ThermoGuard Instruments

Tech Talk

Issue No.4

Diesel Fuel Injection:

Pumps and Injectors

This is the fourth in what is intended to be a series of short articles discussing various diesel engine technical issues. This article discusses fuel injection in diesels and describes common injection pumps and injectors. [This information is presented for the interest of the reader only. The author accepts no responsibility for any adverse outcomes which may result from the reader using all or any of the information presented in practical applications.]

Fuel Injection

For drivers of petrol/gasoline-engined vehicles (spark ignition [SI] engines), fuel injection is a relatively new innovation. Only in the last decade or so has fuel injection become the norm and its predecessor, the humble carburettor, seems destined to the scrap heap of automotive history. Diesel (compression ignition [CI]) engines, on the other hand, have always used fuel injection, since the days of Rudolf Diesel himself.

So, what is Fuel Injection? Well, it describes the way the fuel (usually a liquid fuel) is injected (pumped under pressure) into some part of the engine where it can combine with the air charge in the cylinders and combustion can take place, releasing energy to propel the vehicle.

What's different about diesel [CI] engine injection?

Diesel (compression ignition or CI) and petrol/gasoline (spark ignition or SI) engines go about the task of releasing energy from their fuels in quite different ways. For more information on this topic see our Why Diesels are Different article.

In fuel-injected spark ignition [SI] engines, fuel is always injected into the air charge well before ignition takes place. This necessary because the liquid or gaseous fuel must be thoroughly mixed together with air into a combustible mixture, able to be ignited by the electrical arc generated by the sparkplug. If the ratio of air to fuel is not reasonably close to 15:1 in the vicinity of the sparkplug, the mixture will not ignite at all and a miss-fire results.

Compression ignition [CI] engines always inject the fuel charge directly into a combustion chamber in the engine. Fuel injection and ignition are inextricably tied together in compression ignition [CI] engines. Recall that CI engines only work because they compress the air charge so that it is hot enough to instantly ignite the fuel charge *as it is being injected.* The combustion of the fuel begins at the instant it begins being injected (well, within a couple of milliseconds, if you want to split hairs) into the combustion chamber full of very hot air (more than 400 ºC, often over 700 ºC).

This means the timing of ignition is intimately tied to the fuel injection process. So, the fuel injection system of a CI engine is responsible for regulating both the quantity of fuel to be injected and timing of the beginning of combustion. Many ingenious techniques have been developed to achieve both these tasks with admirable accuracy, long before the advent of sophisticated electronic controls.

How much fuel?

So, how much fuel are we injecting here? Well, let's do a few simple sums based on my 1997 Land Rover Discovery. It has a 4 cylinder 2.5 litre engine. At 100 km/h in 5th gear it's doing very close to 2400 rpm or 2400/60 = 40 revolutions per second. Because it's a 4 cylinder 4 stroke engine, it will be producing 2 power strokes every revolution, so that's 80 power strokes per second.

At a steady cruising speed of 100 km/h, it is likely to be covering 10 km/litre or, in other words, using 10 litres/100 km. Therefore, our fuel burn rate is 10 litres per hour or 10/3600 = 0.00278 litres per second = 2.78 mL/sec.

Now, this 2.78 mL is shared between the 80 power strokes of the engine per second. So, for each power stroke of the engine while we are cruising at 100 km/h, the fuel injection system is delivering 2.78/80 = 0.03472 mL into each cylinder. Not much is it? And the injection system delivers *precisely* this quantity of fuel to one of the cylinders of the engine, 80 times per second and at the *exact instant* the cylinder needs to fire. Not bad for a completely mechanical system with no electronic "smarts" at all, is it?

How much pressure?

SI engine (petrol/gasoline) injection systems typically run at pressure of 2 to 3 bar (30 to 40 psi). In contrast CI (diesel) engines employ injection pressures of at least 350 bar (~5000 psi) and possibly in excess of 2000 bar (>29,000 psi) – quite a bit different to petrol/gasoline systems! This explains why CI injection systems are so solidly built and piped-up with strong steel tubing, etc.

Petrol/gasoline readily vaporises in the air stream entering the engine's cylinders and in contact with the hot cylinder head surfaces, to form an easily ignitable air/vapour mixture. On the other hand, to instantly ignite the much less volatile diesel fuel in the hot air charge of a CI engine it is necessary to spray it into the combustion chamber in extremely small droplets. And to achieve this, extremely high injection pressures are required – the higher the better, in general.

