Fuel injection

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Fuel injection is the introduction of fuel in an internal combustion engine, most commonly automotive engines, by the means of an injector.

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

All diesel engines use fuel injection by design. Petrol engines can use gasoline direct injection, where the fuel is directly delivered into the combustion chamber, or indirect injection where the fuel is mixed with air before the intake stroke.

On petrol engines, fuel injection replaced carburetors from the 1980s onward.[1] The primary difference between carburetors and fuel injection is that fuel injection atomizes the fuel through a small nozzle under high pressure, while a carburetor relies on suction created by intake air accelerated through a Venturi tube to draw the fuel into the airstream.

Contents

Objectives

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

- Power output
- Fuel efficiency
- Emissions performance
- Running on alternative fuels
- Reliability
- Driveability and smooth operation
- Initial cost
- Maintenance cost
- Diagnostic capability
- Range of environmental operation
- Engine tuning

Modern digital electronic fuel injection systems optimize these competing objectives more effectively and consistently than earlier fuel delivery systems (such as carburetors). Carburetors have the potential to atomize fuel better (see Pogue and Allen Caggiano patents).

Benefits

Benefits of fuel injection include smoother and more consistent transient throttle response, such as during quick throttle transitions, easier cold starting, more accurate adjustment to account for extremes of ambient temperatures and changes in air pressure, more stable idling, decreased maintenance needs, and better fuel efficiency.

Fuel injection also dispenses with the need for a separate mechanical choke, which on carburetor-equipped vehicles must be adjusted as the engine warms up to normal temperature. Furthermore, on spark ignition engines, (direct) fuel injection has the advantage of being able to facilitate stratified combustion which have not been possible with carburetors.

It is only with the advent of multi-point fuel injection certain engine configurations such as inline five cylinder gasoline engines have become more feasible for mass production, as traditional carburetor arrangement with single or twin carburetors could not provide even fuel distribution between cylinders, unless a more complicated individual carburetor per cylinder is used.

Fuel injection systems are also able to operate normally regardless of orientation, whereas carburetors with floats are not able to operate upside down or in zero gravity, such as encountered on airplanes.

Environmental benefits

Fuel injection generally increases engine fuel efficiency. With the improved cylinder-to-cylinder fuel distribution of multi-point fuel injection, less fuel is needed for the same power output (when cylinder-to-cylinder distribution varies significantly, some cylinders receive excess fuel as a side effect of ensuring that all cylinders receive *sufficient* fuel).

Exhaust emissions are cleaner because the more precise and accurate fuel metering reduces the concentration of toxic combustion byproducts leaving the engine. The more consistent and predictable composition of the exhaust makes emissions control devices such as catalytic converters more effective and easier to design.

History and development

Herbert Akroyd Stuart developed the first device with a design similar to modern fuel injection, using a 'jerk pump' to meter out fuel oil at high pressure to an injector. This system was used on the hot-bulb engine and was adapted and improved by Bosch and Clessie Cummins for use on diesel engines (Rudolf Diesel's original system employed a cumbersome 'air-blast' system using highly compressed air). Fuel injection was in widespread commercial use in diesel engines by the mid-1920s.

An early use of indirect gasoline injection dates back to 1902, when French aviation engineer Leon Levavasseur installed it on his pioneering Antoinette 8V aircraft powerplant, the first V8 engine of any type ever produced in any quantity.[2]

Another early use of gasoline direct injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925.[3][4] Hesselman engines use the ultra lean-burn principle; fuel is injected toward the end of the compression stroke, then ignited with a spark plug. They are often started on gasoline and then switched to diesel or kerosene.[5]

Direct fuel injection was used in notable World War II aero-engines such as the Junkers Jumo 210, the Daimler-Benz DB 601, the BMW 801, the Shvetsov ASh-82FN (M-82FN). German direct injection petrol engines used injection systems developed by Bosch from their diesel injection systems. Later versions of the Rolls-Royce Merlin and Wright R-3350 used single point fuel injection, at the time called "Pressure Carburettor". Due to the wartime relationship between Germany and Japan, Mitsubishi also had two radial aircraft engines utilizing fuel injection, the Mitsubishi Kinsei (*kinsei* means "venus") and the Mitsubishi Kasei (*kasei* means "mars").

