-divided condition within a firing portion of the cylinder, or in a communicating firing chamber." Another part reads "I have for the first time, so far as my knowledge extends, regulated speed by variably controlling the direct discharge of liquid fuel into the combustion chamber or cylinder into a finely-divided condition highly favorable to immediate combustion". This was likely the first engine to use a lean burn system to regulate engine speed / output. In this manner the engine fired on every power stroke and speed / output was controlled solely by the quantity of fuel injected.

In 1890 Brayton developed and patented a 4 stroke air blast oil engine (US patent #432,260)^[14] The fuel system delivered a variable quantity of vaporized fuel to the center of the cylinder under pressure at or near the peak of the compression stroke. The ignition source was an igniter made from platinum wire. A variable quantity injection pump provided the fuel to an injector where it was mixed with air as it entered the cylinder. A small crank driven compressor provided the source for air. This engine also used the lean burn system.^[15]

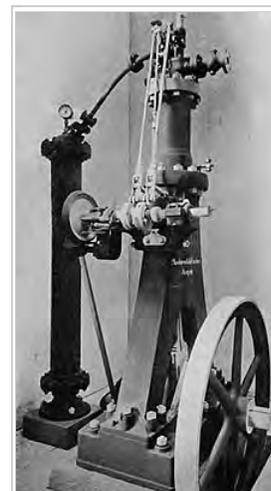
Brayton died in 1893 but would be credited with the invention of the constant pressure Brayton cycle.

In 1885, the English inventor Herbert Akroyd Stuart began investigating the possibility of using paraffin oil (very similar to modern-day diesel) for an engine, which unlike petrol would be difficult to vaporise in a carburettor as its volatility is not sufficient to allow this.^{[16][17]}

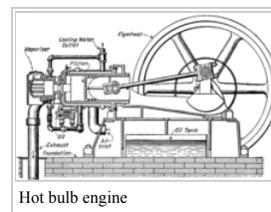
The hot bulb engines, first prototyped in 1886 and built from 1891 by Richard Hornsby and Sons, used a pressurized fuel injection system.^[18] The Hornsby-Akroyd oil engine engine used a comparatively low compression ratio, so that the temperature of the air compressed in the combustion chamber at the end of the compression stroke was not high enough to initiate combustion. Combustion instead took place in a separated combustion chamber, the "vaporizer" or "hot bulb" mounted on the cylinder head, into which fuel was sprayed. Self-ignition occurred from contact between the fuel-air mixture and the hot walls of the vaporizer.^[19] As the engine's load increased, so did the temperature of the bulb, causing the ignition period to advance; to counteract pre-ignition, water was dripped into the air intake.^[20]



Diesel's prototype engine



Diesel's first experimental engine 1893



Hot bulb engine

In 1892, Akroyd Stuart patented a water-jacketed vaporiser to allow compression ratios to be increased. In the same year, Thomas Henry Barton at Hornsbys built a working high-compression version for experimental purposes, whereby the vaporiser was replaced with a cylinder head, therefore not relying on air being preheated, but by combustion through higher compression ratios. It ran for six hours—the first time automatic ignition was produced by compression alone. This was five years before Rudolf Diesel built his well-known high-compression prototype engine in 1897.^[21]

Herbert Akroyd Stuart was a pioneer in developing compression ignition, Rudolf Diesel however, was subsequently credited with the compression ignition engine innovation. Higher compression and thermal efficiency is what distinguishes Diesel's patent of 3,500 kilopascals (508 psi).

In 1892 Diesel received patents in Germany, Switzerland, the United Kingdom and the United States for "Method of and Apparatus for Converting Heat into Work".^[22] In 1893 he described a "slow-combustion engine" that first compressed air thereby raising its temperature above the igniting-point of the fuel, then gradually introducing fuel while letting the mixture expand "against resistance sufficiently to prevent an essential increase of temperature and pressure", then cutting off fuel and "expanding without transfer of heat". In 1894 and 1895 he filed patents and addenda in various countries for his Diesel engine; the first patents were issued in Spain (No. 16,654), France (No. 243,531) and Belgium (No. 113,139) in December 1894, and in Germany (No. 86,633) in 1895 and the United States (No. 608,845) in 1898.^[23] He operated his first successful engine in 1897.^[24]

On February 17, 1894, the redesigned engine ran for 88 revolutions - one minute; with this news, Maschinefabrik Augsburg's stock rose by 30%, indicative of the tremendous anticipated demands for a more efficient engine. In 1896, Rudolph's rushed to have a prototype running, in order to maintain the patent. The first engine ready for testing was built on December 31, 1896; a much different engine than the one they had started with. In 1897, between deal signing, and brainstorming episodes they succeed, the engine runs; 16.93 kW with an efficiency of 16.6%, he is granted the patent. By 1898, Diesel had become a millionaire. His engines were used to power pipelines, electric and water plants, automobiles and trucks, and marine craft. They were soon to be used in mines, oil fields, factories, and transoceanic shipping.^[25]

Timeline

1800's.

- 1806 The Pyr  lophore uses the first fuel injection system.
- 1874 George Brayton's constant pressure "Ready Motor" uses a metered fuel pump and burns oil fuel inside the cylinder.^[26]
- 1886: Herbert Akroyd Stuart builds a prototype hot bulb engine.
- 1887 George Brayton builds an engine that uses a spring loaded injector and solid metered injection system (lean burn combustion).^[27]
- 1890 George Brayton builds an "Air Blast" injection engine with a lean burn system.^[28]
- 1891: Herbert Akroyd Stuart patents an internal combustion engine that uses a "hot bulb" and pressurized fuel injection.
- 1892: February 23, Rudolf Diesel obtained a patent (RP 67207) titled "*Arbeitsverfahren und Ausf  hrungsart f  r Verbrennungsmaschinen*" (Working Methods and Techniques for Internal Combustion Engines).
- 1892: Akroyd Stuart builds his first working Diesel engine.
- 1893: Diesel's essay titled *Theory and Construction of a Rational Motor* appeared.^[29]
- 1893: August 10, Diesel built his first prototype in Augsburg, This engine never ran under its own power.^[30]
- 1894 Diesel's second prototype runs for the first time.^{[25][31]}
- 1895 Diesel applies for a second patent US Patent # 608845^[32]
- 1896 Blackstone & Co, a Stamford farm implement they built lamp start oil engines.
- 1897: Adolphus Busch licenses rights to the Diesel Engine for the US and Canada.^[30]
- 1897 After 4 years Diesel's prototype engine is running and finally ready for efficiency testing and production.^[31]
- 1898: Diesel licensed his engine to Branobel, a Russian oil company interested in an engine that could consume non-distilled oil. Branobel's engineers spent four years designing a ship-mounted engine.
- 1899: Diesel licensed his engine to builders Krupp and Sulzer, who quickly became major manufacturers.

1900s

- 1902: Until 1910 MAN produced 82 copies of the stationary diesel engine.
- 1903: Two first diesel-powered ships were launched, both for river and canal operations: *La Petite-Pierre* in France, powered by Dyckhoff-built diesels, and *Vandal* tanker in Russia, powered by Swedish-built diesels with an electrical transmission.
- 1904: The French built the first diesel submarine, the *Z*.
- 1905: Four diesel engine turbochargers and intercoolers were manufactured by B  chl (CH), as well as a scroll-type supercharger from Creux (F) company.
- 1908: Prosper L'Orange and Deutz developed a precisely controlled injection pump with a needle injection nozzle.
- 1909: The prechamber with a hemispherical combustion chamber was developed by Prosper L'Orange with Benz.

1910s

- 1910: The Norwegian research ship *Fram* was a sailing ship fitted with an auxiliary diesel engine, and was thus the first ocean-going ship with a diesel engine.^[33]
- 1912: The Danish built the first ocean-going ship exclusively powered by a diesel engine, MS *Selandia*.^[33] The first locomotive with a diesel engine also appeared.
- 1913: US Navy submarines used NELSECO units. Rudolf Diesel died mysteriously when he crossed the English Channel on the SS *Dresden*.
- 1914: German U-boats were powered by MAN diesels.
- 1919: Prosper L'Orange obtained a patent on a prechamber insert and made a needle injection nozzle. First diesel engine from Cummins.

1920s

- 1921: Prosper L'Orange built a continuous variable output injection pump.
- 1922: The first vehicle with a (pre-chamber) diesel engine was Agricultural Tractor Type 6 of the Benz S  hne agricultural tractor OE Benz Sendling.
- 1923: The first truck with pre-chamber diesel engine made by MAN and Benz. Daimler-Motoren-Gesellschaft testing the first air-injection diesel-engined truck.
- 1924: The introduction on the truck market of the diesel engine by commercial truck manufacturers in the IAA. Fairbanks-Morse starts building diesel engines.
- 1924-1925 Fairbanks Morse introduced the 2 stroke Y-VA and Model 32. It was the first cold start diesel manufactured by Fairbanks and would be come an icon of American industrial power.^[34]
- 1927: First truck injection pump and injection nozzles of Bosch. First passenger car prototype of Stoewer.