Injectors and Pumps

We now know we need to pump a spray of fuel under high pressure into the combustion chambers of our CI engine. So what equipment do we need to achieve this? Generally we would use at least one high-pressure *pump* and a device called an *injector* for each cylinder of the engine.

The first Diesel Injection Pump for cars, produced by Bosch in

CI engine injectors come in a myriad of sizes, shapes and designs but all have at their end a specialised nozzle through which the fuel is sprayed. Even nozzles designs may be one of very many types, but they all aim to achieve a uniform, very fine spray of fuel when they operate and to stop and start that spray instantly, with minimal leakage or 'dribble'. Usually this is performed by a finely machined 'needle' which uncovers and covers the tiny orifices through which the fuel is forced at very high pressure.

Typical modern Injection Nozzle

More modern injectors are two-spring types. In these, the needle opens a small amount at a lower pressure and then fully at a higher pressure. This gives a 'softer' start to combustion and a reduction in the typical diesel 'rattle' at idle and part-throttle.

The precision and accuracy of modern high-pressure injectors is truly mind-boggling. They are manufactured under super clean conditions to avoid any contamination. If you were to pull the needle out of a modern injector nozzle with your fingers, have a brief look at it and then put it back, you could then throw that hundred dollars or so worth of nozzle into the rubbish bin. The minute amounts of body oil and acid on your skin would have marred the surface of the needle enough to make it inoperable! That is why diesel specialists are always stressing the importance of maintaining clean fuel filters!

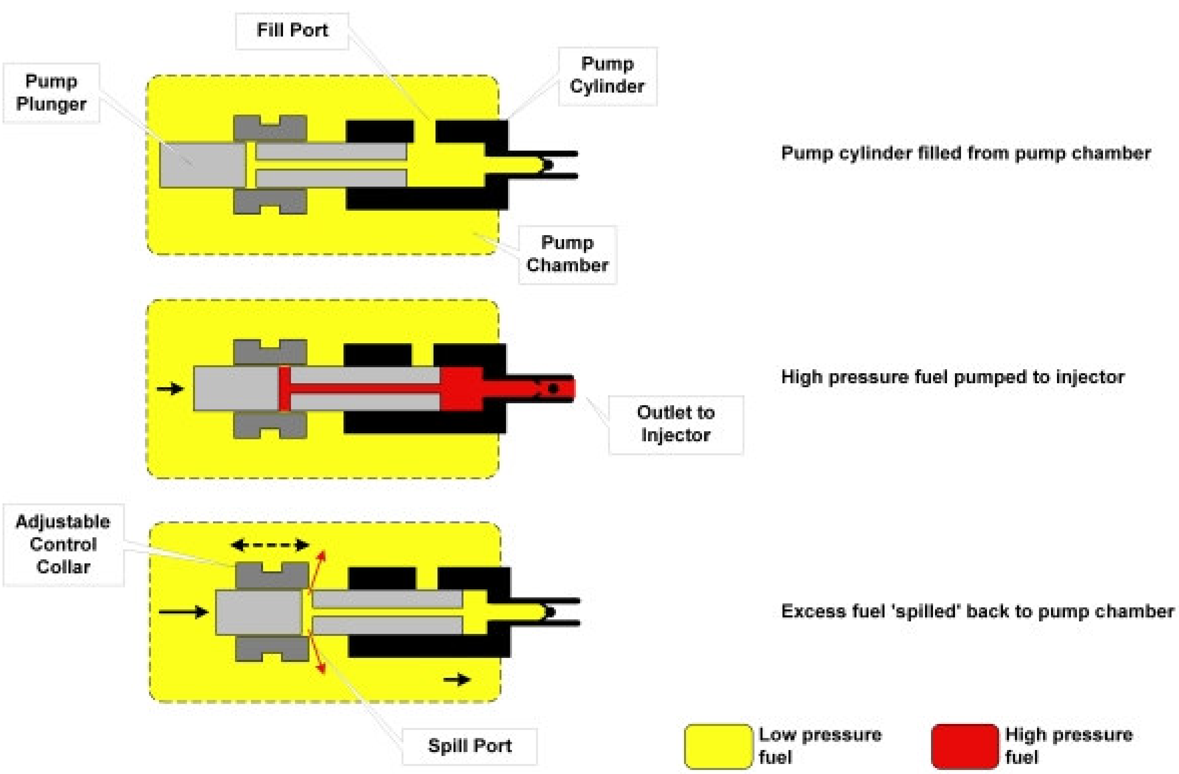
The high-pressure pumps also come in a wide variety of designs but again, they all have a common aim: to generate a precisely metered high-pressure pulse of fuel and deliver it to the right cylinder injector at the right time. Further, as requirements for performance (kW/Litre of engine capacity) and emission control increase, CI injections systems are constantly evolving to produce ever higher injection pressures.