Alfa Romeo tested one of the first **electronic** injection systems (Caproni-Fuscaldo) in Alfa Romeo 6C 2500 with "Ala spessa" body in 1940 Mille Miglia. The engine had six electrically operated injectors and were fed by a semi-high-pressure circulating fuel pump system.[6]

Development in diesel engines

All diesel engines (with the exception of some tractors and scale model engines) have fuel injected into the combustion chamber. See Diesel engine.

Development in gasoline/petrol engines

Mechanical injection

The invention of mechanical injection for gasoline-fueled aviation engines was by the French inventor of the V8 engine configuration, Leon Levavasseur in 1902.[2] Levavasseur designed the original Antoinette firm's series of V-form aircraft engines, starting with the Antoinette 8V to be used by the aircraft the Antoinette firm built that Levavasseur also designed, flown from 1906 to the firm's demise in 1910, with the world's first V16 engine, using Levavasseur's direct injection and producing around 100 hp (75 kW; 101 PS) flying an Antoinette VII monoplane in 1907.

An Antoinette mechanically fuel-injected V8 aviation engine of 1909, mounted in a preserved Antoinette VII monoplane aircraft.

The first post-World War I example of direct gasoline injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925.[7][8] Hesselman engines used the ultra-lean-burn principle and injected the fuel in the end of the compression stroke and then ignited it with a spark plug, it was often started on gasoline and then switched over to run on diesel or kerosene. The Hesselman engine was a low compression design constructed to run on heavy fuel oils.

Direct gasoline injection was applied during the Second World War to almost all higher-output production aircraft powerplants made in Germany (the widely used BMW 801 radial, and the popular inverted inline V12 Daimler-Benz DB 601, DB 603, and DB 605, along with the similar Junkers Jumo 210G, Jumo 211, and Jumo 213, starting as early as 1937 for both the Jumo 210G and DB 601), the Soviet Union (Shvetsov ASh-82FN radial, 1943, Chemical Automatics Design Bureau - KB Khimavtomatika) and the USA (Wright R-3350 *Duplex Cyclone* radial, 1944).

Immediately following the war, hot rodder Stuart Hilborn started to offer mechanical injection for race cars, salt cars, and midget racers,[9] well-known and easily distinguishable because of their prominent velocity stacks projecting upwards from the engines on which they were used.

The first automotive direct injection system used to run on gasoline was developed by Bosch, and was introduced by Goliath for their Goliath GP700 automobile, and Gutbrod in 1952. This was basically a high-pressure diesel direct-injection pump with an intake throttle valve. (Diesels only change the amount of fuel injected to vary output; there is no throttle.) This system used a normal gasoline fuel pump, to provide fuel to a mechanically driven injection pump, which had separate plungers per injector to deliver a very high injection pressure directly into the combustion chamber. The 1954 Mercedes-Benz W196 Formula 1 racing car engine used Bosch direct injection derived from wartime aircraft engines. Following this racetrack success, the 1955 Mercedes-Benz 300SL, the first production sports car to use fuel injection, used direct injection. The 1955 Mercedes-Benz 300SLR, in which Stirling Moss drove to victory in the 1955 Mille Miglia and Pierre Levegh crashed and died in the 1955 Le Mans disaster, had an engine developed from the W196 engine. The Bosch fuel injectors were placed into the bores on the cylinder wall used by the spark plugs in other Mercedes-Benz six-cylinder engines (the spark plugs were relocated to the cylinder head). Later, more mainstream applications of fuel injection favored the less-expensive indirect injection methods.


A 1959 Corvette small-block 4.6 litre V8 with Rochester mechanical fuel injection

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

In 1956, Lucas developed its injection system, which was first used for Jaguar racing cars at Le Mans. The system was subsequently adopted very successfully in Formula One racing, securing championships by Cooper, BRM, Lotus, Brabham, Matra, and Tyrrell in the years 1959 through 1973.[10] While the racing systems used a simple *fuel cam* for metering, a more sophisticated *Mk 2* vacuum based *shuttle metering* was developed for production cars. This mechanical system was used by some Maserati, Aston Martin, and Triumph models between 1963 and 1975.[11]

During the 1960s, other mechanical injection systems such as Hilborn were occasionally used on modified American V8 engines in various racing applications such as drag racing, oval racing, and road racing.[12] These racing-derived systems were not suitable for everyday street use, having no provisions for low speed metering, or often none even for starting (starting required that fuel be squirted into the injector tubes while cranking the engine). However, they were a favorite in the aforementioned competition trials in which essentially wide-open throttle operation was prevalent. Constant-flow injection systems continue to be used at the highest levels of drag racing, where full-throttle, high-RPM performance is key.[13]

In 1967, one of the first Japanese designed cars to use mechanical fuel injection was the Daihatsu Compagno.