1930s

- 1930s: Caterpillar started building diesels for their tractors.
- 1930: First US diesel-power passenger car (Cummins powered Packard) built in Columbus, Indiana (US).^[35]

- 1930: Beardmore Tornado diesel engines power the British airship R101.
- 1932: Introduction of the strongest diesel truck in the world by MAN with 160 hp (120 kW).
- 1933: First European passenger cars with diesel engines (Citroën Rosalie); Citroën used an engine of the English diesel pioneer Sir Harry Ricardo.^[36] The car did not go into production due to legal restrictions on the use of diesel engines.
- 1934: First turbo diesel engine for a railway train by Maybach. First streamlined, stainless steel passenger train in the US, the Pioneer Zephyr, using a Winton engine.
- 1934: First tank equipped with diesel engine, the Polish 7TP.
- 1934–35: Junkers Motorenwerke in Germany started production of the Jumo aviation diesel engine family, the most famous of these being the Jumo 205, of which over 900 examples were produced by the outbreak of World War II.
- 1936: Mercedes-Benz built the 260D diesel car.^[37] AT&SF inaugurated the diesel train Super Chief. The airship Hindenburg was powered by diesel engines. First series of passenger cars manufactured with diesel engine (Mercedes-Benz 260 D, Hanomag and Saurer). Daimler Benz airship diesel engine 602LOF6 for the LZ129 *Hindenburg* airship.
- 1937: The Soviet Union developed the Kharkiv model V-2 diesel engine, later used in the T-34 tanks, widely regarded as the best tank chassis of World War II.
- 1937: BMW 114 experimental airplane diesel engine development.
- 1938: General Motors forms the GM Diesel Division, later to become Detroit Diesel, and introduces the Series 71 inline high-speed medium-horsepower two stroke engine; GM's EMD subsidiary introduces the 567 two stroke medium-speed high-horsepower engine for locomotive, ship and stationary applications; These GM and EMD engines utilize GM's patented Unit injector.
- 1938: First turbo diesel engine of Saurer.

1940s

- 1942: Tatra started production of Tatra 111 with air-cooled V12 diesel engine.
- 1943–46: The common-rail (CRD) system was invented (and patented by) Clessie Cummins^[38]
- 1944: Development of air cooling for diesel engines by Klöckner Humboldt Deutz AG (KHD) for the production stage, and later also for Magirus Deutz.

1950s

- 1953: Turbo-diesel truck for Mercedes in small series.
- 1954: Turbo-diesel truck in mass production by Volvo. First diesel engine with an overhead cam shaft of Daimler Benz.^[39]
- 1958 EMD introduces turbocharging for its 567 series of medium speed, high horsepower locomotive, stationary and marine engines. Every subsequent engine (645 and 710) would incorporate this turbocharger.

1960s

- 1960: The diesel drive displaced steam turbines and coal fired steam engines.
- 1962–65: A diesel compression braking system, eventually to be manufactured by Jacobs (of drill chuck fame) and nicknamed the "Jake Brake", was invented and patented by Clessie Cummins.^[40]
- 1968: Peugeot introduced the first 204 small cars with a transversally mounted diesel engine and front-wheel drive.

1970s

- 1973: DAF produced an air-cooled diesel engine.
- 1976 February: Tested a diesel engine for the Volkswagen Golf passenger car. The Cummins Common Rail injection system was further developed by the ETH Zurich from 1976 to 1992.
- 1978: Mercedes-Benz produced the first passenger car with a turbo-diesel engine (Mercedes-Benz 300 SD).^[37] Oldsmobile introduced the first passenger car diesel engine produced by an American car company.
- 1979: Peugeot 604, the first turbo-diesel car to be sold in Europe.^[41]

1980s

- 1985: ATI Intercooler diesel engine from DAF. European Truck Common Rail system with the IFA truck type W50 introduced.
- 1986: BMW 524td, the world's first passenger car equipped with an electronically controlled injection pump (developed by Bosch).^[42] The same year, the Fiat Croma was the first passenger car in the world to have a direct injection (turbocharged) diesel engine.^[43]
- 1987: Most powerful production truck with a 460 hp (340 kW) MAN diesel engine.
- 1989: Audi 100, the first passenger car in the world with a turbocharged direct injection and electronic control diesel engine.^[44]

1990s

- 1991: European emission standards Euro 1 met with the truck diesel engine of Scania.
- 1993: Pump nozzle injection introduced in Volvo truck engines.
- 1994: Unit injector system by Bosch for diesel engines. Mercedes-Benz unveils the first automotive diesel engine with four valves per cylinder.^[45] Medium speed high horsepower locomotive, ship and stationary diesel engines have utilized four valves per cylinder since at least 1938.
- 1995: First successful use of common rail in a production vehicle, by Denso in Japan, Hino "Rising Ranger" truck.
- 1996: First diesel engine with direct injection and four valves per cylinder, used in the Opel Vectra.^[46]
- 1997: First common rail diesel engine in a passenger car, the Alfa Romeo 156.^[47]
- 1998: BMW made history by winning the 24 Hour Nürburgring race with the 320d, powered by a two-litre, four-cylinder diesel engine. The combination of high-performance with better fuel efficiency allowed the team to make fewer pit stops during the long endurance race. Volkswagen introduces three and four-cylinder turbodiesel engines, with Bosch-developed electronically controlled unit injectors.^[48] Smart presented the first common rail three-cylinder diesel engine used in a passenger car (the Smart City Coupé).^[49]
- 1999: Euro 3 of Scania and the first common rail truck diesel engine of Renault.

2000s

- 2002: A street-driven Dodge Dakota pickup with a 735 horsepower (548 kW) diesel engine built at Gale banks engineering hauls its own service trailer to the Bonneville Salt Flats and set an FIA land speed record as the world's fastest pickup truck with a one-way run of 222 mph (357 km/h) and a two-way average of 217 mph (349 km/h).



One of the eight-cylinder 3200 I.H.P. Harland and Wolff—Burmeister & Wain Diesel engines installed in the motorship *Glenapp*. This was the highest powered Diesel engine yet (1920) installed in a ship. Note man standing lower right for size comparison.



Rudolf Diesel's 1893 patent on his engine design



Fairbanks-Morse opposed piston diesel engines on the WWII submarine USS *Pampanito* (SS-383) (on display in San Francisco)

- 2003: Piezoelectric injector technology by Bosch,^[50] Siemens and Delphi.^[51]
- 2004: In Western Europe, the proportion of passenger cars with diesel engine exceeded 50%. Selective catalytic reduction (SCR) system in Mercedes, Euro 4 with EGR system and particle filters of MAN. Audi A8 3.0 TDI is the first production vehicle in the world with common rail injection and piezoelectric injectors.^[52]
- 2006: Audi R10 TDI won the 12 Hours of Sebring and defeated all other engine concepts. The same car won the 2006 24 Hours of Le Mans. Euro 5 for all Iveco trucks. JCB Dieselmax broke the FIA diesel land speed record from 1973, eventually setting the new record at over 350 mph (563 km/h).
- 2007: Lombardini develops a new 440 cc twin-cylinder common rail diesel engine,^[53] which two years later sees application in automotive use, in the Ligier microcars.^[54] At the time, this engine was considered to be the smallest twin-cylinder engine with a common rail system.^[55]
- 2008: Subaru introduced the first horizontally opposed diesel engine to be fitted to a passenger car. This is a Euro 5 compliant engine with an EGR system. SEAT wins the drivers' title and the manufacturers' title in the FIA World Touring Car Championship with the SEAT León TDI. The achievements are repeated in the following season.
- 2009: Volkswagen won the 2009 Dakar Rally held in Argentina and Chile. The first diesel to do so. Race Touareg 2 models finished first and second. The same year, Volvo is claimed the world's strongest truck with their FH16 700. An inline 6-cylinder, 16 L (976 cu in) 700 hp (522 kW) diesel engine producing 3150 Nm (2323.32 lb•ft) of torque and fully complying with Euro 5 emission standards.^[56]

2010s

- 2010: Mitsubishi developed and started mass production of its 4N13 1.8 L DOHC I4, the world's first passenger car diesel engine that features a variable valve timing system.^{[57][58]} Scania AB's V8 had the highest torque and power ratings of any truck engine, 730 hp (544 kW) and 3,500 N·m (2,581 ft·lb).^[59]
- 2011: Piaggio launches a twin-cylinder turbodiesel engine, with common rail injection, on its new range of microvans.^[60]
- 2012: Common rail systems working with pressures of 2,500 bar launched.^{[61][62]}

Operating principle

The diesel internal combustion engine differs from the gasoline powered Otto cycle by using highly compressed hot air to ignite the fuel rather than using a spark plug (*compression ignition* rather than *spark ignition*).

In the true diesel engine, only air is initially introduced into the combustion chamber. The air is then compressed with a compression ratio typically between 15:1 and 23:1. This high compression causes the temperature of the air to rise. At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. This may be into a (typically toroidal) void in the top of the piston or a *pre-chamber* depending upon the design of the engine. The fuel injector ensures that the fuel is broken down into small droplets, and that the fuel is distributed evenly. The heat of the compressed air vaporizes fuel from the surface of the droplets. The vapour is then ignited by the heat from the compressed air in the combustion chamber, the droplets continue to vaporise from their surfaces and burn, getting smaller, until all the fuel in the droplets has been burnt. Combustion occurs at a substantially constant pressure during the initial part of the power stroke. The start of vaporisation causes a delay before ignition and the characteristic diesel knocking sound as the vapour reaches ignition temperature and causes an abrupt increase in pressure above the piston (not shown on the P-V indicator diagram). When combustion is complete the combustion gases expand as the piston descends further; the high pressure in the cylinder drives the piston downward, supplying power to the crankshaft.^[63]

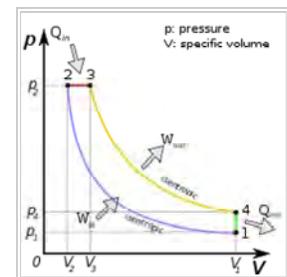
As well as the high level of compression allowing combustion to take place without a separate ignition system, a high compression ratio greatly increases the engine's efficiency. Increasing the compression ratio in a spark-ignition engine where fuel and air are mixed before entry to the cylinder is limited by the need to prevent damaging pre-ignition. Since only air is compressed in a diesel engine, and fuel is not introduced into the cylinder until shortly before top dead centre (TDC), premature detonation is not a problem and compression ratios are much higher.

