EMISSION CONTROL BY ENGINE VARIABLES AND EGR

The Lecture Contains:

EMISSION CONTROL BY ENGINE VARIABLES AND EGR

FUEL INJECTION VARIABLES

Demands Made on Injection System

To achieve low soot formation, rates of fuel-air mixing are to be enhanced. Fuel injection and air motion in the cylinder are key parameters to achieve rapid fuel-air mixing. The following strategy is adopted to improve fuel air mixing and the diesel engine combustion, which leads to reduction both in the soot and NO_x formation:

- Use of high fuel injection pressures and smaller nozzle hole size to produce very fine fuel atomization for rapid fuel evaporation and mixing with air.
- Fuel spray not to impinge on walls but fuel to be distributed mainly within the air inside the combustion chamber.
- Matching of injection spray configuration and development with in-cylinder air motion for rapid fuel-air mixing throughout the injection duration period
- Use of variable injection timing, multiple –injection and injection rate shaping technology

High Injection Pressures

The mass flow rate of fuel injected, m_f is given by:

$$m_f = C_d A_n \sqrt{2\rho_f \left(P_{inj} - P_{cyl}\right)} \frac{\Delta\theta}{6N}, \text{ kg / cycle} \qquad \textbf{(6.1)}$$

where C_d is coefficient of discharge, A_n is nozzle flow area in m^2, ρ_f is fuel density in kg / m^3, $(P_{inj}-P_{cyl})$ is the pressure drop across nozzle orifice in Pascals, Δθ is the injection duration in degrees crank angle and N is the engine speed in RPM.

Generally, $P_{inj} >> P_{cyl}$.,
Thus, for a given injection rate $\dot{m}_f$ and injection duration $\Delta\theta$ in crank angles, the injection pressure should vary with speed as,

$$P_{inj} \propto N^2 \qquad \textbf{(6.2)}$$

The speed of engines for road vehicles from lowest working speed to rated speed may vary by a factor of; N_{max}/N_{min} = 4 to 5..To achieve similar injection duration and spray penetration from the lowest to rated engine speed, the injection pressure therefore, is required to vary by a factor of 16 to 25. This of course is not possible in practice but it has led to use of as high an injection pressure as possible. In the pre-1990 engines,

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maximum injection pressures were limited to about 700 bars. Since then, the injection pressures have increased to a value exceeding 2000 bars. Modern electronic fuel injection systems employing unit injectors, common rail systems etc. provide use of very high injection pressures.

The beneficial effects of high injection pressure are;

- Improved fuel atomization producing finer fuel droplets.
- The smaller fuel droplets evaporate at a faster rate resulting in rapid fuel-air mixing.
- A shorter injection duration
- With shorter injection duration injection timing may be retarded. Fuel may now be injected closer to TDC in hotter air giving shorter ignition delay, resulting in emission benefits
- Higher spray penetration and better air utilization.

The effect of peak injection pressure on PM-NO_x trade off is shown on Fig. 6.3. The width of band on this figure relates to the contribution of lubricating oil to the particulate emissions. With increase in peak injection pressure, the PM-NO_x trade-off curve moves closer to origin indicating reduction both in the PM and NO_x , although the reductions in PM at a given NO_x level are more obvious as seen in Fig 6.3 .