Another mechanical system, made by Bosch called Jetronic, but injecting the fuel into the port above the intake valve, was used by several European car makers, particularly Porsche from 1969 until 1973 in the 911 production range and until 1975 on the Carrera 3.0 in Europe. Porsche continued using this system on its racing cars into the late seventies and early eighties. Porsche racing variants such as the 911 RSR 2.7 & 3.0, 904/6, 906, 907, 908, 910, 917 (in its regular normally aspirated or 5.5 Liter/1500 HP turbocharged form), and 935 all used Bosch or Kugelfischer built variants of injection. The early Bosch Jetronic systems were also used by Audi, Volvo, BMW, Volkswagen, and many others. The Kugelfischer system was also used by the BMW 2000/2002 Tii and some versions of the Peugeot 404/504 and Lancia Flavia.

A system similar to the Bosch inline mechanical pump was built by SPICA for Alfa Romeo, used on the Alfa Romeo Montreal and on U.S. market 1750 and 2000 models from 1969 to 1981. This was designed to meet the U.S. emission requirements with no loss in performance and it also reduced fuel consumption.

Electronic injection

The first commercial electronic fuel injection (EFI) system was Electrojector, developed by the Bendix Corporation and was offered by American Motors Corporation (AMC) in 1957.[14][15] The Rambler Rebel, showcased AMC's new 327 cu in (5.4 L) engine. The Electrojector was an option and rated at 288 bhp (214.8 kW).[16] The EFI produced peak torque 500 rpm lower than the equivalent carburetored engine[12] The Rebel Owners Manual described the design and operation of the new system.[17] (due to cooler, therefore denser, intake air). The cost of the EFI option was US$395 and it was available on 15 June 1957.[18] Electrojector's teething problems meant only pre-production cars were so equipped: thus, very few cars so equipped were ever sold[19] and none were made available to the public.[20] The EFI system in the Rambler ran fine in warm weather, but suffered hard starting in cooler temperatures.[18]

Chrysler offered Electrojector on the 1958 Chrysler 300D, DeSoto Adventurer, Dodge D-500, and Plymouth Fury, arguably the first series-production cars equipped with an EFI system. It was jointly engineered by Chrysler and Bendix. The early electronic components were not equal to the rigors of underhood service, however, and were too slow to keep up with the demands of "on the fly" engine control. Most of the 35 vehicles originally so equipped were field-retrofitted with 4-barrel carburetors. The Electrojector patents were subsequently sold to Bosch.

Bosch developed an electronic fuel injection system, called *D-Jetronic* (*D* for *Druck*, German for "pressure"), which was first used on the VW 1600TL/E in 1967. This was a speed/density system, using engine speed and intake manifold air density to calculate "air mass" flow rate and thus fuel requirements. This system was adopted by VW, Mercedes-Benz, Porsche, Citroën, Saab, and Volvo. Lucas licensed the system for production in Jaguar cars, initially in D-Jetronic form before switching to L-Jetronic in 1978 on the XK6 engine.

Bosch superseded the D-Jetronic system with the *K-Jetronic* and *L-Jetronic* systems for 1974, though some cars (such as the Volvo 164) continued using D-Jetronic for the following several years. In 1970, the Isuzu 117 Coupé was introduced with a Bosch-supplied D-Jetronic fuel injected engine sold only in Japan. In 1984 Rover fitted Lucas electronic fuel injection, which was based on some L-Jetronic patents, to the S-Series engine as used in the 200 model.

Chevrolet Cosworth Vega engine showing Bendix electronic fuel injection (in orange).