The p–V diagram is a simplified and idealised representation of the events involved in a Diesel engine cycle, arranged to illustrate the similarity with a Carnot cycle. Starting at 1, the piston is at bottom dead centre and both valves are closed at the start of the compression stroke; the cylinder contains air at atmospheric pressure. Between 1 and 2 the air is compressed adiabatically—that is without heat transfer to or from the environment—by the rising piston. (This is only approximately true since there will be some heat exchange with the cylinder walls.) During this compression, the volume is reduced, the pressure and temperature both rise. At or slightly before 2 (TDC) fuel is injected and burns in the compressed hot air. Chemical energy is released and this constitutes an injection of thermal energy (heat) into the compressed gas. Combustion and heating occur between 2 and 3. In this interval the pressure remains constant since the piston descends, and the volume increases; the temperature rises as a consequence of the energy of combustion. At 3 fuel injection and combustion are complete, and the cylinder contains gas at a higher temperature than at 2. Between 3 and 4 this hot gas expands, again approximately adiabatically. Work is done on the system to which the engine is connected. During this expansion phase the volume of the gas rises, and its temperature and pressure both fall. At 4 the exhaust valve opens, and the pressure falls abruptly to atmospheric (approximately). This is unresisted expansion and no useful work is done by it. Ideally the adiabatic expansion should continue, extending the line 3–4 to the right until the pressure falls to that of the surrounding air, but the loss of efficiency caused by this unresisted expansion is justified by the practical difficulties involved in recovering it (the engine would have to be much larger). After the opening of the exhaust valve, the exhaust stroke follows, but this (and the following induction stroke) are not shown on the diagram. If shown, they would be represented by a low-pressure loop at the bottom of the diagram. At 1 it is assumed that the exhaust and induction strokes have been completed, and the cylinder is again filled with air. The piston-cylinder system absorbs energy between 1 and 2—this is the work needed to compress the air in the cylinder, and is provided by mechanical kinetic energy stored in the flywheel of the engine. Work output is done by the piston-cylinder combination between 2 and 4. The difference between these two increments of work is the indicated work output per cycle, and is represented by the area enclosed by the p–V loop. The adiabatic expansion is in a higher pressure range than that of the compression because the gas in the cylinder is hotter during expansion than during compression. It is for this reason that the loop has a finite area, and the net output of work during a cycle is positive.

Major advantages

Diesel engines have several advantages over other internal combustion engines:

- They burn less fuel than a petrol engine performing the same work, due to the engine's higher temperature of combustion and greater expansion ratio.^[1] Gasoline engines are typically 30% efficient while diesel engines can convert over 45% of the fuel energy into mechanical energy (see Carnot cycle for further explanation).^[64]
- They have no high voltage electrical ignition system, resulting in high reliability and easy adaptation to damp environments. The absence of coils, spark plug wires, etc., also eliminates a source of radio frequency emissions which can interfere with navigation and communication equipment, which is especially important in marine and aircraft applications, and for preventing interference with radio telescopes.



p-V Diagram for the Ideal Diesel cycle. The cycle follows the numbers 1–4 in clockwise direction. The horizontal axis is Volume of the cylinder. In the diesel cycle the combustion occurs at almost constant pressure. On this diagram the work that is generated for each cycle corresponds to the area within the loop.



Diesel engine model, left side



Diesel engine model, right side

- The longevity of a diesel engine is generally about twice that of a petrol engine due to the increased strength of parts used.^{[65][66]} Diesel fuel has better lubrication properties than petrol as well. Indeed, in unit injectors, the fuel is employed for three distinct purposes: injector lubrication, injector cooling and injection for combustion.
- Diesel fuel is distilled directly from petroleum. Distillation yields some gasoline, but the yield would be inadequate without catalytic reforming, which is a more costly process.
- Although diesel fuel will burn in open air using a wick, it does not release a large amount of flammable vapor which could lead to an explosion. The low vapor pressure of diesel is especially advantageous in marine applications, where the accumulation of explosive fuel-air mixtures is a particular hazard. For the same reason, diesel engines are immune to vapor lock.
- For any given partial load the fuel efficiency (mass burned per energy produced) of a diesel engine remains nearly constant, as opposed to petrol and turbine engines which use proportionally more fuel with partial power outputs.^{[67][68][69]}
- They generate less waste heat in cooling and exhaust.^[1]
- Diesel engines can accept super- or turbo-charging pressure without any natural limit, constrained only by the strength of engine components. This is unlike petrol engines, which inevitably suffer detonation at higher pressure.
- The carbon monoxide content of the exhaust is minimal.^[70]
- Biodiesel is an easily synthesized, non-petroleum-based fuel (through transesterification) which can run directly in many diesel engines, while gasoline engines either need adaptation to run synthetic fuels or else use them as an additive to gasoline (e.g., ethanol added to gasohol).



Bus powered by biodiesel

Early fuel injection systems

Diesel's original engine injected fuel with the assistance of compressed air, which atomized the fuel and forced it into the engine through a nozzle (a similar principle to an aerosol spray). The nozzle opening was closed by a pin valve lifted by the camshaft to initiate the fuel injection before top dead centre (TDC). This is called an **air-blast injection**. Driving the compressor used some power but the efficiency and net power output was more than any other combustion engine at that time.^[71]

Diesel engines in service today raise the fuel to extreme pressures by mechanical pumps and deliver it to the combustion chamber by pressure-activated injectors without compressed air. With direct injected diesels, injectors spray fuel through 4 to 12 small orifices in its nozzle. The early air injection diesels always had a superior combustion without the sharp increase in pressure during combustion. Research is now being performed and patents are being taken out to again use some form of air injection to reduce the nitrogen oxides and pollution, reverting to Diesel's original implementation with its superior combustion and possibly quieter operation. In all major aspects, the modern diesel engine holds true to Rudolf Diesel's original design, that of igniting fuel by compression at an extremely high pressure within the cylinder. With much higher pressures and high technology injectors, present-day diesel engines use the so-called solid injection system applied by Herbert Akroyd Stuart for his hot bulb engine. The indirect injection engine could be considered the latest development of these low speed *hot bulb* ignition engines.

Fuel delivery

Over the years many different injection methods have been used. These can be described as:

- Air blast, where the fuel is blown into the cylinder by a blast of air.
- Solid fuel / hydraulic injection where the fuel is pushed through a spring loaded valve / injector to produce a combustible mist.
- Mechanical Unit injector where the injector is directly operated by a cam and fuel quantity is controlled by a rack or lever .
- Mechanical Electronic Unit Injector where the injector is operated by a cam and fuel quantity is controlled electronically.
- Common Rail Mechanical Injection, Fuel is at high pressure in a common rail and controlled by mechanical means.
- Common Rail electronic injection, Fuel is at high pressure in a common rail and controlled electronically.

Diesel engines are also produced with two significantly different injection locations. "Direct" and "Indirect". Indirect injected engines place the injector in a pre-combustion chamber in the head which due to thermal losses generally require a "glow plug" to start and very high compression ratio, usually in the range of 21:1 to 23:1 ratio. Direct injected engines use a generally donut shaped combustion chamber void on the top of the piston. Thermal efficiency losses are significantly lower in DI engines which facilitates a much lower compression ratio generally between 14:1 and 20:1 but most DI engines are closer to 17:1. The direct injected process is significantly more internally violent and thus requires careful design, and more robust construction. The lower compression ratio also creates challenges for emissions due to partial burn. Turbocharging is particularly suited to DI engines since the low compression ratio facilitates meaningful forced induction, and the increase in airflow allows capturing additional fuel efficiency not only from more complete combustion, but also from lowering parasitic efficiency losses when properly operated, by widening both power and efficiency curves. The violent combustion process of direct injection also creates more noise, but modern designs using "split shot" injectors or similar multi shot processes have dramatically amended this issue by firing a small charge of fuel before the main delivery which pre-charges the combustion chamber for a less abrupt and in most cases slightly cleaner burn. {citation needed}

A vital component of all diesel engines is a mechanical or electronic governor which regulates the idling speed and maximum speed of the engine by controlling the rate of fuel delivery. Unlike Otto-cycle engines, incoming air is not throttled and a diesel engine without a governor cannot have a stable idling speed and can easily overspeed, resulting in its destruction. Mechanically governed fuel injection systems are driven by the engine's gear train.^[72] These systems use a combination of springs and weights to control fuel delivery relative to both load and speed.^[72] Modern electronically controlled diesel engines control fuel delivery by use of an electronic control module (ECM) or electronic control unit (ECU). The ECM/ECU receives an engine speed signal, as well as other operating parameters such as intake manifold pressure and fuel temperature, from a sensor and controls the amount of fuel and start of injection timing through actuators to maximise power and efficiency and minimise emissions. Controlling the timing of the start of injection of fuel into the cylinder is a key to minimizing emissions, and maximizing fuel economy (efficiency), of the engine. The timing is measured in degrees of crank angle of the piston before top dead centre. For example, if the ECM/ECU initiates fuel injection when the piston is 10° before TDC, the start of injection, or timing, is said to be 10° BTDC. Optimal timing will depend on the engine design as well as its speed and load, and is usually 4° BTDC in 1,350–6,000 HP, net, "medium speed" locomotive, marine and stationary diesel engines.