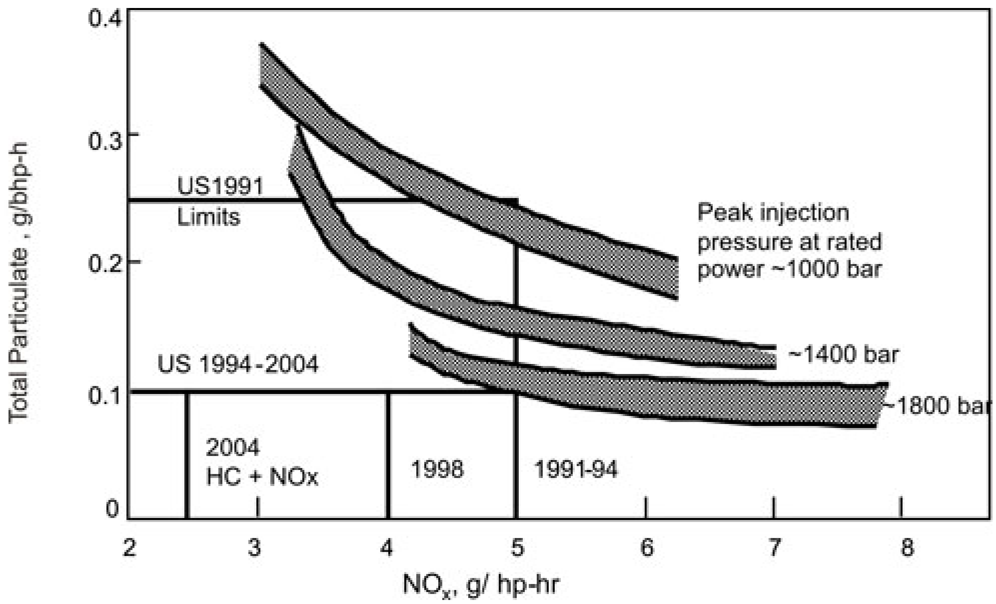

Figure 6.3	Effect of peak injection pressure on PM-NOx trade-off for a turbocharged, inter-cooled, DI diesel engine.

Injection Rate Shaping and Multiple Injection

NO_x formation is influenced by

(i) duration of ignition delay,
(ii) amount of fuel injected during delay period, and
(iii) the rate of mixture preparation within the combustion chamber.

The shape of ideal rate of injection curve during ignition delay and the main injection period depends on engine load and speed. General principles of fuel injection scheduling are;

- rate of fuel injection within the delay period must be kept small to reduce the amount of fuel burned during 'pre-mixed' combustion phase, and
- during the main injection period, rate of injection should be increased steeply to inject fuel within a short period when the temperature and pressure in the combustion chamber are high for rapid combustion of the injected fuel.

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The pilot injection is a form of multiple-injection with two injection pulses. In the pilot injection, a small quantity of fuel (about 10% of fuel per cycle) is injected 3 to 10 crank angle degrees before the main injection event. The pilot-injected fuel has more time to undergo precombustion reactions .When the main fuel injection is made, the combustion begins soon after, resulting in a short delay period. As the pilot fuel quantity injected during delay period is rather small, the peak rate of combustion pressure rise and peak pressures are reduced. Typical pilot injection strategy and cylinder pressure are shown on Fig. 6.4.

