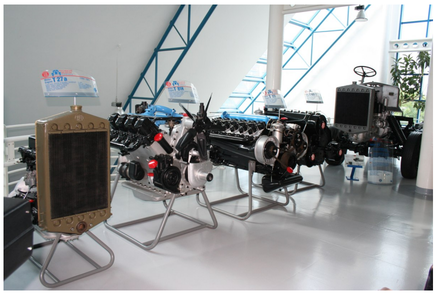
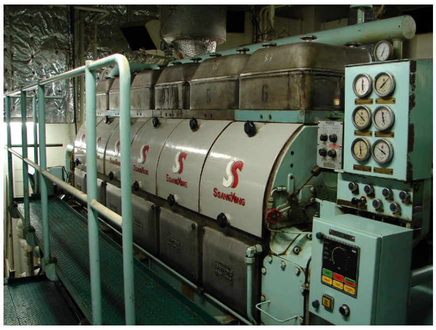
Diesel engine



Diesel engines in a museum

A **diesel engine** (also known as a **compression-ignition engine** and sometimes capitalized as **Diesel engine**) is an internal combustion engine that uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression. This is in contrast to spark-ignition engines such as a petrol engine (gasoline engine) or gas engine (using a gaseous fuel as opposed to gasoline), which uses a spark plug to ignite an air-fuel mixture. The diesel engine is modeled on the Diesel cycle. The engine and thermodynamic cycle were both developed by Rudolf Diesel in 1897.

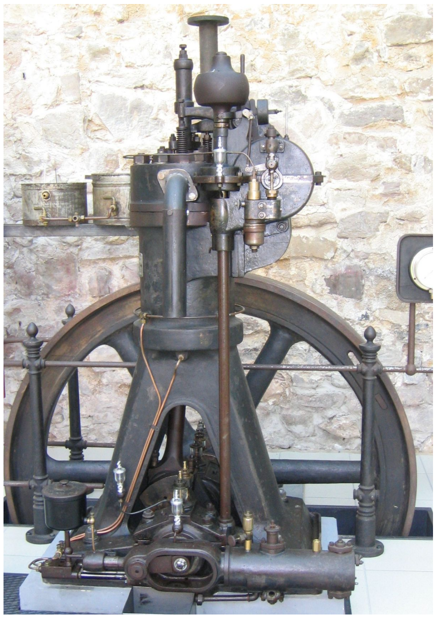


Diesel generator on an oil tanker

The diesel engine has the highest thermal efficiency of any regular internal or external combustion engine due to its very high compression ratio. 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 percent.[1] [2] [3] [4]

Diesel 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, large trucks and electric generating plants followed later. In the 1930s, they slowly began to be used in a few automobiles. Since the 1970s, the use of diesel engines in larger on-road and off-road vehicles in the USA increased. As of 2007, about 50 percent of all new car sales in Europe are diesel.[5]

The world's largest diesel engine is currently a Wärtsilä marine diesel of about 80 MW output.[6]



A diesel engine built by MAN AG in 1906

History

Rudolf Diesel, of German ethnicity, was born in 1858 in Paris where his parents were German immigrants.[7] He was educated at Munich Polytechnic. After graduation he was employed as a refrigerator engineer, but his true love lay in engine design. Diesel designed many heat engines, including a solar-powered air engine. In 1892 he received patents in Germany, Switzerland, the United Kingdom and filed in the United States for "Method of and Apparatus for Converting Heat into Work".[8] 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.[9] He operated his first successful engine in 1897.

His engine was the first to prove that fuel could be ignited without a spark.

Though best known for his invention of the pressure-ignited heat engine that bears his name, Rudolf Diesel was also a well-respected thermal engineer and a social theorist. Diesel's inventions have three points in common: they relate to heat transfer by natural physical processes or laws; they involve markedly creative mechanical design; and they were initially motivated by the inventor's concept of sociological needs. Rudolf Diesel originally conceived the diesel engine to enable independent craftsmen and artisans to compete with industry.[10]

At Augsburg, on August 10, 1893, Rudolf Diesel's prime model, a single 10-foot (3.0 m) iron cylinder with a flywheel at its base, ran on its own power for the first time. Diesel spent two more years making improvements and in 1896 demonstrated another model with a theoretical efficiency of 75 percent, in contrast to the 10 percent efficiency of the steam engine. 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.