Advancing the start of injection (injecting before the piston reaches to its SOI-TDC) results in higher in-cylinder pressure and temperature, and higher efficiency, but also results in increased engine noise due to faster cylinder pressure rise and increased oxides of nitrogen (NO_x) formation due to higher combustion temperatures. Delaying start of injection causes incomplete combustion, reduced fuel efficiency and an increase in exhaust smoke, containing a considerable amount of particulate matter and unburned hydrocarbons. {citation needed}

Mechanical and electronic injection

Many configurations of fuel injection have been used over the course of the 20th century.

Most present-day diesel engines use a mechanical single plunger high-pressure fuel pump driven by the engine crankshaft. For each engine cylinder, the corresponding plunger in the fuel pump measures out the correct amount of fuel and determines the timing of each injection. These engines use injectors that are very precise spring-loaded valves that open and close at a specific fuel pressure. Separate high-pressure fuel lines connect the fuel pump with each cylinder. Fuel volume for each single combustion is controlled by a slanted groove in the plunger which rotates only a few degrees releasing the pressure and is controlled by a mechanical governor, consisting of weights rotating at engine speed constrained by springs and a lever. The injectors are held open by the fuel pressure. On high-speed engines the plunger pumps are together in one unit.^[73] The length of fuel lines from the pump to each injector is normally the same for each cylinder in order to obtain the same pressure delay.

A cheaper configuration on high-speed engines with fewer than six cylinders is to use an axial-piston distributor pump, consisting of one rotating pump plunger delivering fuel to a valve and line for each cylinder (functionally analogous to points and distributor cap on an Otto engine).^[72]

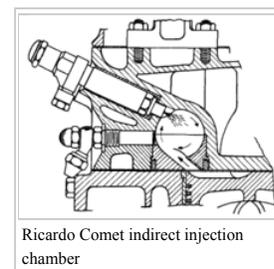
Many modern systems have a single fuel pump which supplies fuel constantly at high pressure with a common rail (single fuel line common) to each injector. Each injector has a solenoid operated by an electronic control unit, resulting in more accurate control of injector opening times that depend on other control conditions, such as engine speed and loading, and providing better engine performance and fuel economy.

Both mechanical and electronic injection systems can be used in either direct or indirect injection configurations.

Two-stroke diesel engines with mechanical injection pumps can be inadvertently run in reverse, albeit in a very inefficient manner, possibly damaging the engine. Large ship two-stroke diesels are designed to run in either direction, obviating the need for a gearbox.

Indirect injection

An indirect Diesel injection system (IDI) engine delivers fuel into a small chamber called a swirl chamber, pre combustion chamber, pre chamber or ante-chamber, which is connected to the cylinder by a narrow air passage. Generally the goal of the pre chamber is to create increased turbulence for better air / fuel mixing. This system also allows for a smoother, quieter running engine, and because fuel mixing is assisted by turbulence, injector pressures can be lower. Most IDI systems tend to use a single orifice injector. The pre-chamber has the disadvantage of lowering efficiency due to increased heat loss to the engine's cooling system, restricting the combustion burn, thus reducing the efficiency by 5–10%. IDI engines are also more difficult to start and usually require the use of glow plugs. IDI engines may be cheaper to build but generally require a higher compression ratio than the DI counterpart. IDI also makes it easier to produce smooth, quieter running engines with a simple mechanical injection system since exact injection timing is not as critical. Most modern automotive engines are DI which have the benefits of greater efficiency, easier starting, however IDI engines can still be found in the many ATV and small Diesel applications.^[74]



Ricardo Comet indirect injection chamber

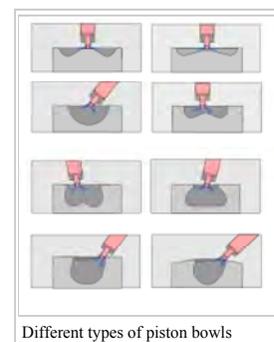
Direct injection

Direct injection diesel engines inject fuel directly into the cylinder. Usually there is a combustion cup in the top of the piston where the fuel is sprayed. Many different methods of injection can be used.

Electronic control of the fuel injection transformed the direct injection engine by allowing much greater control over the combustion.^[75]

Unit direct injection

Unit direct injection also injects fuel directly into the cylinder of the engine. In this system the injector and the pump are combined into one unit positioned over each cylinder controlled by the camshaft. Each cylinder has its own unit eliminating the high-pressure fuel lines, achieving a more consistent injection. This type of injection system, also developed by Bosch, is used by Volkswagen AG in cars (where it is called a *Pumpe-Düse-System*—literally *pump-nozzle system*) and by Mercedes-Benz ("PLD") and most major diesel engine manufacturers in large commercial engines (MAN SE, CAT, Cummins, Detroit Diesel, Electro-Motive Diesel, Volvo). With recent advancements, the pump pressure has been raised to 2,400 bars (240 MPa; 35,000 psi),^[76] allowing injection parameters similar to common rail systems.^[77]



Different types of piston bowls

Common rail direct injection

"Common Rail" injection was first used in production by Atlas Imperial Diesel in the 1920s. The rail pressure was kept at a steady 2,000 - 4,000 psi. In the injectors a needle was mechanically lifted off of the seat to create the injection event.^[78] Modern common rail systems use very high-pressures. In these systems an engine driven pump pressurizes fuel at up to 2,500 bar (250 MPa; 36,000 psi),^[79] in a "common rail". The common rail is a tube that supplies each computer-controlled injector containing a precision-machined nozzle and a plunger driven by a solenoid or piezoelectric actuator.

Cold weather problems

Starting

In cold weather, high speed diesel engines can be difficult to start because the mass of the cylinder block and cylinder head absorb the heat of compression, preventing ignition due to the higher surface-to-volume ratio. Pre-chambered engines make use of small electric heaters inside the pre-chambers called glowplugs, while direct-injected engines have these glowplugs in the combustion chamber.

Many engines use resistive heaters in the intake manifold to warm the inlet air for starting, or until the engine reaches operating temperature. Engine block heaters (electric resistive heaters in the engine block) connected to the utility grid are used in cold climates when an engine is turned off for extended periods (more than an hour), to reduce startup time and engine wear. Block heaters are also used for emergency power standby Diesel-powered generators which must rapidly pick up load on a power failure. In the past, a wider variety of cold-start methods were used. Some engines, such as Detroit Diesel^[80] engines used a system to introduce small amounts of ether into the inlet manifold to start combustion. Others used a mixed system, with a resistive heater burning methanol. An impromptu method, particularly on out-of-tune engines, is to manually spray an aerosol can of ether-based engine starter fluid into the intake air stream (usually through the intake air filter assembly).

Gelling

Diesel fuel is also prone to *waxing* or *gelling* in cold weather; both are terms for the solidification of diesel oil into a partially crystalline state. The crystals build up in the fuel line (especially in fuel filters), eventually starving the engine of fuel and causing it to stop running. Low-output electric heaters in fuel tanks and around fuel lines are used to solve this problem. Also, most engines have a *spill return* system, by which any excess fuel from the injector pump and injectors is returned to the fuel tank. Once the engine has warmed, returning warm fuel prevents waxing in the tank.

Due to improvements in fuel technology with additives, waxing rarely occurs in all but the coldest weather when a mix of diesel and kerosene may be used to run a vehicle. Gas stations in regions with a cold climate are required to offer winterized diesel in the cold seasons that allow operation below a specific Cold Filter Plugging Point. In Europe these diesel characteristics are described in the EN 590 standard.

Supercharging and turbocharging

Many diesels are now turbocharged and some are both turbo charged and supercharged. A turbocharged engine can produce more power than a naturally aspirated engine of the same configuration. A supercharger is powered mechanically by the engine's crankshaft, while a turbocharger is powered by the engine exhaust. Turbocharging can improve the fuel economy^[81] of diesel engines by recovering waste heat from the exhaust, increasing the excess air factor, and increasing the ratio of engine output to friction losses.

A two-stroke engine does not have a discrete exhaust and intake stroke and thus is incapable of self-aspiration. Therefore, all two-stroke engines must be fitted with a blower or some form of compressor to charge the cylinders with air and assist in dispersing exhaust gases, a process referred to as scavenging. In some cases, the engine may also be fitted with a turbocharger, whose output is directed into the blower inlet.

A few designs employ a hybrid blower / turbocharger (a turbo-compressor system) for scavenging and charging the cylinders, which device is mechanically driven at cranking and low speeds to act as a blower, but which acts as a true turbocharger at higher speeds and loads. A hybrid turbocharger can revert to compressor mode during commands for large increases in engine output power.