Piston/Plunger Pump systems

All mechanical and many electronically-controlled CI injection systems use a piston or plunger pump. These are a type of positive displacement pump, in which a plunger slides in a cylinder to push a volume of fuel out of the pump to an injector, just like, say, a hypodermic syringe.

Now a fixed size of plunger and pump will always pump the same volume of liquid with each stroke, so how is the volume of fuel injected into the engine varied over the wide range necessary? In general, the 'spill' method is used. At the beginning of each injection pulse, the plunger begins to move fuel out to an injector.

Once the required volume of fuel has been injected, the rest of the fuel in the plunger cylinder is 'spilled', by opening a 'spill port' in the side of the cylinder. The fuel is not spilled out all over your engine, but back into the pump chamber, ready for use in the next injection pulse. It is the precise control of the spill point that determines the volume of fuel injected in each pump stroke.

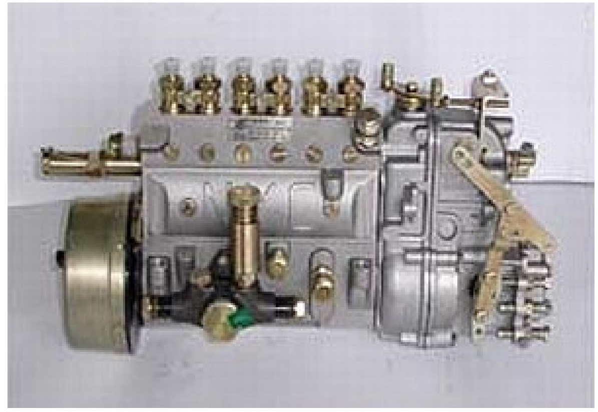


Spill method of pump delivery control

In-line pumps

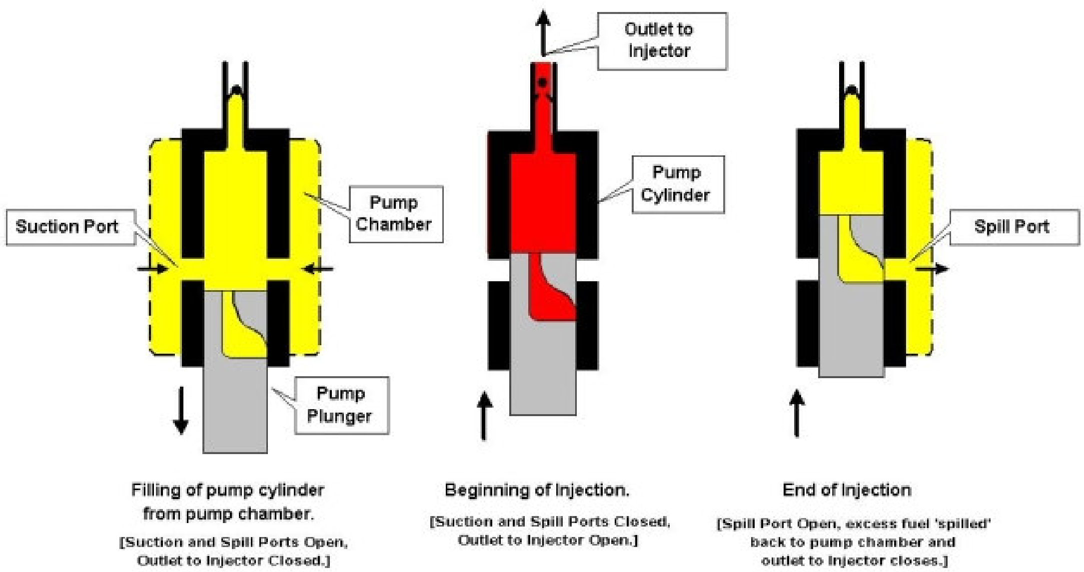
The 'traditional' style of injection pump is the in-line pump. They have been used for many decades and are still commonly found on agricultural and stationary diesels, and very many older model diesel road vehicles still employ them, including the Toyota Landcruiser 2H diesel.. They are typically capable of generating injection nozzle pressures up to about 750 bar in light road vehicles – towards the lower end of the range that is required these days.