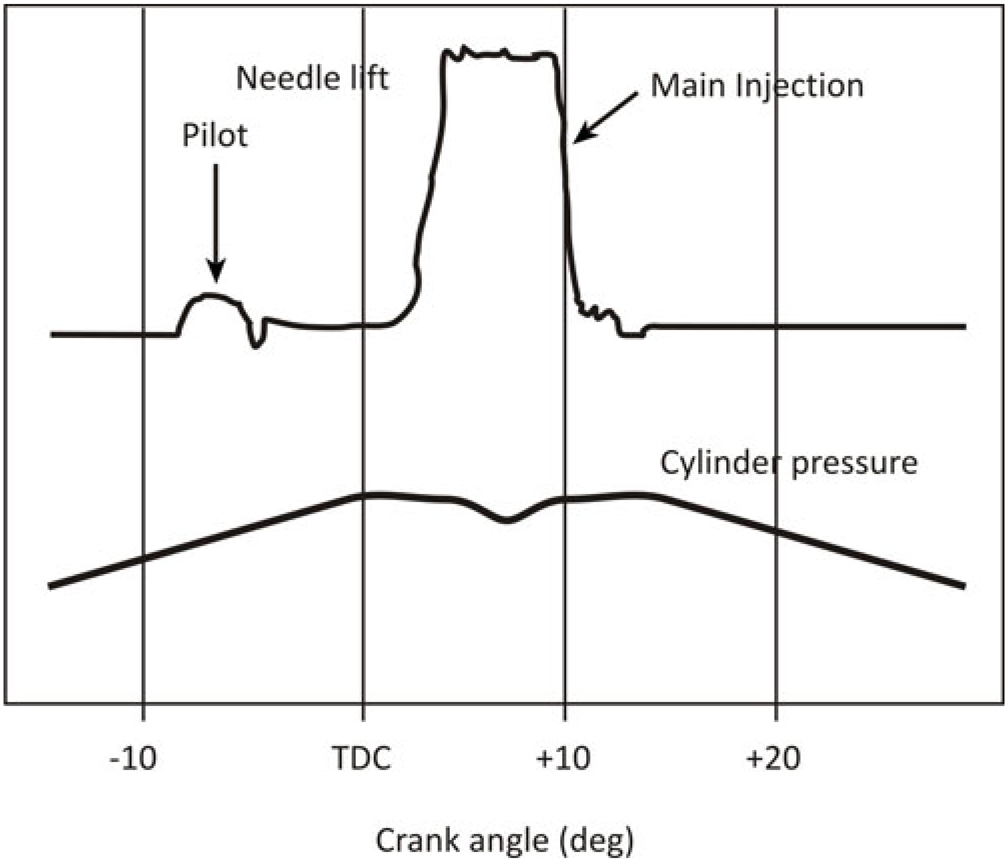

Figure 6.4	Pilot injection, injector needle lift and combustion pressure traces in a naturally aspirated diesel engine at low loads.

With pilot injection, the injection timing of main fuel can be retarded to give low NO_X emissions without adversely affecting the engine power and fuel efficiency. Also, with pilot injection less fuel burns as pre-mixed and a larger fraction of fuel burns in diffusion combustion mode. In the normal engine, NO_X reduction is obtained by retarding the injection timing which results in higher smoke and PM emissions, and higher BSFC. Results with pilot injection and conventional engine with retarded injection are compared in Table 6.2. At the same NO_X emission levels of 5.5 g/kWh, with pilot injection typically 23 % lower PM, 50% lower HC and 4 % lower BSFC were obtained.

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Table 6.2

Comparison of Performance and Emissions of Pilot Injection and Conventional Injection with Retarded Timing

	Conventional Retarded Injection Timing	Pilot Injection
NO_x, g/ kW-h	5.5	5.5
PM, g/kW-h	0.58	0.45
HC, g/kW-h	2.57	1.25
BSFC, g/kW-h	249	238

ELECTRONIC FUEL INJECTION (EFI) SYSTEMS

Electronically controlled fuel injection systems have the capability to fulfill the ideal injection rate requirements,. The EFI also are capable of providing multiple injections. Electronically controlled diesel fuel injection systems have the following advantages over the mechanically controlled injection systems as they provide:

- Very high injection pressures exceeding 2000 bar
- Precise control of injection timing.
- Precise fuel metering to control power output and limit smoke.
- Extremely low cylinder to cylinder variation in the quantity of fuel injected.
- Injection rate shaping with controlled initial rate of injection to reduce noise and emissions
- Sharp end-of-injection to eliminate nozzle dribble, prevent nozzle fouling and, reduce smoke and hydrocarbon emissions.
- Injection rate shaping for controlling heat release rates during pre-mixed and diffusion combustion phases for controlling smoke and NO_x formation.

Electronically controlled unit injectors, distributor pumps and common rail injection systems are in use.