In Japan, the Toyota Celica used electronic, multi-port fuel injection in the optional 18R-E engine in January 1974.[21] Nissan offered electronic, multi-port fuel injection in 1975 with the Bosch L-Jetronic system used in the Nissan L28E engine and installed in the Nissan Fairlady Z, Nissan Cedric, and the Nissan Gloria. Nissan also installed multi-point fuel injection in the Nissan Y44 V8 engine in the Nissan President. Toyota soon followed with the same technology in 1978 on the 4M-E engine installed in the Toyota Crown, the Toyota Supra, and the Toyota Mark II. In the 1980s, the Isuzu Piazza and the Mitsubishi Starion added fuel injection as standard equipment, developed separately with both companies history of diesel powered engines. 1981 saw Mazda offer fuel injection in the Mazda Luce with the Mazda FE engine and, in 1983, Subaru offered fuel injection in the Subaru EA81 engine installed in the Subaru Leone. Honda followed in 1984 with their own system, called PGM-FI in the Honda Accord, and the Honda Vigor using the Honda ES3 engine.

The limited production Chevrolet Cosworth Vega was introduced in March 1975 using a Bendix EFI system with pulse-time manifold injection, four injector valves, an electronic control unit (ECU), five independent sensors, and two fuel pumps. The EFI system was developed to satisfy stringent emission control requirements and market demands for a technologically advanced responsive vehicle. 5000 hand-built Cosworth Vega engines were produced but only 3,508 cars were sold through 1976.[22]

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

In 1980, Motorola (now NXP Semiconductors) introduced the first electronic engine control unit, the EEC-III.[23] Its integrated control of engine functions (such as fuel injection and spark timing) is now the standard approach for fuel injection systems. The Motorola technology was installed in Ford North American products.

Elimination of carburetors

In the 1970s and 1980s in the U.S. and Japan, the respective federal governments imposed increasingly strict exhaust emission regulations. During that time period, the vast majority of gasoline-fueled automobile and light truck engines did not use fuel injection. To comply with the new regulations, automobile manufacturers often made extensive and complex modifications to the engine carburetor(s). While a simple carburetor system is cheaper to manufacture than a fuel injection system, the more complex carburetor systems installed on many engines in the 1970s were much more costly than the earlier simple carburetors. To more easily comply with emissions regulations, automobile manufacturers began installing fuel injection systems in more gasoline engines during the late 1970s.

Open-loop fuel injection systems had already improved cylinder-to-cylinder fuel distribution and engine operation over a wide temperature range, but did not offer further scope to sufficient control fuel/air mixtures, in order to further reduce exhaust emissions. Later closed-loop fuel injection systems improved the air–fuel mixture control with an exhaust gas oxygen sensor. Although not part of the injection control, a catalytic converter further reduces exhaust emissions.

Fuel injection was phased in through the latter 1970s and 80s at an accelerating rate, with the German, French, and U.S. markets leading and the UK and Commonwealth markets lagging somewhat. Since the early 1990s, almost all gasoline passenger cars sold in first world markets are equipped with electronic fuel injection (EFI). The carburetor remains in use in developing countries where vehicle emissions are unregulated and diagnostic and repair infrastructure is sparse. Fuel injection is gradually replacing carburetors in these nations too as they adopt emission regulations conceptually similar to those in force in Europe, Japan, Australia, and North America.

Many motorcycles still utilize carburetored engines, though all current high-performance designs have switched to EFI.

NASCAR finally replaced carburetors with fuel-injection, starting at the beginning of the 2012 NASCAR Sprint Cup Series season.[24][25][26]

System components

System overview

The process of determining the necessary amount of fuel, and its delivery into the engine, are known as fuel metering. Early injection systems used mechanical methods to meter fuel, while nearly all modern systems use electronic metering.

Determining how much fuel to supply

The primary factor used in determining the amount of fuel required by the engine is the amount (by weight) of air that is being taken in by the engine for use in combustion. Modern systems use a mass airflow sensor to send this information to the engine control unit.

Data representing the amount of power output desired by the driver (sometimes known as "engine load") is also used by the engine control unit in calculating the amount of fuel required. A throttle position sensor (TPS) provides this information. Other engine sensors used in EFI systems include a coolant temperature sensor, a camshaft or crankshaft position sensor (some systems get the position information from the distributor), and an oxygen sensor which is installed in the exhaust system so that it can be used to determine how well the fuel has been combusted, therefore allowing closed loop operation.