They have a separate pump plunger for each cylinder of the engine, so a 4 cylinder engine has a four plunger pump, a 6 cylinder engine has a six plunger pump, etc. The pump is run at half engine crankshaft speed and has a central shaft with four/six etc. cam lobes attached. So, each plunger is operated by it's cam once every two crankshaft revolutions, coinciding of course with the power stroke of its engine cylinder.



Typical In-line Injection Pump. This is a 6-cylinder engine version.

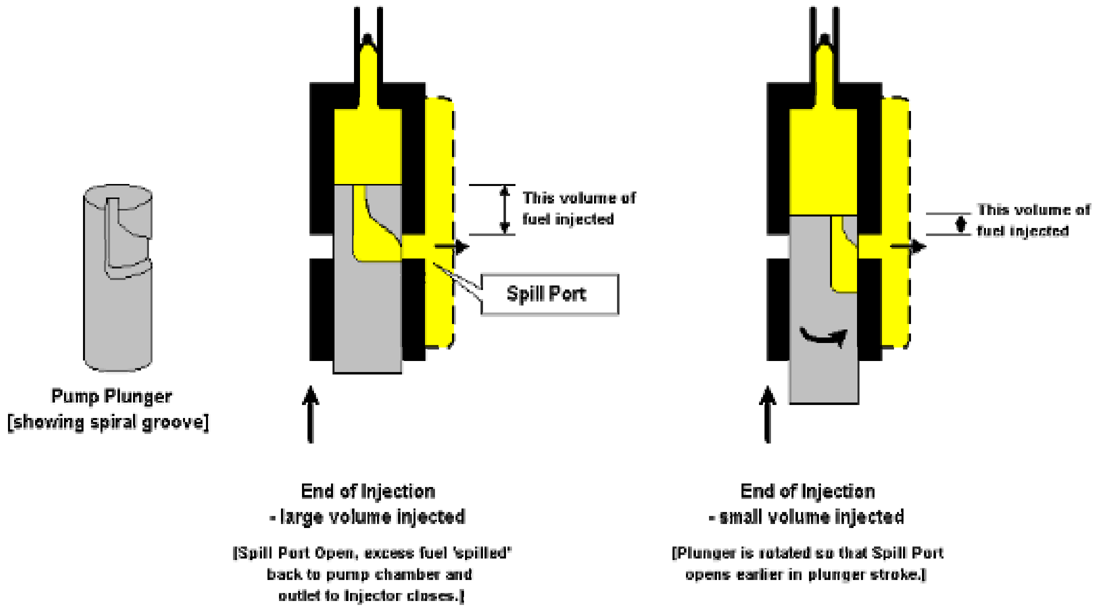
Each plunger has a spiral groove or helix machined on it's side and cut through to the top of the plunger. When operated, the plunger is pushed up by its cam lobe. At a certain point the spiral groove will line up with a spill port on the side of the plunger cylinder and the rest of the fuel is 'spilled'.



Operation of a plunger pump showing the spill method of delivery volume control.

Because the groove is a spiral shape, the point in the plunger stroke when it uncovers the spill port will vary as the plunger is rotated a few degrees either way. This adjusts the spill point and hence, the volume of its fuel charge to the engine cylinder.

So that all engine cylinders receive the same sized fuel charge, all of the plungers are rotated together. This is achieved by each plunger having gear teeth machined to it's circumference which are engaged by a common gear rack which runs through the pump body. As the rack moves back and forth, all four (or six or more) plungers are rotated together. The extremes of travel of the pump rack control the minimum and maximum fuel charge quantities the pump is capable of delivering.