Electronic Unit Injectors

In the electronic unit injectors (EUI) the injection pumping element that raises the fuel to injection pressure and the injector nozzle are integrated into one unit. One each of the EUI is directly mounted on every engine cylinder. The injection pump plunger of every EUI is driven directly by the engine camshaft via a rocker arm. The electronic unit injectors were introduced on heavy-duty diesel truck engines in the USA around 1990 as these could develop much higher pressures than the in-line mechanical injection systems. A EUI design is shown in Fig. 6.5. In this design, metering of the fuel delivery is done by the plunger and the injection timing is controlled by opening and closing events of the solenoid valve of the EUI. Normally, the fuel from the plunger bypasses the solenoid valve and the fuel goes back to the return fuel line. As soon as the solenoid valve closes the fuel bypass passage, a high pressure is generated in the fuel passage above the

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injector nozzle and the fuel is injected. Opening of the solenoid valve releases the fuel pressure and the injection ends. Another design of EUI developed by Cummins Engine Company, Inc. consists of two plungers in the same unit injector, one controls injection timing and the other controls the injection quantity. As the dead volume between the pumping plunger and injector nozzle is very small, very high injection pressures can be used with a high reliability and injection efficiency. Operation of the EUI at more than 2500 bars has been demonstrated.

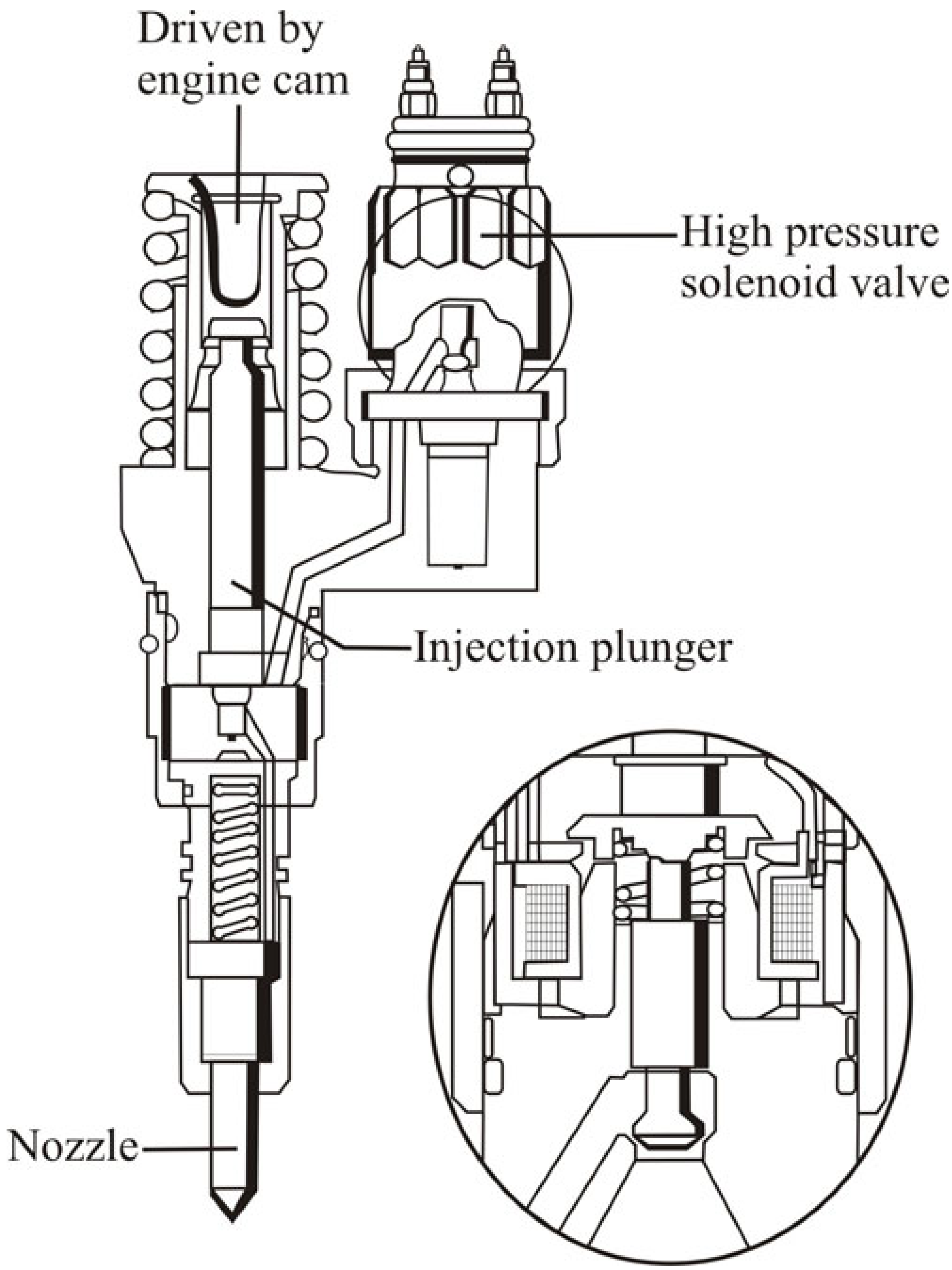

Figure 6.5	A typical electronic unit injector for high pressure.

The EUI can be used to provide pilot injection. A constant fuel temperature at each injector must be kept so that each injector delivers the same mass of fuel to each engine cylinder. A number of sensors provide input data on the engine speed, load, camshaft position, inlet manifold air temperature and pressure, coolant temperature etc., to the electronic control unit (ECU) for control of fuel injection quantity and injection timing. For small high-speed diesel engines, EUI is not employed due to its large size and high cost. Instead, electronic distributor pumps are used. Now, the common rail injection systems are finding wider application in the small size, high speed multicylinder diesel engines.

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Common Rail Diesel Injection (CRDI) Systems

In the common rail systems, the high fuel pressure is generated by a common pump that is separate from the injectors. The fuel pressure is independent of engine speed and load. A typical layout of the common rail systems is shown in Fig. 6.6.The CRDI has four main components;

(i) high-pressure pump

(ii) high-pressure distribution rail (common rail) and pipes

(iii) injectors, and

(iv) Electronic engine control unit (ECU).

A mechanical pump raises the fuel pressure and feeds the common rail with fuel at high pressure. The common rail is connected to the injectors by short pipes. A solenoid valve in each injector controls the injection timing and quantity.