Supplying the fuel to the engine

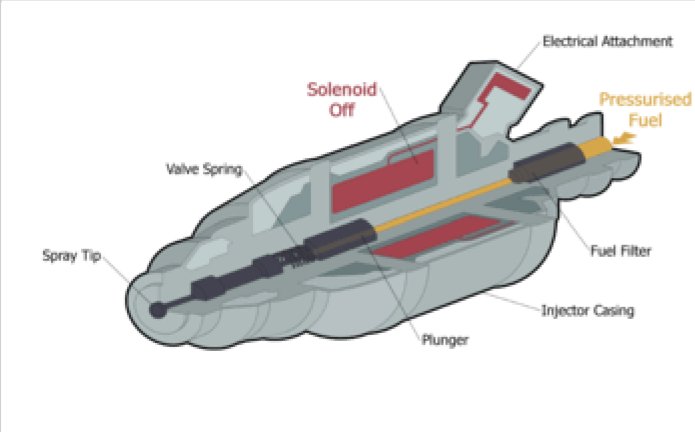
Fuel is transported from the fuel tank (via fuel lines) and pressurised using fuel pump(s). Maintaining the correct fuel pressure is done by a fuel pressure regulator. Often a fuel rail is used to divide the fuel supply into the required number of cylinders. The fuel injector injects liquid fuel into the intake air (the location of the fuel injector varies between systems).

Unlike carburetor-based systems, where the float chamber provides a reservoir, fuel injected systems depend on an uninterrupted flow of fuel. To avoid fuel starvation when subject to lateral G-forces, vehicles are often provided by an anti-surge vessel, usually integrated in the fuel tank, but sometimes as a separate, small anti-surge tank.

EFI gasoline engine components

These examples specifically apply to a modern EFI gasoline engine. Parallels to fuels other than gasoline can be made, but only conceptually.

- Injectors
- Fuel Pump
- Fuel Pressure Regulator
- Engine control unit
- Wiring Harness
- Various Sensors (Some of the sensors required are listed here.)
  - Crank/Cam Position: Hall effect sensor
  - Airflow: MAF sensor, sometimes this is inferred with a MAP sensor
  - Exhaust Gas Oxygen: oxygen sensor, EGO sensor, UEGO sensor



Animated cut through diagram of a typical fuel injector. Click to see animation.

Engine control unit

The engine control unit is central to an EFI system. The ECU interprets data from input sensors to, among other tasks, calculate the appropriate amount of fuel to inject.

Fuel injector

When signaled by the engine control unit the fuel injector opens and sprays the pressurised fuel into the engine. The duration that the injector is open (called the pulse width) is proportional to the amount of fuel delivered. Depending on the system design, the timing of when injector opens is either relative each individual cylinder (for a sequential fuel injection system), or injectors for multiple cylinders may be signalled to open at the same time (in a batch fire system).

Target air–fuel ratios

The relative proportions of air and fuel vary according to the type of fuel used and the performance requirements (i.e. power, fuel economy, or exhaust emissions).

See Air–fuel ratio, Stoichiometry, and Combustion.

Various injection schemes

Single-point injection

Single-point injection (SPI) uses a single injector at the throttle body (the same location as was used by carburetors).

It was introduced in the 1940s in large aircraft engines (then called the pressure carburetor) and in the 1980s in the automotive world (called Throttle-body Injection by General Motors, Central Fuel Injection by Ford, PGM-CARB by Honda, and EGI by Mazda). Since the fuel passes through the intake runners (like a carburetor system), it is called a "wet manifold system".

The justification for single-point injection was low cost. Many of the carburetor's supporting components - such as the air cleaner, intake manifold, and fuel line routing - could be reused. This postponed the redesign and tooling costs of these components. Single-point injection was used extensively on American-made passenger cars and light trucks during 1980-1995, and in some European cars in the early and mid-1990s.

Continuous injection

In a continuous injection system, fuel flows at all times from the fuel injectors, but at a variable flow rate. This is in contrast to most fuel injection systems, which provide fuel during short pulses of varying duration, with a constant rate of flow during each pulse. Continuous injection systems can be multi-point or single-point, but not direct.