History timeline

- 1892: February 23, Rudolf Diesel obtained a patent (RP 67207) titled "*Arbeitsverfahren und Ausführungsart für Verbrennungsmaschinen*".
- 1893: Diesel's essay titled *Theory and Construction of a Rational Heat-engine to Replace the Steam Engine and Combustion Engines Known Today* appeared.
- 1897: August 10, Diesel built his first working prototype in Augsburg.
- 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.
- 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: *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 Büchl (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.
- 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.[11]
- 1912: The Danish built the first ocean-going ship exclusively powered by a diesel engine, MS *Selandia*.[11] The first locomotive with a diesel engine also appeared.
- 1913: U.S. 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.
- 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 Mercedes-Benz agricultural tractor OE Benz Sendling.
- 1923: The first truck with diesel engine made by MAN, Benz and Daimler is tested.

- 1924: The introduction on the truck market of the diesel engine by commercial truck manufacturers in the IAA. Fairbanks-Morse starts building diesel engines.
- 1927: First truck injection pump and injection nozzles of Bosch. First passenger car prototype of Stoewer.
- 1930s: Caterpillar started building diesels for their tractors.
- 1930: First diesel-power passenger car (Cummins powered Packard) built in Columbus, Indiana (USA) [12]
- 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.[13] 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.
- 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. 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.

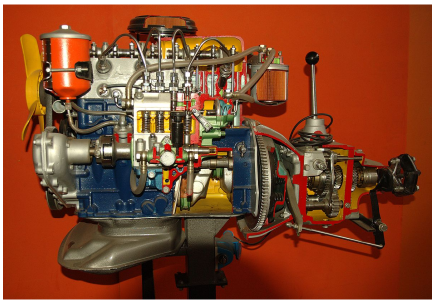

PATENT-URKUNDE
№ 67207
AUF GRUND DER ANGEHEFTETEN BESCHREIBUNG UND ZEICHNUNG IST DURCH BESCHLUSS DES KAISERLICHEN PATENTAMTES
an Rudolf Diesel, Ingenieur, in Berlin
EIN PATENT ERTHEILT WORDEN.
GEGENSTAND DES PATENTES IST:
Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen.
GESETZ v. 7. APRIL 1891
ANFANG DES PATENTES: 28. Februar 1892.
DIE RECHTE UND PFLICHTEN DES PATENTINHABERS SIND DURCH DAS PATENTGESETZ VOM 7. APRIL 1891 (REICHS-GESETZBLATT FÜR 1891 SEITE 79) BESTIMMT.
ZU URKUND DER ERTHEILUNG DES PATENTES IST DIESE AUSFERTIGUNG ERFOLGT.
Berlin, den 23. Februar 1893.
KAISERLICHES PATENTAMT.
Beglaubigt durch Frank
Bureau-Vorsteher des Kaiserlichen Patentamtes.

Rudolf Diesel's 1893 patent on his engine design

- 1937: The Soviet Union chose a diesel engine for its T-34 tank, widely regarded as the best tank chassis of World War II.
- 1937: BMW 114 experimental airplane diesel engine development.
- 1938: First turbo diesel engine of Saurer.
- 1943-'46: The Common-rail (CRD) system was invented (and patented by) Clessie Cummins [14]
- 1944: Development of air cooling for diesel engines by Klöckner Humboldt Deutz AG (KHD) for the production stage, and later also for Magirus Deutz.
- 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.[15]
- 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.[16]
- 1968: Peugeot introduced the first 204 small cars with a transversally mounted diesel engine and front-wheel drive.
- 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.
- 1977: Mercedes produced the first passenger car turbo-diesels (Mercedes 300 SD).
- 1985: ATI Intercooler diesel engine from DAF. European Truck Common Rail system with the IFA truck type W50 introduced.
- 1986: Electronic Diesel Control (EDC) of Bosch with the BMW 524tD.
- 1986: The Fiat Croma was the first passenger car in the world to have a direct injection turbodiesel engine in (1986).[17]