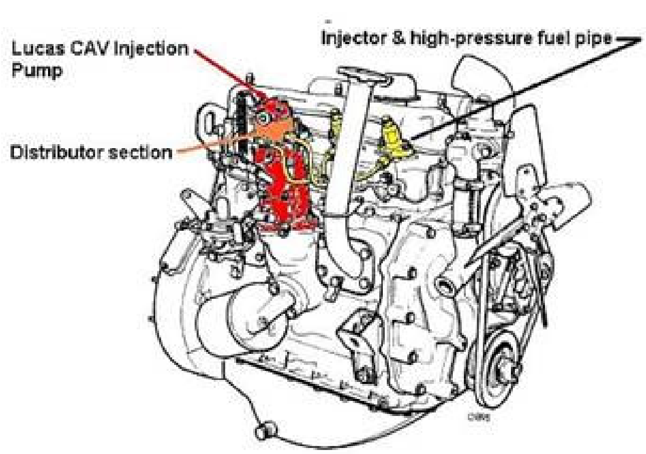


Operation of a plunger pump showing delivery volume adjustment by plunger rotation.

In-line pumps have the advantage of a straightforward method of operation but suffer a couple of important disadvantages. They consist of a large number of moving parts which must operating in close match to give efficient operation. When it comes to high performance applications, it becomes increasingly difficult to keep the numerous plungers and control collars exactly matched in their delivery, especially if they begin to wear unevenly. As a result, most higher performance applications these days use a type of single plunger distributor pump.

Axial Piston Distributor Pumps

The most common type of single-plunger injection pump is the axial piston distributor pump. The pertinent word here is 'distributor'. Just as many SI engines have (or at least, used to have) a distributor to distribute the high voltage pulses to each spark plug in the firing order of the engine, a distributor-type injection pumps distributes high-pressure fuel pulses to each injector in the firing order of the engine. (In fact, in some older engine designs, where the same basic engine block was utilised for both petrol [SI] and diesel [CI] versions, the diesel distributor pump sits near-vertically up on the side of the block, in the same position as the petrol engine's ignition distributor.