As turbocharged or supercharged engines produce more power for a given engine size as compared to naturally aspirated engines, attention must be paid to the mechanical design of components, lubrication, and cooling to handle the power. Pistons are usually cooled with lubrication oil sprayed on the bottom of the piston. Large "Low speed" engines may use water, sea water, or oil supplied through telescoping pipes attached to the crosshead to cool the pistons.^[82]

Types

Size groups

There are three size groups of Diesel engines^[83]

- Small—under 188 kW (252 hp) output
- Medium
- Large

Basic types

There are two basic types of Diesel Engines^[83]

- Four stroke cycle
- Two stroke cycle

Early engines

In 1897, when the first Diesel engine was completed Adolphus Busch traveled to Cologne and negotiated exclusive right to produce the Diesel engine in the US and Canada. In his examination of the engine, it was noted that the Diesel at that time operated at thermodynamic efficiencies of 27%, while a typical expansion steam engine would operate at about 7-10%.^[84]

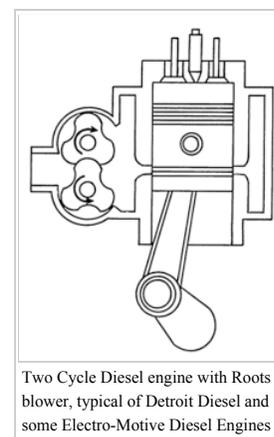
In the early decades of the 20th century, when large diesel engines were first being used, the engines took a form similar to the compound steam engines common at the time, with the piston being connected to the connecting rod by a crosshead bearing. Following steam engine practice some manufacturers made double-acting two-stroke and four-stroke diesel engines to increase power output, with combustion taking place on both sides of the piston, with two sets of valve gear and fuel injection. While it produced large amounts of power, the double-acting diesel engine's main problem was producing a good seal where the piston rod passed through the bottom of the lower combustion chamber to the crosshead bearing, and no more were built. By the 1930s turbochargers were fitted to some engines. Crosshead bearings are still used to reduce the wear on the cylinders in large long-stroke main marine engines.

Modern high and medium-speed engines

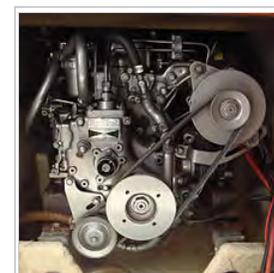
As with petrol engines, there are two classes of diesel engines in current use: two-stroke and four-stroke. The four-stroke type is the "classic" version, tracing its lineage back to Rudolf Diesel's prototype. It is also the most commonly used form, being the preferred power source for many motor vehicles, especially buses and trucks. Much larger engines, such as used for railroad locomotion and marine propulsion, are often two-stroke units, offering a more favourable power-to-weight ratio, as well as better fuel economy. The most powerful engines in the world are two-stroke diesels of mammoth dimensions.^[85]

Two-stroke diesel engine operation is similar to that of petrol counterparts, except that fuel is not mixed with air before induction, and the crankcase does not take an active role in the cycle. The traditional two-stroke design relies upon a mechanically driven positive displacement blower to charge the cylinders with air before compression and ignition. The charging process also assists in expelling (scavenging) combustion gases remaining from the previous power stroke.

The archetype of the modern form of the two-stroke diesel is the (high-speed) Detroit Diesel Series 71 engine, designed by Charles F. "Boss" Kettering and his colleagues at General Motors Corporation in 1938, in which the blower pressurizes a chamber in the engine block that is often referred to as the "air box". The (very much larger medium-speed) Electro-Motive Diesel engine^[86] is used as the prime mover in EMD diesel-electric locomotive, marine and stationary applications, and was designed by the same team, and is built to the same principle. However, a significant improvement built into most later EMD engines is the mechanically assisted turbo-



Two Cycle Diesel engine with Roots blower, typical of Detroit Diesel and some Electro-Motive Diesel Engines



A Yanmar 2GM20 marine diesel engine, installed in a sailboat

compressor, which provides charge air using mechanical assistance during starting (thereby obviating the necessity for Roots-blown scavenging), and provides charge air using an exhaust gas-driven turbine during normal operations—thereby providing true turbocharging and additionally increasing the engine's power output by at least fifty percent.^[a]

In a two-stroke diesel engine, as the cylinder's piston approaches the bottom dead centre exhaust ports or valves are opened relieving most of the excess pressure after which a passage between the air box and the cylinder is opened, permitting air flow into the cylinder.^[87] The air flow blows the remaining combustion gases from the cylinder—this is the scavenging process. As the piston passes through bottom centre and starts upward, the passage is closed and compression commences,^[88] culminating in fuel injection and ignition.^[89] Refer to two-stroke diesel engines for more detailed coverage of aspiration types and supercharging of two-stroke diesel engines.

Normally, the number of cylinders are used in multiples of two, although any number of cylinders can be used as long as the load on the crankshaft is counterbalanced to prevent excessive vibration. The inline-six-cylinder design is the most prolific in light- to medium-duty engines, though small V8 and larger inline-four displacement engines are also common. Small-capacity engines (generally considered to be those below five litres in capacity) are generally four- or six-cylinder types, with the four-cylinder being the most common type found in automotive uses. Five-cylinder diesel engines have also been produced, being a compromise between the smooth running of the six-cylinder and the space-efficient dimensions of the four-cylinder. Diesel engines for smaller plant machinery, boats, tractors, generators and pumps may be four, three or two-cylinder types, with the single-cylinder diesel engine remaining for light stationary work. Direct reversible two-stroke marine diesels need at least three cylinders for reliable restarting forwards and reverse, while four-stroke diesels need at least six cylinders.

The desire to improve the diesel engine's power-to-weight ratio produced several novel cylinder arrangements to extract more power from a given capacity. The uniflow opposed-piston engine uses two pistons in one cylinder with the combustion cavity in the middle and gas in- and outlets at the ends. This makes a comparatively light, powerful, swiftly running and economic engine suitable for use in aviation. An example is the Junkers Jumo 204/205. The Napier Deltic engine, with three cylinders arranged in a triangular formation, each containing two opposed pistons, the whole engine having three crankshafts, is one of the better known.

Gas generator

Before 1950, Sulzer started experimenting with two-stroke engines with boost pressures as high as 6 atmospheres, in which all the output power was taken from an exhaust gas turbine. The two-stroke pistons directly drove air compressor pistons to make a positive displacement gas generator. Opposed pistons were connected by linkages instead of crankshafts. Several of these units could be connected to provide power gas to one large output turbine. The overall thermal efficiency was roughly twice that of a simple gas turbine.^[90] This system was derived from Raúl Pateras Pescara's work on free-piston engines in the 1930s.

Advantages and disadvantages versus spark-ignition engines

Fuel economy

The MAN S80ME-C7 low speed diesel engines use 155 grams (5.5 oz) of fuel per kWh for an overall energy conversion efficiency of 54.4%, which is the highest conversion of fuel into power by any single-cycle internal or external combustion engine^[1] (The efficiency of a combined cycle gas turbine system can exceed 60%.^[91]) Diesel engines are more efficient than gasoline (petrol) engines of the same power rating, resulting in lower fuel consumption. A common margin is 40% more miles per gallon for an efficient turbodiesel. For example, the current model Škoda Octavia, using Volkswagen Group engines, has a combined Euro rating of 6.2 L/100 km (46 mpg_{imp}, 38 mpg_{us}) for the 102 bhp (76 kW) petrol engine and 4.4 L/100 km (64 mpg_{imp}, 53 mpg_{us}) for the 105 bhp (78 kW) diesel engine.

However, such a comparison does not take into account that diesel fuel is denser and contains about 15% more energy by volume. Although the calorific value of the fuel is slightly lower at 45.3 MJ/kg (megajoules per kilogram) than petrol at 45.8 MJ/kg, liquid diesel fuel is significantly denser than liquid petrol. This is significant because volume of fuel, in addition to mass, is an important consideration in mobile applications.

Adjusting the numbers to account for the energy density of diesel fuel, the overall energy efficiency is still about 20% greater for the diesel version.

While a higher compression ratio is helpful in raising efficiency, diesel engines are much more efficient than gasoline (petrol) engines when at low power and at engine idle. Unlike the petrol engine, diesels lack a butterfly valve (throttle) in the inlet system, which closes at idle. This creates parasitic loss and destruction of availability of the incoming air, reducing the efficiency of petrol engines at idle. In many applications, such as marine, agriculture, and railways, diesels are left idling and unattended for many hours, sometimes even days. These advantages are especially attractive in locomotives (see dieselisation).

Even though diesel engines have a theoretical fuel efficiency of 75%, in practice it is lower. Engines in large diesel trucks, buses, and newer diesel cars can achieve peak efficiencies around 45%,^[92] and could reach 55% efficiency in the near future.^[93] However, average efficiency over a driving cycle is lower than peak efficiency. For example, it might be 37% for an engine with a peak efficiency of 44%.^[94]

Torque

Diesel engines produce more torque than petrol engines for a given displacement due to their higher compression ratio. Higher pressure in the cylinder and higher forces on the connecting rods and crankshaft require stronger, heavier components. Heavier rotating components prevent diesel engines from revving as high as petrol engines for a given displacement. Diesel engines generally have similar power and inferior power to weight ratios as compared to petrol engines. Petrol engines must be geared lower to get the same torque as a comparable diesel but since petrol engines rev higher both will have similar acceleration. An arbitrary amount of torque at the wheels can be gained by gearing any power source down sufficiently (including a hand crank). For example, a theoretical engine with a constant 200 ft.lbs of torque and a 3000 rpm rev limit has just as much power (a little over 114 hp) as another theoretical engine with a constant maximum 100 ft.lbs of torque and a 6000 rpm rev limit. A (lossless) 2 to 1 reduction gear on the second engine will output a constant maximum 200 ft.lbs of torque at a maximum of 3000 rpm, with no change in power. Comparing engines based on (maximum) torque is just as useful as comparing them based on (maximum) rpm.