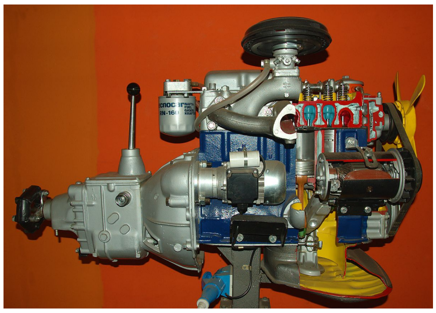
- 1987: Most powerful production truck with a 460 hp (340 kW) MAN diesel engine.
- 1991: European emission standards euro 1 met with the truck diesel engine of Scania.
- 1993: Pump nozzle injection introduced in Volvo truck engines.
- 1994: Unit injector system by Bosch for diesel engines.
- 1995: First successful use of common rail in a production vehicle, by Denso in Japan, Hino "Rising Ranger" truck.
- 1997: First common rail in passenger car, Alfa Romeo 156.
- 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.
- 1999: euro 3 of Scania and the first Common Rail truck diesel engine of Renault.
- 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).
- 2004: In Western Europe, the proportion of passenger cars with diesel engine exceeded 50 percent. Selective catalytic reduction (SCR) system in Mercedes, Euro 4 with EGR system and particle filters of MAN. Piezoelectric injector technology by Bosch.
- 2006: Audi R10 TDI won 12 hours running in Sebring and defeated all other engine concepts. Euro 5 for all Iveco trucks.
- 2006: JCB_Dieselmax broke the FIA Diesel Land speed record from 1973, eventually setting the new record at over 350mph.
- 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.
- 2009: Volvo claimed the world's strongest truck with their FH16 700. An inline 6 cylinder, 16 litre 700 hp (522 kW) diesel engine producing 3150 Nm (2323.32 lb•ft) of torque and fully complying with Euro 5 emission standards.[18]
- 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.[19] [20]
- 2010: Scania AB's V8 had the highest torque and power ratings of any truck engine: 3500 Nm and 730 hp.[21]

How diesel engines work


Diesel engine model, left side

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 22:1 resulting in 40-bar (4.0 MPa; 580 psi) pressure compared to 8 to 14 bars (0.80 to 1.4 MPa) (about 200 psi) in the petrol engine. This high compression heats the air to 550 °C (1022 °F). 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



Diesel engine model, right side

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. The start of vaporisation causes a delay period during ignition, and the characteristic diesel knocking sound as the vapor reaches ignition temperature and causes an abrupt increase in pressure above the piston. The rapid expansion of combustion gases then drives the piston downward, supplying power to the crankshaft.[22] Engines for scale-model aeroplanes use a variant of the Diesel principle but premix fuel and air via a carburation system external to the combustion chambers.

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 an issue and compression ratios are much higher.

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 three stage compressor used some power but the efficiency and net power output was more than any other combustion engine at that time.

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

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.[23] These systems use a combination of springs and weights to control fuel delivery relative to both load and speed.[23] 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 degrees 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.

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 elevated engine noise and increased oxides of nitrogen (NO_x) emissions 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.

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.[] Gasoline engines are typically 30 percent efficient while diesel engines can convert over 45 percent of the fuel energy into mechanical energy.[24] due to the increased strength of parts used. Diesel fuel has better lubrication properties than petrol as well.
- Diesel fuel is considered safer than petrol in many applications. Although diesel fuel will burn in open air using a wick, it will not explode and does not release a large amount of flammable vapor. 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.[25] [26] [27] [28]

Bus powered by **biodiesel**

- They generate less waste heat in cooling and exhaust.[]
- 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, therefore diesel engines are used in underground mines.[29]
- 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), making diesel engines the clearly preferred choice for sustainability.

Mechanical and electronic injection

Many configurations of fuel injection have been used over the past century (1901–2000).

Most present day (2008) diesel engines make use of a camshaft, rotating at half crankshaft speed, lifted mechanical single plunger high pressure fuel pump driven by the engine crankshaft. For each cylinder, its plunger measures the 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. For each cylinder a plunger pump is connected to an injector with a high pressure fuel line. 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.[30] Each fuel line should have the same length 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).[23] This contrasts with the more modern method of having 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. This design is also mechanically simpler than the combined pump and valve design, making it generally more reliable, and less noisy, than its mechanical counterpart.