The most common automotive continuous injection system is Bosch's K-Jetronic, introduced in 1974. K-Jetronic was used for many years between 1974 and the mid-1990s by BMW, Lamborghini, Ferrari, Mercedes-Benz, Volkswagen, Ford, Porsche, Audi, Saab, DeLorean, and Volvo. Chrysler used a continuous fuel injection system on the 1981-1983 Imperial.

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

Central port injection

From 1992 to 1996 General Motors implemented a system called Central Port Injection or Central Port Fuel Injection. The system uses tubes with poppet valves from a central injector to spray fuel at each intake port rather than the central throttle-body. Fuel pressure is similar to a single-point injection system. CPFI (used from 1992 to 1995) is a batch-fire system, while CSFI (from 1996) is a sequential system.[27]

Multipoint fuel injection

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

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

Direct injection

In a direct injection engine, fuel is injected into the combustion chamber as opposed to injection before the intake valve (petrol engine) or a separate pre-combustion chamber (diesel engine).[28]

In a common rail system, the fuel from the fuel tank is supplied to the common header (called the accumulator). This fuel is then sent through tubing to the injectors, which inject it into the combustion chamber. The header has a high pressure relief valve to maintain the pressure in the header and return the excess fuel to the fuel tank. The fuel is sprayed with the help of a nozzle that is opened and closed with a needle valve, operated with a solenoid. When the solenoid is not activated, the spring forces the needle valve into the nozzle passage and prevents the injection of fuel into the cylinder. The solenoid lifts the needle valve from the valve seat, and fuel under pressure is sent in the engine cylinder. Third-generation common rail diesels use piezoelectric injectors for increased precision, with fuel pressures up to 1,800 bar or 26,000 psi.

Direct fuel injection costs more than indirect injection systems: the injectors are exposed to more heat and pressure, so more costly materials and higher-precision electronic management systems are required.

Diesel engines

Most diesel engines (with the exception of some tractors and scale model engines) have fuel injected into the combustion chamber.

Earlier systems, relying on simpler injectors, often injected into a sub-chamber shaped to swirl the compressed air and improve combustion; this was known as indirect injection. However, this was less efficient than the now common direct injection in which initiation of combustion takes place in a depression (often toroidal) in the crown of the piston.

Throughout the early history of diesels, they were always fed by a mechanical pump with a small separate chamber for each cylinder, feeding separate fuel lines and individual injectors. Most such pumps were in-line, though some were rotary.

Most modern diesel engines use common rail or unit injector direct injection systems.

Gasoline engines

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

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

Swirl injection

Swirl injectors are used in liquid rocket, gas turbine, and diesel engines to improve atomization and mixing efficiency.

The circumferential velocity component is first generated as the propellant enters through helical or tangential inlets producing a thin, swirling liquid sheet. A gas-filled hollow core is then formed along the centerline inside the injector due to centrifugal force of the liquid sheet. Because of the presence of the gas core, the discharge coefficient is generally low. In swirl injector, the spray cone angle is controlled by the ratio of the circumferential velocity to the axial velocity and is generally wide compared with nonswirl injectors.[29]

Maintenance hazards

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 psi (6.9 bar) pressure.[30] The first known such injury occurred in 1937 during a diesel engine maintenance operation.[31]

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Further reading

Patents

- U.S. Patent 3,430,616 (https://www.google.com/patents/US3430616) — *Fuel Injection Control System* — Otto Glöckler, et al.
- U.S. Patent 3,500,801 (https://www.google.com/patents/US3500801) — *Actuator Circuit for Electronic Precision Fuel Metering Systems* — E. David Long and Keith C. Richardson
- U.S. Patent 3,504,657 (https://www.google.com/patents/US3504657) — *Cold Start Fuel Enrichment* — Dieter Eichler, et al.
- U.S. Patent 3,548,791 (https://www.google.com/patents/US3548791) — *Precision Fuel Metering ...* — E. David Long
- U.S. Patent 4,069,795 (https://www.google.com/patents/US4069795) — *Start-up Control for Fuel Injection System* — E. David Long and Keith C. Richardson

External links

- History of the D Jetronic system (http://members.rennlist.com/pbanders/djetfund.htm)
- How Fuel Injection Systems Work (http://auto.howstuffworks.com/fuel-injection.htm)