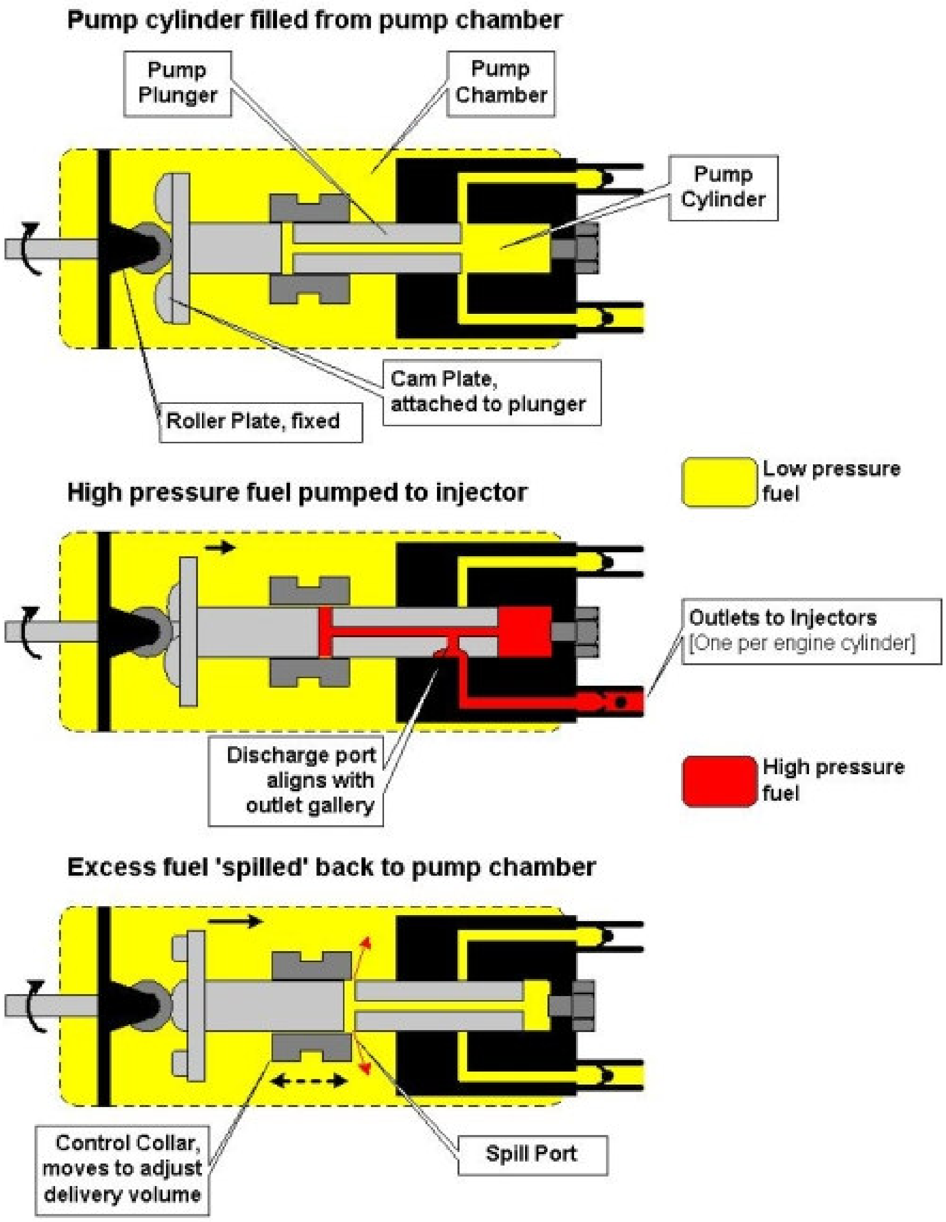


The Land Rover 2.25L diesels from the late 1950s to the early 1980s are an example of this design, using Lucas CAV injection pumps.)

In a distributor pump, every fuel pulse is generated by the same, single plunger, so each cylinder's fuel pulse is pretty-well guaranteed to be of the same volume.

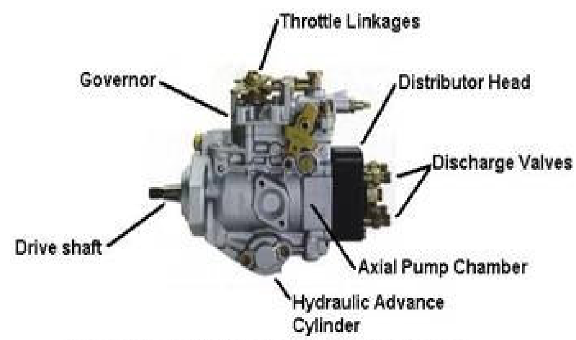
The 'axial piston' part of the name comes from the single pump piston or plunger lying along the axis of the pump's drive shaft, at the non-drive end. This plunger rotates with the pump drive shaft and is stroked by a cam plate with one cam lobe for each cylinder of the engine which rolls over a roller plate.

At the discharge end of the plunger cylinder is a valve body with a gallery and outlet valve for each engine cylinder's injector. The plunger has a discharge port on its side which lines up with each cylinders outlet gallery, in the firing order of the engine, as it rotates. At the other end of the plunger is a spill port which is covered by an adjustable control collar, to vary the spill point and hence the fuel charge size.



VE Distributor Pump Delivery Volume Control

Probably the most common form of this type of pump is the Bosch VE type. They have been manufactured in the millions by Bosch and, under licence, by many other manufacturers including the Japanese builders Nippon Denso and Diesel Kiki. Mechanically-controlled VE type pumps can generate nozzle pressure up to about 1200 bar.



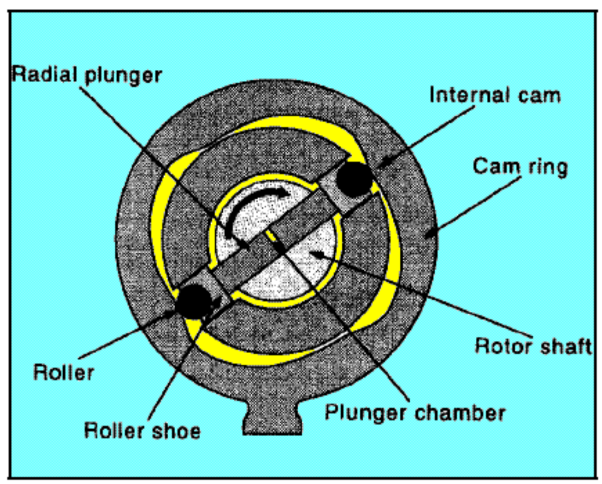
Bosch VE Axial Piston Distributor Pump
(with mechancial governor)

Probably most light road vehicle CI engine designs of the 1990s utilised VE type pumps, either mechanically-controlled or, in more recent years, versions with various electronically-controlled functions. VE type pumps are used in, amongst many others, Land Rover Tdi, Mitsubishi 2.8 TD Pajero/Shoguns, Isuzu/Holden 2.8TDs, Toyota 4.2 1HZ/1HD and Nissan Patrol TD42/T engines.