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

Older diesel engines with mechanical injection pumps could be inadvertently run in reverse, albeit very inefficiently, as witnessed by massive amounts of soot being ejected from the air intake. This was often a consequence of push starting a vehicle using the wrong gear. Large ship diesels can run either way.

Indirect injection

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, called a pre-chamber or ante-chamber, where combustion begins and then spreads into the main combustion chamber, assisted by turbulence created in the chamber. This system allows for a smoother, quieter running engine, and because combustion is assisted by turbulence, injector pressures can be lower, about 100 bar (10 MPa; 1500 psi), using a single orifice tapered jet injector. Mechanical injection systems allowed high-speed running suitable for road vehicles (typically up to speeds of around 4,000 rpm). The pre-chamber had the disadvantage of increasing heat loss to the engine's cooling system, and restricting the combustion burn, which reduced the efficiency by 5–10 percent.[31] Indirect injection engines were used in small-capacity, high-speed diesel engines in automotive, marine and construction uses from the 1950s, until direct injection technology advanced in the 1980s. Indirect injection engines are cheaper to build and it is easier to produce smooth, quiet-running vehicles with a simple mechanical system. In road-going vehicles most prefer the greater efficiency and better controlled emission levels of direct injection. Indirect injection diesels can still be found in the many ATV diesel applications.

Direct injection

Modern diesel engines make use of one of the following direct injection methods:

Direct injection injectors are mounted in the top of the combustion chamber. The problem with these vehicles was the harsh noise they produced. Fuel consumption was about 15 to 20 percent lower than indirect injection diesels, which for some buyers was enough to compensate for the extra noise.

This type of engine was transformed by electronic control of the injection pump, pioneered by Fiat in 1986 (Croma). The injection pressure was still only around 300 bar (30 MPa; 4400 psi), but the injection timing, fuel quantity, EGR and turbo boost were all electronically controlled. This gave more precise control of these parameters which eased refinement and lowered emissions.

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 (CAT, Cummins, Detroit Diesel, Volvo). With recent advancements, the pump pressure has been raised to 2400 bar (240 MPa; 35000 psi),[32] allowing injection parameters similar to common rail systems.[33]

Common rail direct injection

In common rail systems, the separate pulsing high pressure fuel line to each cylinder's injector is also eliminated. Instead, a high-pressure pump pressurizes fuel at up to 2500 bar (250 MPa; 36000 psi),[34] 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

Starting

In cold weather, high speed diesel engines that are pre-chambered 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 therefore make use of small electric heaters inside the pre-chambers called glowplugs. These engines also generally have a higher compression ratio of 19:1 to 21:1. Low-speed and compressed-air-started larger and intermediate-speed diesels do not have glowplugs and compression ratios are around 16:1.

Some engines (e.g., some Cummins models) use resistive grid heaters in the intake manifold to warm the inlet air until the engine reaches operating temperature. Engine block heaters (electric resistive heaters in the engine block) connected to the utility grid are often used when an engine is turned off for extended periods (more than an hour) in cold weather to reduce startup time and engine wear. In the past, a wider variety of cold-start methods were used. Some engines, such as Detroit Diesel [35] engines and Lister-Petter engines, used a system to introduce small amounts of ether into the inlet manifold to start combustion. Saab-Scania marine engines, Field Marshall tractors (among others) used slow-burning solid-fuel 'cigarettes' which were fitted into the cylinder head as a primitive glow plug.

Lucas developed the *Thermostart*, where an electrical heating element was combined with a small fuel valve in the inlet manifold. Diesel fuel slowly dripped from the valve onto the hot element and ignited. The flame heated the inlet manifold and when the engine was cranked, the flame was drawn into the cylinders to start combustion.

International Harvester developed a tractor in the 1930s that had a 7-litre 4-cylinder engine which started as a gasoline engine and ran on diesel after warming up. The cylinder head had valves which opened for a portion of the compression stroke to reduce the effective compression ratio, and a magneto produced the spark. An automatic ratchet system automatically disengaged the ignition system and closed the valves once the engine had run for 30 seconds. The operator then switched off the petrol fuel system and opened the throttle on the diesel injection system.