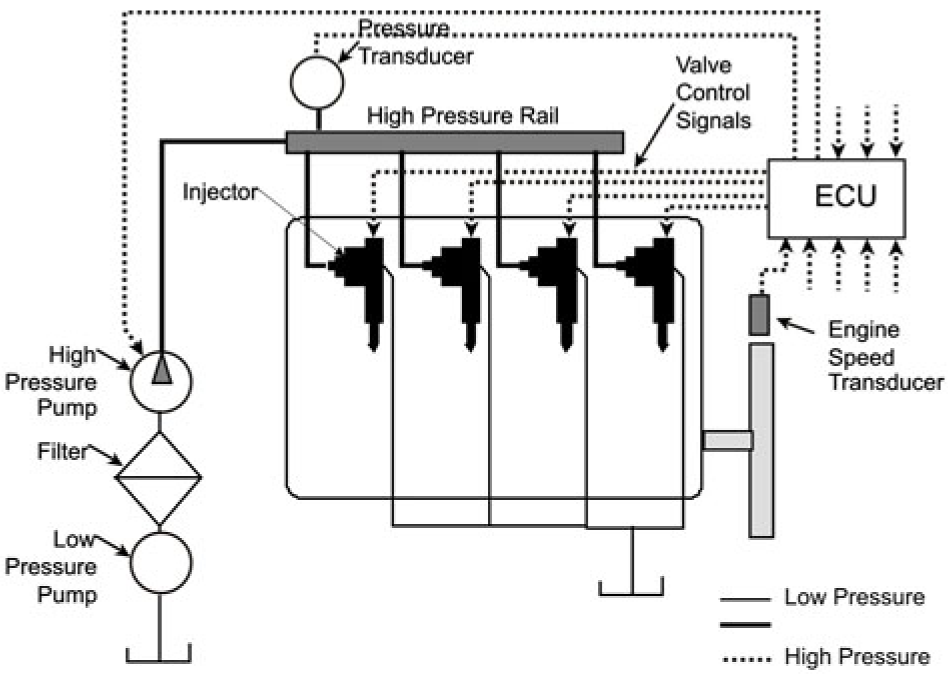

Figure 6.6	Schematic layout of a common rail diesel injection system

In one design of the common rail systems, the rail pressure is same as the injection pressure. In another design known as 'intensified' CRDI system, the fuel pressure in rail is lower and it is multiplied by a factor of 3:1 to 10:1 in the injector body by a stepped piston to raise it to the injection pressure. The CRDI systems mostly operate at pressures of around 1600 bars.

The injection pressure characteristics of the CRDI, EUI and inline pump- nozzle systems are compared in Fig 6.7. The main advantage of the common rail system over the conventional in-line jerk pumps is that injection pressure is constant and independent of engine speed and load. For inline pump- nozzle systems, the injection pressure is quite

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low at low engine speeds which increase due to inertia effects at high speeds. It is therefore, difficult to obtain the required engine performance with low emissions throughout the engine speed range with inline fuel injection systems. Electronic unit injectors are better than the inline systems but the CRDI provides more flexibility as a constant injection pressure is maintained at all engine speeds. In the common rail systems, the injection timing and rate can be varied precisely depending upon the engine requirements.

As very high injection pressures are possible with electronically controlled CRDI, its benefits are available through out the engine speed range. Because of reduction in particulate emissions due to high injection pressures, higher EGR rates can be used at part loads to reduce NO_x emissions, which lead to a better NO_x-particulate trade off. With the common rail systems, injection rate shaping and pilot injection are also easier to implement.

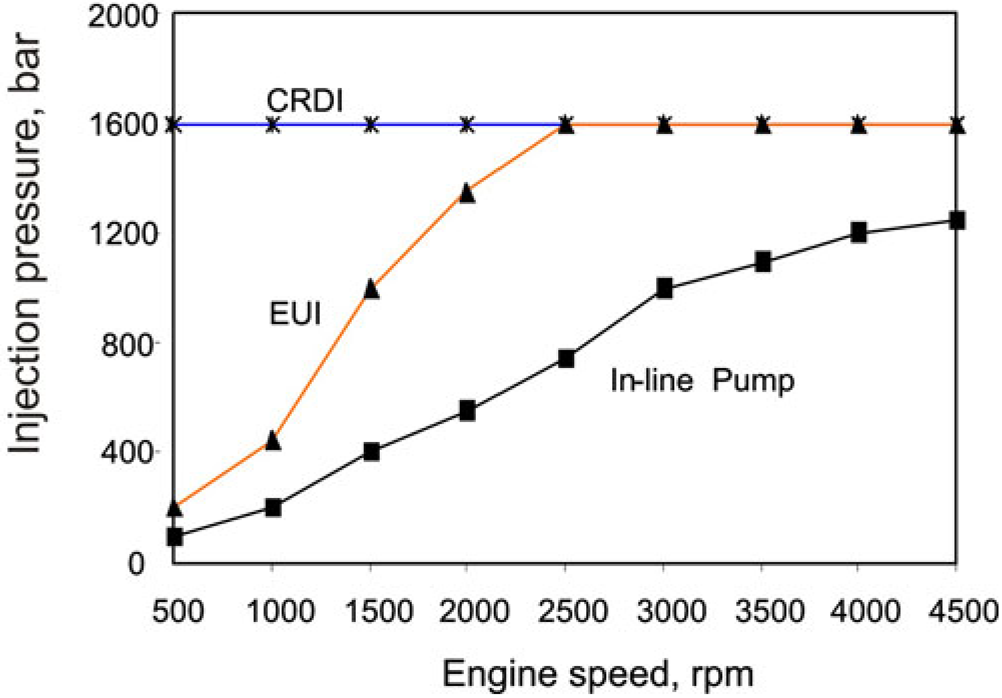

Figure 6.7	Peak injection pressure as a function of engine speed for different fuel injection systems.

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