The Nissan TD42Ti (TD6) Patrol uses a variant of the VE type pump with added electronically controlled timing advance (Covec-T) and some late Land Rover 300tdi engines used the Bosch VE-EDC (Electronic Diesel Control) version with fully electronic control of both fuel quantity and timing.

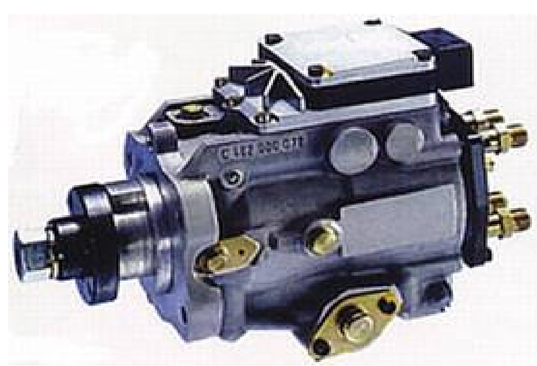
Radial Piston Distributor Pumps

While the axial piston injection pump is capable of moderately high nozzle pressures, it is limited by the fact that the axial plunger design places enormous axial (thrust) loads on the pump shaft bearings. To overcome this, Bosch developed the radial piston pump.



A single pumping chamber and the rotating distributor valve are retained but in the radial piston pump, an annular cam ring forces two small pistons/plungers inward toward each other in the common chamber or cylinder. In this way, the enormous pressure forces on each plunger act radially and cancel each other, giving no axial load on the pump shaft bearings.

The Bosch VR-MV radial piston distributor is fully electronically controlled and is capable of nozzle pressures up to 1700 bar. This is significantly higher even than the capability of the first generations of Common Rail Injection systems. The Nissan Patrol 3.0 ZD30 engine uses a version of the VR type radial piston distributor pump (VP44).

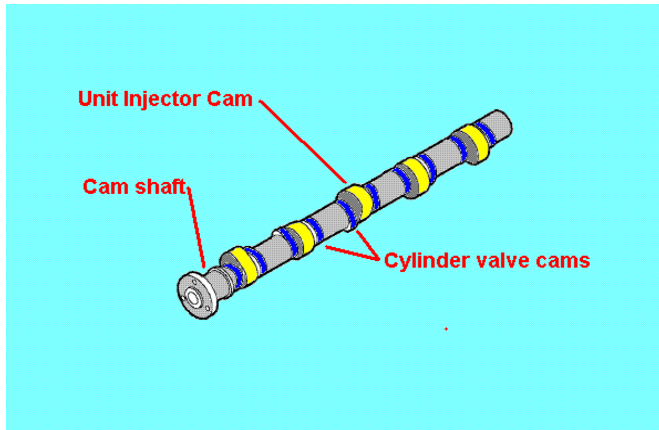


Bosch VP44 Radial Piston Distributor Pump

Unit Injector Systems

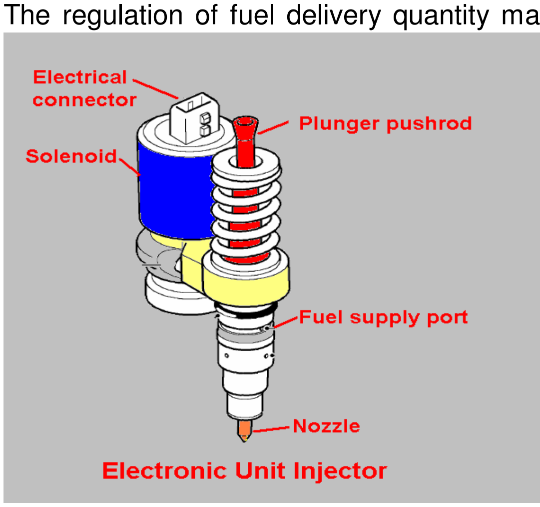
Cummins cam-operated Unit Injector

To attain even higher nozzle pressures, unit injector systems were developed. Instead of a 'central' high-pressure injection pump and high-pressure pipes feeding individual cylinder injectors, this system combines a small high-pressure pump *into each injector assembly*. A common low pressure feed pump supplies each unit injector with fuel.