Power

Conditions in the diesel engine differ from the spark-ignition engine due to the different thermodynamic cycle. In addition the power and engine speed are directly controlled by the fuel supply, rather than by controlling the air supply as in an otto cycle engine.

The average diesel engine has a poorer power-to-weight ratio than the petrol engine. This is because the diesel must operate at lower engine speeds due to the need for heavier, stronger parts to resist the operating pressure caused by the high compression ratio of the engine, which increases the forces on the parts due to inertial forces.^[95] In addition, diesels are often built with stronger parts to give them longer lives and better reliability, important considerations in industrial applications.Template:Questionable



Three English Electric 7SRL diesel alternator sets being installed at the Saateni Power Station, Zanzibar 1955

Diesel engines usually have longer stroke lengths chiefly to facilitate achieving the necessary compression ratios. As a result, piston and connecting rods are heavier and more force must be transmitted through the connecting rods and crankshaft to change the momentum of the piston. This is another reason that a diesel engine must be stronger for the same power output as a petrol engine.

Yet it is this characteristic that has allowed some enthusiasts to acquire significant power increases with turbocharged engines by making fairly simple and inexpensive modifications. A petrol engine of similar size cannot put out a comparable power increase without extensive alterations because the stock components cannot withstand the higher stresses placed upon them. Since a diesel engine is already built to withstand higher levels of stress, it makes an ideal candidate for performance tuning at little expense. However, it should be said that any modification that raises the amount of fuel and air put through a diesel engine will increase its operating temperature, which will reduce its life and increase service requirements. These are issues with newer, lighter, *high-performance* diesel engines which are not "overbuilt" to the degree of older engines and they are being pushed to provide greater power in smaller engines.

Emissions

Since the diesel engine uses less fuel than the petrol engine per unit distance, the diesel produces less carbon dioxide (CO₂) per unit distance. Recent advances in production and changes in the political climate have increased the availability and awareness of biodiesel, an alternative to petroleum-derived diesel fuel with a much lower net-sum emission of CO₂, due to the absorption of CO₂ by plants used to produce the fuel. However, the use of waste vegetable oil, sawmill waste from managed forests in Finland, and advances in the production of vegetable oil from algae demonstrate great promise in providing feed stocks for sustainable biodiesel that are not in competition with food production.

When a diesel engine runs at low power, there is enough oxygen present to burn the fuel—diesel engines only make significant amounts of carbon monoxide when running under a load.

Diesel fuel is injected just before the power stroke. As a result, the fuel cannot burn completely unless it has a sufficient amount of oxygen. This can result in incomplete combustion and black smoke in the exhaust if more fuel is injected than there is air available for the combustion process. Modern engines with electronic fuel delivery can adjust the timing and amount of fuel delivered, and so operate with less waste of fuel. In a mechanical system fuel timing system, the injection and duration must be set to be efficient at the anticipated operating rpm and load, and so the settings are less than ideal when the engine is running at any other RPM. The electronic injection can "sense" engine revs, load, even boost and temperature, and continuously alter the timing to match the given situation. In the petrol engine, air and fuel are mixed for the entire compression stroke, ensuring complete mixing even at higher engine speeds.

Diesel exhaust is well known for its characteristic smell, but this smell in recent years has become much less due to use of low sulfur fuel.

Diesel exhaust has been found to contain a long list of toxic air contaminants. Among these pollutants, fine particle pollution is an important as a cause of diesel's harmful health effects. However, when diesel engines burn their fuel with high oxygen levels, this results in high combustion temperatures and higher efficiency, and these particles tend to burn, but the amount of NO_x pollution tends to increase.

NO_x pollution can be reduced with diesel exhaust fluid, which is injected into the exhaust stream, and catalytically destroys the NO_x chemical species. Exhaust gas recirculation which works by recirculating a portion of an engine's exhaust gas back to the engine cylinders also has very positive effects on NO_x emissions.

Noise

The distinctive noise of a diesel engine is variably called diesel clatter, diesel nailing, or diesel knock.^[96] Diesel clatter is caused largely by the diesel combustion process; the sudden ignition of the diesel fuel when injected into the combustion chamber causes a pressure wave. Engine designers can reduce diesel clatter through: indirect injection; pilot or pre-injection; injection timing; injection rate; compression ratio; turbo boost; and exhaust gas recirculation (EGR).^[97] Common rail diesel injection systems permit multiple injection events as an aid to noise reduction. Diesel fuels with a higher octane rating modify the combustion process and reduce diesel clatter.^[96] CN (Cetane number) can be raised by distilling higher quality crude oil, by catalyzing a higher quality product or by using a cetane improving additive.

A combination of improved mechanical technology such as multi-stage injectors which fire a short "pilot charge" of fuel into the cylinder to initiate combustion before delivering the main fuel charge, higher injection pressures that have improved the atomisation of fuel into smaller droplets, and electronic control (which can adjust the timing and length of the injection process to optimise it for all speeds and temperatures), have partially mitigated these problems in the latest generation of common-rail designs, while improving engine efficiency.

Reliability

For most industrial or nautical applications, reliability is considered more important than light weight and high power.

The lack of an electrical ignition system greatly improves the reliability. The high durability of a diesel engine is also due to its overbuilt nature (see above). Diesel fuel is a better lubricant than petrol and thus, it is less harmful to the oil film on piston rings and cylinder bores as occurs in petro powered engines; it is routine for diesel engines to cover 400,000 km (250,000 mi) or more without a rebuild.

Due to the greater compression ratio and the increased weight of the stronger components, starting a diesel engine is harder than starting a gasoline engine of similar design and displacement. More torque from the starter motor is required to push the engine through the compression cycle when starting compared to a petrol engine. This can cause difficulty when starting in winter time if using conventional automotive batteries because of the lower current available.

Either an electrical starter or an air-start system is used to start the engine turning. On large engines, pre-lubrication and slow turning of an engine, as well as heating, are required to minimise the amount of engine damage during initial start-up and running. Some smaller military diesels can be started with an explosive cartridge, called a Coffman starter, which provides the extra power required to get the machine turning. In the past, Caterpillar and John Deere used a small petrol *pony* engine in their tractors to start the primary diesel engine. The pony engine heated the diesel to aid in ignition and used a small clutch and transmission to spin up the diesel engine. Even more unusual was an International Harvester design in which the diesel engine had its own carburetor and ignition system, and started on petrol. Once warmed, the operator moved two levers to switch the engine to diesel operation, and work could begin. These engines had very complex cylinder heads, with their own petrol combustion chambers, and were vulnerable to expensive damage if special care was not taken (especially in letting the engine cool before turning it off).

Cylinder cavitation and erosion damage

One phenomenon that can affect water-cooled diesel engines is cylinder cavitation and erosion. This is due to a phenomenon in high-compression engines where the ignition of the fuel in the cylinder causes a high-frequency vibration that causes bubbles to form in the coolant in contact with the cylinder. When these tiny bubbles collapse, coolant impacts the cylinder wall, over time causing small holes to form in the cylinder wall.^[98] This damage is mitigated in some engines with coatings, or with a coolant additive specifically designed to prevent cavitation and erosion damage. Engines damaged in this way will require the affected cylinder to be repaired (where possible) or will be rendered unusable.

Quality and variety of fuels

Petrol/gasoline engines are limited in the variety and quality of the fuels they can burn. Older petrol engines fitted with a carburetor required a volatile fuel that would vaporise easily to create the necessary air-fuel ratio for combustion. Because both air and fuel are admitted to the cylinder, if the compression ratio of the engine is too high or the fuel too volatile (with too low an octane rating), the fuel will ignite under compression, as in a diesel engine, before the piston reaches the top of its stroke. This pre-ignition causes a power loss and over time major damage to the piston and cylinder. The need for a fuel that is volatile enough to vaporise but not too volatile (to avoid pre-ignition) means that petrol engines will only run on a narrow range of fuels. There has been some success at dual-fuel engines that use petrol and ethanol, petrol and propane, and petrol and methane.

In diesel engines, a mechanical injector system vaporizes the fuel directly into the combustion chamber or a pre-combustion chamber (as opposed to a Venturi jet in a carburetor, or a fuel injector in a fuel injection system vaporising fuel into the intake manifold or intake runners as in a petrol engine). This *forced vaporisation* means that less-volatile fuels can be used. More crucially, because only air is inducted into the cylinder in a diesel engine, the compression ratio can be much higher as there is no risk of pre-ignition provided the injection process is accurately timed. This means that cylinder temperatures are much higher in a diesel engine than a petrol engine, allowing less volatile fuels to be used.

Diesel fuel is a form of light fuel oil, very similar to kerosene (paraffin), but diesel engines, especially older or simple designs that lack precision electronic injection systems, can run on a wide variety of other fuels. Some of the most common alternatives are Jet A-1 type jet fuel or vegetable oil from a very wide variety of plants. Some engines can be run on vegetable oil without modification, and most others require fairly basic alterations. Biodiesel is a pure diesel-like fuel refined from vegetable oil and can be used in nearly all diesel engines. Requirements for fuels to be used in diesel engines are the ability of the fuel to flow along the fuel lines, the ability of the fuel to lubricate the injector pump and injectors adequately, and its ignition qualities (ignition delay, cetane number). Inline mechanical injector pumps generally tolerate poor-quality or bio-fuels better than distributor-type pumps. Also, indirect injection engines generally run more satisfactorily on bio-fuels than direct injection engines. This is partly because an indirect injection engine has a much greater 'swirl' effect, improving vaporisation and combustion of fuel, and because (in the case of vegetable oil-type fuels) lipid depositions can condense on the cylinder walls of a direct-injection engine if combustion temperatures are too low (such as starting the engine from cold).