Recent direct-injection systems are advanced to the extent that pre-chambers systems are not needed by using a common rail fuel system with electronic fuel injection.

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 should be used to run a vehicle.

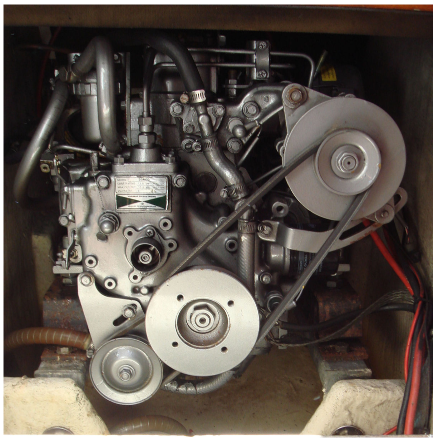
Types

Early

Rudolf Diesel intended his engine to replace the steam engine as the primary power source for industry. As such, diesel engines in the late 19th and early 20th centuries used the same basic layout and form as industrial steam engines, with long-bore cylinders, external valve gear, cross-head bearings and an open crankshaft connected to a large flywheel. Smaller engines would be built with vertical cylinders, while most medium- and large-sized industrial engines were built with horizontal cylinders, just as steam engines had been. Engines could be built with more than one cylinder in both cases. The largest early diesels resembled the triple-expansion steam reciprocating engine, being tens of feet high with vertical cylinders arranged in-line. These early engines ran at very slow speeds—partly due to the limitations of their air-blast injector equipment and partly so they would be compatible with the majority of industrial equipment designed for steam engines; maximum speeds of between 100 and 300 rpm were common. Engines were usually started by allowing compressed air into the cylinders to turn the engine, although smaller engines could be started by hand.[36]

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 manufactures 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 and was very efficient, 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



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

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.[37]

Two-stroke diesel 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 Detroit Diesel engine, in which the blower pressurizes a chamber in the engine block that is often referred to as the "air box". The (much larger) Electromotive prime mover used in EMD diesel-electric locomotives is built to the same principle.

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.[38] [39] 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, culminating in fuel injection and ignition. 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.[40] This system was derived from Raúl Pateras Pescara's work on free-piston engines in the 1930s.

Advantages and disadvantages versus spark-ignition engines

Power and fuel economy

The MAN S80ME-C7 low speed diesel engines use 155 gram fuel per kWh for an overall energy conversion efficiency of 54.4 percent, which is the highest conversion of fuel into power by any internal or external combustion engine.[] Diesel engines are more efficient than gasoline (petrol) engines of the same power rating, resulting in lower fuel consumption. A common margin is 40 percent 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 (38 miles per US gallon, 16 km/L) for the 102 bhp (76 kW) petrol engine and 4.4 L/100 km (54 mpg, 23 km/L) 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 percent 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. No vehicle has an unlimited volume available for fuel storage.

Adjusting the numbers to account for the energy density of diesel fuel, the overall energy efficiency is still about 20 percent 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).

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[41] and because it needs heavier, stronger parts to resist the operating pressure caused by the high compression ratio of the engine and the large amounts of torque generated to the crankshaft. In addition, diesels are often built with stronger parts to give them longer lives and better reliability, important considerations in industrial applications.

For most industrial or nautical applications, reliability is considered more important than light weight and high power. 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 delivery (by changing the duration of the injection pulse), and so operate with less waste of fuel. In a mechanical system, the injection timing 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 than what it is timed for. 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 engines usually have longer stroke lengths in order to achieve 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. The addition of a turbocharger or supercharger to the engine greatly assists in increasing fuel economy and power output, mitigating the fuel-air intake speed limit mentioned above for a given engine displacement. Boost pressures can be higher on diesels than on petrol engines, due to the latter's susceptibility to knock, and the higher compression ratio allows a diesel engine to be more efficient than a comparable spark ignition engine. Because the burned gases are expanded further in a diesel engine cylinder, the exhaust gas is cooler, meaning turbochargers require less cooling, and can be more reliable, than with spark-ignition engines.

With a diesel, boost pressure is essentially unlimited. It is literally possible to run as much boost as the engine will physically stand before breaking apart.