Each cylinder of an engine with a UIS system has an extra lobe on the cam shaft. This lobe acts on the unit injector (either directly or through a rocker arm) to operate it's high-pressure plunger.

The regulation of fuel delivery quantity may be achieve by a common rack system as in in-line pumps. Many Cummins heavy duty diesel engines used a unit injector system with an ingenious totally-mechanical system to vary both delivery quantity and timing.



The Bosch UIS-P1 electronically controlled system uses a high-speed electric solenoid valve built into each unit injector to control both injection quantity and timing. It is capable of nozzle pressures up to 2050 bar. The Land Rover Td5 engine uses a fully electronically-controlled UIS.

The latest electronic unit injectors use piezo-crystal wafer stacks instead of solenoids for higher speeds of operation. This is explained more fully in the next section.

Common Rail Injection Systems

While high-pressure injection systems such as radial piston pumps and unit injection systems have greatly improved the precision and efficiency of diesel injection, they still suffer a fundamental limitation. The actual injection process into each engine cylinder is limited to a single event for each power stroke. That is, for each power stroke, the injector opens (at the optimum timing) and stays open until the 'correct' fuel charge for the current load on the engine has been delivered, then it closes until the next power stroke.

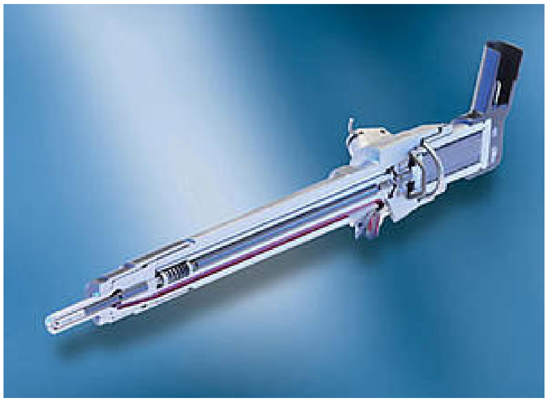
However, to even further improve the emission control and fuel efficiency of a CI engine it becomes desirable to spread the injection process over longer periods of the power stroke. This means being able to open and shut each injector several times during each delivery cycle. Modern Common Rail (CR) injection systems allow this.

The "Common Rail" part of the system is simply a pipe full of very high-pressure diesel fuel - a fuel manifold or accumulator, or fuel 'rail' in automotive jargon. It is a relatively large diameter steel pipe (say, around 20mm ID) running along the cylinder head of the engine, quite close to the actual injectors.

A common high-pressure pump keeps the rail *continuously* supplied with fuel at pressures up to 2000 bar. A short high-pressure pipe then supplies each injector. As far as each injector is concerned, the rail represents an 'infinite' source of high-pressure fuel. It simply needs to open and shut at the appropriates times to deliver this fuel to the combustion chamber.

Bosch released the first CR system in 1997, capable of nozzle pressures up to 1350 bar. This was increased to 1600 bar with the second generation system in 2001. However, the real revolution arrived with the third generation systems in 2003. The 1st and 2nd generation systems used injectors with electric solenoids to lift/release the needles and hence open and close the nozzles.

However, the 3rd generation systems did something completely new in this field. Instead of electric solenoids, they used stacks of piezo crystal wafers to operate the nozzle needles. Piezo crystals are remarkable materials which actually change their shape when electric signals are applied to them. Piezo crystal wafer stacks have the ability not only to operate nozzle needles against the enormous fluid pressures involved but to do it extremely quickly and repetitively if required.



The rapid speed at which the injectors can switch makes it possible to reduce the intervals between injections and split the quantity of fuel delivered into a large number of separate injections for each power stroke. This has allowed a quantum improvement in emissions and noise control in modern diesels.

Next?

We've had a look at the common techniques and equipment used to inject the all-important fuel charges into the diesel engine's cylinder. But what determines the precise quantity of the injection charge and the exact instant at which it occurs? These are the tasks of the fuel injection control system and will be the subject of the next article in this series.