It is often reported that Diesel designed his engine to run on peanut oil, but this is false. Patent number 608845 describes his engine as being designed to run on pulverulent solid fuel (coal dust). Diesel stated in his published papers, "at the Paris Exhibition in 1900 (*Exposition Universelle*) there was shown by the Otto Company a small diesel engine, which, at the request of the French Government ran on Arachide (earth-nut or peanut) oil (see biodiesel), and worked so smoothly that only a few people were aware of it. The engine was constructed for using mineral oil, and was then worked on vegetable oil without any alterations being made. The French Government at the time thought of testing the applicability to power production of the Arachide, or earth-nut, which grows in considerable quantities in their African colonies, and can easily be cultivated there." Diesel himself later conducted related tests and appeared supportive of the idea.^[99]

Most large marine diesels run on heavy fuel oil (sometimes called "bunker oil"), which is a thick, viscous and almost flameproof fuel which is very safe to store and cheap to buy in bulk as it is a waste product from the petroleum refining industry. The fuel must not only be pre-heated, but must be kept heated during handling and storage in order to maintain its pumpability. This is usually accomplished by steam tracing on fuel lines and steam coils in fuel oil tanks. The fuel is then preheated to over 100C before entering the engine in order to attain the proper viscosity for atomisation.

Fuel and fluid characteristics

Diesel engines can operate on a variety of different fuels, depending on configuration, though the eponymous diesel fuel derived from crude oil is most common. The engines can work with the full spectrum of crude oil distillates, from natural gas, alcohols, petrol, wood gas to the *fuel oils* from diesel oil to residual fuels. Many automotive diesel engines would run on 100% biodiesel without any modifications.

The type of fuel used is selected to meet a combination of service requirements, and fuel costs. Good-quality diesel fuel can be synthesised from vegetable oil and alcohol. Diesel fuel can be made from coal or other carbon base using the Fischer–Tropsch process. Biodiesel is growing in popularity since it can frequently be used in unmodified engines, though production remains limited. Recently, biodiesel from coconut, which can produce a very promising coco methyl ester (CME), has characteristics which enhance lubricity and combustion giving a regular diesel engine without any modification more power, less particulate matter or black smoke, and smoother engine performance. The Philippines pioneers in the research on Coconut based CME with the help of German and American scientists. Petroleum-derived diesel is often called *petrodiesel* if there is need to distinguish the source of the fuel.

Pure plant oils are increasingly being used as a fuel for cars, trucks and remote combined heat and power generation especially in Germany where hundreds of decentralised small- and medium-sized oil presses cold press oilseed, mainly rapeseed, for fuel. There is a Deutsches Institut für Normung fuel standard for rapeseed oil fuel.

Residual fuels are the "dregs" of the distillation process and are a thicker, heavier oil, or oil with higher viscosity, which are so thick that they are not readily pumpable unless heated. Residual fuel oils are cheaper than clean, refined diesel oil, although they are dirtier. Their main considerations are for use in ships and very large generation sets, due to the cost of the large volume of fuel consumed, frequently amounting to many tonnes per hour. The poorly refined biofuels straight vegetable oil (SVO) and waste vegetable oil (WVO) can fall into this category, but can be viable fuels on non-common rail or TDI PD diesels with the simple conversion of fuel heating to 80 to 100 degrees Celsius to reduce viscosity, and adequate filtration to OEM standards. Engines using these heavy oils have to start and shut down on standard diesel fuel, as these fuels will not flow through fuel lines at low temperatures. Moving beyond that, use of low-grade fuels can lead to serious maintenance problems because of their high sulphur and lower lubrication properties. Most diesel engines that power ships like supertankers are built so that the engine can safely use low-grade fuels due to their separate cylinder and crankcase lubrication.

Normal diesel fuel is more difficult to ignite and slower in developing fire than petrol because of its higher flash point, but once burning, a diesel fire can be fierce.

Fuel contaminants such as dirt and water are often more problematic in diesel engines than in petrol engines. Water can cause serious damage, due to corrosion, to the injection pump and injectors; and dirt, even very fine particulate matter, can damage the injection pumps due to the close tolerances that the pumps are machined to. All diesel engines will have a fuel filter (usually much finer than a filter on a petrol engine), and a water trap. The water trap (which is sometimes part of the fuel filter) often has a float connected to a warning light, which warns when there is too much water in the trap, and must be drained before damage to the engine can result. The fuel filter must be replaced much more often on a diesel engine than on a petrol engine, changing the fuel filter every 2–4 oil changes is not uncommon for some vehicles.

Safety

Fuel flammability

Diesel fuel is less flammable than petrol, leading to a lower risk of fire caused by fuel in a vehicle equipped with a diesel engine.

In yachts, diesel engines are often used because the petrol (gasoline) that fuels spark-ignition engines releases combustible vapors which can lead to an explosion if it accumulates in a confined space such as the bottom of a vessel. Ventilation systems are mandatory on petrol-powered vessels.^[100]

The United States Army and NATO use only diesel engines and turbines because of fire hazard. Although neither gasoline nor diesel is explosive in liquid form, both can create an explosive air/vapor mix under the right conditions. However, diesel fuel is less prone due to its lower vapor pressure, which is an indication of evaporation rate. The Material Safety Data Sheet^[101] for ultra-low sulfur diesel fuel indicates a vapor explosion hazard for diesel indoors, outdoors, or in sewers.

US Army gasoline-engined tanks during World War II were nicknamed Ronsons, because of their greater likelihood of catching fire when damaged by enemy fire, although tank fires were usually caused by detonation of the ammunition rather than fuel, while diesel tanks such as the Soviet T-34 were less prone to catching fire.

Maintenance hazards

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 pounds per square inch (690 kPa) pressure.^[102] The first known such injury occurred in 1937 during a diesel engine maintenance operation.^[103]

Cancer

Diesel exhaust has been classified as an IARC Group 1 carcinogen. It causes lung cancer and is associated with an increased risk for bladder cancer.^[104]

Applications

The characteristics of diesel have different advantages for different applications.

Passenger cars

Diesel engines have long been popular in bigger cars and have been used in smaller cars such as superminis in Europe since the 1980s. They were popular in larger cars earlier, as the weight and cost penalties were less noticeable.^[105] Diesel engines tend to be more economical at regular driving speeds and are much better at city speeds. Their reliability and life-span tend to be better (as detailed). Some 40 percent or more of all cars sold in Europe are diesel-powered where they are considered a low CO₂ option. Mercedes-Benz in conjunction with Robert Bosch GmbH produced diesel-powered passenger cars starting in 1936 and very large numbers are used all over the world (often as "Grande Taxis" in the Third World). Diesel-powered passenger cars are very popular in India too, since the price of diesel fuel there is lower as compared to petrol. As a result, predominantly petrol-powered car manufacturers including the Japanese car manufacturers produce and market diesel-powered cars in India. Diesel-powered cars also dominate the Indian taxi industry.

Railroad rolling stock

Diesel engines have eclipsed steam engines as the prime mover on all non-electrified railroads in the industrialized world. The first diesel locomotives appeared in the early 20th century, and diesel multiple units soon after. While electric locomotives have replaced the diesel locomotive for some passenger traffic in Europe and Asia, diesel is still today very popular for cargo-hauling freight trains and on tracks where electrification is not feasible. Most modern diesel locomotives are actually diesel-electric locomotives: the diesel engine is used to power an electric generator that in turn powers electric traction motors with no mechanical connection between diesel engine and traction. After 2000, environmental requirements has caused higher development cost for engines, and it has become common for passenger multiple units to use engines and automatic mechanical gearboxes made for trucks. Up to four such combinations might be used to achieve enough power in a train.

Other transport uses

Larger transport applications (trucks, buses, etc.) also benefit from the Diesel's reliability and high torque output. Diesel displaced paraffin (or tractor vaporising oil, TVO) in most parts of the world by the end of the 1950s with the US following some 20 years later.

- Aircraft
- Marine
- Motorcycles

In merchant ships and boats, the same advantages apply with the relative safety of Diesel fuel an additional benefit. The German pocket battleships were the largest Diesel warships, but the German torpedo-boats known as E-boats (*Schnellboot*) of the Second World War were also Diesel craft. Conventional submarines have used them since before World War I, relying on the almost total absence of carbon monoxide in the exhaust. American World War II Diesel-electric submarines operated on two-stroke cycle, as opposed to the four-stroke cycle that other navies used.

Non-road diesel engines

Non-road diesel engines include mobile equipment and vehicles that are not used on the public roadways such as construction equipment and agricultural tractors.

Military fuel standardisation

NATO has a single vehicle fuel policy and has selected diesel for this purpose. The use of a single fuel simplifies wartime logistics. NATO and the United States Marine Corps have even been developing a diesel military motorcycle based on a Kawasaki off road motorcycle the KLR 650, with a purpose designed naturally aspirated direct injection diesel at Cranfield University in England, to be produced in the US, because motorcycles were the last remaining gasoline-powered vehicle in their inventory. Before this, a few civilian motorcycles had been built using adapted stationary diesel engines, but the weight and cost disadvantages generally outweighed the efficiency gains.