The increased fuel economy of the diesel engine over the petrol engine means that the diesel produces less carbon dioxide (CO_2) 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 CO_2, due to the absorption of CO_2 by plants used to produce the fuel. Although concerns are now being raised as to the negative effect this is having on the world food supply, as the growing of crops specifically for biofuels takes up land that could be used for food crops and uses water that could be used by both humans and animals. 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.

Diesel engines have a lower rotational speed than an equivalent size petrol engine because the diesel-air mixture burns slower than the petrol-air mixture. A combination of improved mechanical technology (such as multi-stage injectors which fire a short "pilot charge" of fuel into the cylinder to warm the combustion chamber 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 mitigated most of these problems in the latest generation of common-rail designs, while greatly improving engine efficiency. Poor power and narrow torque bands have been addressed by superchargers, turbochargers, (especially variable geometry turbochargers), intercoolers, and a large efficiency increase from about 35 percent for IDI to 45 percent for the latest engines in the last 15 years.

Even though diesel engines have a theoretical fuel efficiency of 75 percent, in practice it is lower. Engines in large diesel trucks, buses, and newer diesel cars can achieve peak efficiencies around 45 percent,[42] and could reach 55 percent efficiency in the near future.[43] However, average efficiency over a driving cycle is lower than peak efficiency. For example, it might be 37 percent for an engine with a peak efficiency of 44 percent.[44]

Emissions

In diesel engines, conditions in the engine differ from the spark-ignition engine, since power is directly controlled by the fuel supply, rather than by controlling the air supply. Thus when the engine runs at low power, there is enough oxygen present to burn the fuel, and diesel engines only make significant amounts of carbon monoxide when running under a load.

Diesel exhaust is well known for its characteristic smell; but in Britain this smell in recent years has become much less (while diesel fuel getting more expensive) because the sulfur is now removed from the fuel in the oil refinery.

Diesel exhaust has been found to contain a long list of toxic air contaminants. Among these pollutants, fine particle pollution is perhaps the most important as a cause of diesel's deleterious health effects.

Power and torque

For commercial uses requiring towing, load carrying and other tractive tasks, diesel engines tend to have better torque characteristics. Diesel engines tend to have their torque peak quite low in their speed range (usually between 1600 and 2000 rpm for a small-capacity unit, lower for a larger engine used in a truck). This provides smoother control over heavy loads when starting from rest, and, crucially, allows the diesel engine to be given higher loads at low speeds than a petrol engine, making them much more economical for these applications. This characteristic is not so desirable in private cars, so most modern diesels used in such vehicles use electronic control, variable geometry turbochargers and shorter piston strokes to achieve a wider spread of torque over the engine's speed range, typically peaking at around 2500–3000 rpm.

While diesel engines tend to have more torque at lower engine speeds than petrol engines, diesel engines tend to have a narrower power band than petrol engines. Naturally aspirated diesels tend to lack power and torque at the top of their speed range. This narrow band is a reason why a vehicle such as a truck may have a gearbox with as many as 18 or more gears, to allow the engine's power to be used effectively at all speeds. Turbochargers tend to improve power at high engine speeds; superchargers improve power at lower speeds; and variable geometry turbochargers improve the engine's performance equally by flattening the torque curve.

Noise

The characteristic noise of a diesel engine is variably called diesel clatter, diesel nailing, or diesel knock.[45] 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).[46] Common rail diesel injection systems permit multiple injection events as an aid to noise reduction. Diesel fuels with a higher cetane rating modify the combustion process and reduce diesel clatter.[45] 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. Some oil companies market high cetane or premium diesel. Biodiesel has a higher cetane number than petrodiesel, typically 55CN for 100% biodiesel.

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 mostly mitigated these problems in the latest generation of common-rail designs, while improving engine efficiency.

Reliability

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), a benefit that is magnified by the lower rotating speeds in diesels. Diesel fuel is a better lubricant than petrol so is less harmful to the oil film on piston rings and cylinder bores; it is routine for diesel engines to cover 250,000 miles (400,000 km) or more without a rebuild.

Due to the greater compression force required and the increased weight of the stronger components, starting a diesel engine is harder. More torque is required to push the engine through compression.

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 up, 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).

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. 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 pea-nut) 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.[47]

Most large marine diesels (often called *cathedral engines* due to their size) 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 be heated to thin it out (often by the exhaust header) and is often passed through multiple injection stages to vaporise it.

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.[48]

The type of fuel used is 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 has low flammability, leading to a low risk of fire caused by fuel in a vehicle equipped with a diesel engine.

In yachts diesels are used because petrol engines generate combustible vapors, which can accumulate in the bottom of the vessel, sometimes causing explosions. Therefore ventilation systems on petrol powered vessels are required.[49]

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[50] 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.)

Maintenance hazards

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 psi pressure.[51] The first known such injury occurred in 1937 during a diesel engine maintenance operation.[52]

Diesel applications

The characteristics of diesel have different advantages for different applications.

Passenger cars

Diesel engines have long been popular in bigger cars and this is spreading to smaller cars. 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% or more of all cars sold in Europe are diesel-powered where they are considered a low CO_2 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).

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 now replaced the diesel locomotive almost completely on 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 engines with no mechanical connection between diesel engine and traction.

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 U.S. following some 20 years later.

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 the First World War, 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.

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, with a purpose designed naturally aspirated direct injection diesel at Cranfield University in England, to be produced in the USA, 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.

Engine speeds

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

- High speed engines,
- medium speed engines, and
- slow speed engines

High and medium speed engines are predominantly four stroke engines. 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, and these engine are capable of utilising lower fuel grades (slower burning) fuels than high speed engines.

High-speed engines

High-speed (approximately 1,000 rpm and greater) engines are used to power trucks (wagons), 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.

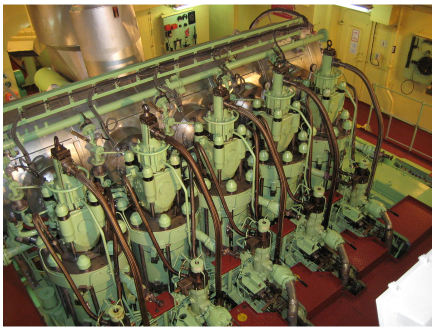
As of 2009, the largest medium speed engines in current production have outputs up to approximately 20 MW (27000 hp). and are supplied by companies like MAN B&W, Wärtsilä,[53] and Rolls-Royce (who acquired Ulstein Bergen Diesel in 1999). Most medium speed engines produced are four-stroke machines, however 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.[48] 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.[48] [54] [55]

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 (hp), operate in the range from approximately 60 to 200 rpm and are up to 15 m (50 ft) tall, and can weigh over 2000 short tons (1800 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. The heat for fuel heating is often provided by waste heat recovery boilers located in the exhaust ducting of the engine, which produce the steam required for fuel heating. Provided the heavy fuel system is kept warm and circulating, engines can be started and stopped on heavy fuel.



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.

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 utilise 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, (formerly Burmeister & Wain) and Wärtsilä (which acquired Sulzer Diesel) 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 114800 hp (85.6 MW). It was put into service in September 2006, aboard 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.

Supercharging and turbocharging

Most diesels are now turbocharged and some are both turbo charged and supercharged. Because diesels do not have fuel in the cylinder before combustion is initiated, more than one bar (100 kPa) of air can be loaded in the cylinder without preignition. A turbocharged engine can produce significantly more power than a naturally aspirated engine of the same configuration, as having more air in the cylinders allows more fuel to be burned and thus more power to be produced. A supercharger is powered mechanically by the engine's crankshaft, while a turbocharger is powered by the engine exhaust, not requiring any mechanical power. Turbocharging can improve the fuel economy[56] 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 an exhaust and intake stroke. These are performed when the piston is at the bottom of the cylinder. Therefore large two-stroke engines have a piston pump, or electrical driven turbo at startup. Smaller two stroke engines (for example, Detroit 71 series) are fitted with turbochargers and a mechanically driven supercharger. Because 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 diesels may use water, sea water, or oil supplied through telescoping pipes attached to the cross head.

Other applications

- Aircraft diesel engine
- Motorcycles

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.[57]

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.[58]

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).[59]

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 on 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.[60] [61]

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- They can deliver much more of their rated power on a continuous basis than a petrol engine.

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