Non-transport uses

Diesel engines are also used to power permanent, portable, and backup generators, irrigation pumps,^[106] corn grinders,^[107] and coffee de-pulpers.^[108]

Engine speeds

Within the diesel engine industry, engines are often categorized by their rotational speeds into three unofficial groups:

- High-speed engines (> 1,000 rpm),
- Medium-speed engines (300–1,000 rpm), and

- Slow-speed engines (< 300 rpm).

High- and medium-speed engines are predominantly four-stroke engines; except for the Detroit Diesel two-stroke range. Medium-speed engines are physically larger than high-speed engines and can burn lower-grade (slower-burning) fuel than high-speed engines. Slow-speed engines are predominantly large two-stroke crosshead engines, hence very different from high- and medium-speed engines. Due to the lower rotational speed of slow- and medium-speed engines, there is more time for combustion during the power stroke of the cycle, allowing the use of slower-burning fuels than high-speed engines.

High-speed engines

High-speed (approximately 1,000 rpm and greater) engines are used to power trucks (lorries), buses, tractors, cars, yachts, compressors, pumps and small electrical generators. As of 2008, most high-speed engines have direct injection. Many modern engines, particularly in on-highway applications, have common rail direct injection, which is cleaner burning.

Medium-speed engines

Medium-speed engines are used in large electrical generators, ship propulsion and mechanical drive applications such as large compressors or pumps. Medium speed diesel engines operate on either diesel fuel or heavy fuel oil by direct injection in the same manner as low-speed engines.

Engines used in electrical generators run at approximately 300 to 1000 rpm and are optimized to run at a set synchronous speed depending on the generation frequency (50 or 60 hertz) and provide a rapid response to load changes. Typical synchronous speeds for modern medium-speed engines are 500/514 rpm (50/60 Hz), 600 rpm (both 50 and 60 Hz), 720/750 rpm, and 900/1000 rpm.

As of 2009, the largest medium-speed engines in current production have outputs up to approximately 20 MW (27,000 hp) and are supplied by companies like MAN B&W, Wärtsilä,^[109] and Rolls-Royce (who acquired Ulstein Bergen Diesel in 1999). Most medium-speed engines produced are four-stroke machines, however there are some two-stroke medium-speed engines such as by EMD (Electro-Motive Diesel), and the Fairbanks Morse OP (Opposed-piston engine) type.

Typical cylinder bore size for medium-speed engines ranges from 20 cm to 50 cm, and engine configurations typically are offered ranging from in-line 4-cylinder units to V-configuration 20-cylinder units. Most larger medium-speed engines are started with compressed air direct on pistons, using an air distributor, as opposed to a pneumatic starting motor acting on the flywheel, which tends to be used for smaller engines. There is no definitive engine size cut-off point for this.

It should also be noted that most major manufacturers of medium-speed engines make natural gas-fueled versions of their diesel engines, which in fact operate on the Otto cycle, and require spark ignition, typically provided with a spark plug.^[110] There are also dual (diesel/natural gas/coal gas) fuel versions of medium and low speed diesel engines using a lean fuel air mixture and a small injection of diesel fuel (so-called "pilot fuel") for ignition. In case of a gas supply failure or maximum power demand these engines will instantly switch back to full diesel fuel operation.^{[110][111][112]}

Low-speed engines

Also known as *slow-speed*, or traditionally *oil engines*, the largest diesel engines are primarily used to power ships, although there are a few land-based power generation units as well. These extremely large two-stroke engines have power outputs up to approximately 85 MW (114,000 hp), operate in the range from approximately 60 to 200 rpm and are up to 15 m (50 ft) tall, and can weigh over 2,000 short tons (1,800 t). They typically use direct injection running on cheap low-grade heavy fuel, also known as bunker C fuel, which requires heating in the ship for tanking and before injection due to the fuel's high viscosity. Often, the waste heat recovery steam boilers attached to the engine exhaust ducting generate the heat required for fuel heating. Provided the heavy fuel system is kept warm and circulating, engines can be started and stopped on heavy fuel.

Large and medium marine engines are started with compressed air directly applied to the pistons. Air is applied to cylinders to start the engine forwards or backwards because they are normally directly connected to the propeller without clutch or gearbox, and to provide reverse propulsion either the engine must be run backwards or the ship will use an adjustable propeller. At least three cylinders are required with two-stroke engines and at least six cylinders with four-stroke engines to provide torque every 120 degrees.

Companies such as MAN B&W Diesel, and Wärtsilä design such large low-speed engines. They are unusually narrow and tall due to the addition of a crosshead bearing. As of 2007, the 14-cylinder Wärtsilä-Sulzer 14RTFLEX96-C turbocharged two-stroke diesel engine built by Wärtsilä licensee Doosan in Korea is the most powerful diesel engine put into service, with a cylinder bore of 960 mm (37.8 in) delivering 114,800 hp (85.6 MW). It was put into service in September 2006, aboard what was then the world's largest container ship *Emma Maersk* which belongs to the A.P. Moller-Maersk Group. Typical bore size for low-speed engines ranges from approximately 35 to 98 cm (14 to 39 in). As of 2008, all produced low-speed engines with crosshead bearings are in-line configurations; no Vee versions have been produced.

Low-speed diesel engines (as used in ships and other applications where overall engine weight is relatively unimportant) often have a thermal efficiency which exceeds 50%.^{[11][2]}

Current and future developments

As of 2008, many common rail and unit injection systems already employ new injectors using stacked piezoelectric wafers in lieu of a solenoid, giving finer control of the injection event.^[113]

Variable geometry turbochargers have flexible vanes, which move and let more air into the engine depending on load. This technology increases both performance and fuel economy. Boost lag is reduced as turbo impeller inertia is compensated for.^[114]

Accelerometer pilot control (APC) uses an accelerometer to provide feedback on the engine's level of noise and vibration and thus instruct the ECU to inject the minimum amount of fuel that will produce quiet combustion and still provide the required power (especially while idling).^[115]

The next generation of common rail diesels is expected to use variable injection geometry, which allows the amount of fuel injected to be varied over a wider range, and variable valve timing (see Mitsubishi's 4N13 diesel engine) similar to that of petrol engines. Particularly in the United States, coming tougher emissions regulations present a considerable challenge to diesel engine manufacturers. Ford's HyTrans Project has developed a system which starts the ignition in 400 ms, saving a significant amount of fuel on city routes, and there are other methods to achieve even more efficient combustion, such as homogeneous charge compression ignition, being studied.^{[116][117]}



A 1944 V12 2,300 kW power plant undergoing testing & restoration



The MAN B&W 5S50MC 5-cylinder, 2-stroke, low-speed marine diesel engine. This particular engine is found aboard a 29,000 tonne chemical carrier.

Japanese and Swedish vehicle manufacturers are also developing diesel engines that run on dimethyl ether (DME).^{[118][119]}

Some recent diesel engine models utilize a copper alloy heat exchanger technology (CuproBraz) to take advantage of benefits in terms of thermal performance, heat transfer efficiency, strength/durability, corrosion resistance, and reduced emissions from higher operating temperatures.

Low heat rejection engines

A special class of experimental prototype internal combustion piston engines has been developed over several decades with the goal of improving efficiency by reducing heat loss.^[120] These engines are variously called adiabatic engines; due to better approximation of adiabatic expansion; low heat rejection engines, or high temperature engines.^[121] They are generally piston engines with combustion chamber parts lined with ceramic thermal barrier coatings.^[122] Some make use of pistons and other parts made of titanium which has a low thermal conductivity^[123] and density. Some designs are able to eliminate the use of a cooling system and associated parasitic losses altogether.^[124] Developing lubricants able to withstand the higher temperatures involved has been a major barrier to commercialization.^[125]

See also

- Aircraft diesel engine
- Bore
- Carbureted compression ignition model engine
- Control theory
- Diesel locomotive
- Diesel automobile racing
- Diesel-electric transmission
- Diesel cycle
- Diesel generator
- Dieselisation
- Forced induction
- Gasoline direct injection
- Glow plug (model engine)
- Hesselman engine
- Hulsebos-Hesselman axial oil engines
- History of the internal combustion engine
- Hot bulb engine
- Hybrid power source
- Indirect injection
- Junkers Jumo 205—The more successful of the first series of production diesel aircraft engines.
- Napier Deltic—a high-speed, lightweight diesel engine used in fast naval craft and some diesel locomotives.
- Otto engine
- Partially premixed combustion
- Perkins Engines
- Petrol engine, petrol
- Relative cost of electricity generated by different sources
- Six-stroke engine—40% improved efficiency over 4-stroke by using wasted heat to generate steam.
- Stirling engine
- Stroke
- SVO—straight vegetable oil—alternative fuel for diesel engines.
- Turbocharger
- Wärtsilä-Sulzer RTA96-C—world's most powerful, most efficient and largest Diesel engine.
- WVO—waste vegetable oil—filtered, alternative fuel for diesel engines.

Notes

- ↑ In the 16-cylinder variant of EMD's 645F series, a Roots-blown engine could produce a maximum of 2,000 horsepower (1,500 kW). A turbocharged engine could produce up to 3,500 horsepower (2,600 kW)—a 75% increase—although the engine was not particularly reliable at this rating; however a 50% increase to 3,000 horsepower (2,200 kW) proved to be exceptionally reliable and most such examples are still operating today, some forty years after these were built.

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External links/recommended videos

- "The Diesel Story" 1952 documentary (<https://www.youtube.com/watch?v=U7CxoJhjHR4>) on YouTube
- "Introduction to Two Stroke Marine Diesel Engine" (<https://www.youtube.com/watch?v=DDLJgUaBpmM>) on YouTube
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