EMISSION CONTROL FOR SI ENGINES/VEHICLES

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AN OVERVIEW AND CONTROL OF ENGINE-OUT EMISSIONS

During 1950s the road vehicles were found to be the principal source of air pollution in the US cities. Carbon monoxide, unburned fuel (hydrocarbons), nitrogen oxides and smoke particulates were identified as the main air pollutants. Now, carbon dioxide has been added to the list of harmful gaseous emissions due to its global warming effect. Initially, to solve the local air pollution problem during 1960s efforts were mainly focused on reduction of CO from gasoline vehicles and black smoke emissions from diesel vehicles. Another area of priority attention was the prevention of blue smoke emissions caused by excessive consumption of engine lubricating oil which resulted from worn out piston rings, cylinder bore etc.

The first emission control for the spark ignition engines involved adjustments of air-fuel ratio. It was followed by control and adjustment of other engine parameters such as mixture control under idling, acceleration and deceleration, spark timing, precision manufacturing of key engine components such as piston, rings, cylinder head gasket to minimize crevice volume, cams, valves etc. Positive crankcase ventilation (PCV) system was introduced on gasoline vehicles during mid 1960’s to prevent release into atmosphere of hydrocarbon-rich crankcase blow by gases

As the emission standards were tightened, exhaust aftertreatment devices such as catalytic converters were introduced for the first time in 1974-75 and more advanced modifications in engine design and fuel system were employed. Electronic fuel and engine management become necessary during 1980s to meet the then emission regulations. Further advancements in engine, fuel system and emission control technology have emerged in the meantime. Multi-valve cylinder engines became common and variable valve actuation was applied in production vehicles during late 1980s. In mid 1990s, gasoline direct injection stratified charge (DISC) engines were put into production by Japanese auto-manufacturers.

Besides all-round advancements in engine technology and aftertreatment systems happening all the time, in the past few years alternative power trains also for vehicles have been developed which provide a higher fuel efficiency in addition to low emissions. Hybrid electric vehicles (HEV) are already in market place. The HEV has IC engine as a primary source of power but employ electric propulsion powered by storage batteries as the main propulsion unit. Fuel cell vehicles using hydrogen as energy source are in an advanced stage of development and they completely eliminate the use of IC engines as a propulsion system

Categorization of Emission Control Techniques

The emission control techniques may be grouped into the following broad categories:

- Engine design and fuel system parameters
- Engine add-ons to enable reduction of engine-out emissions and
- Exhaust aftertreatment

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ENGINE DESIGN PARAMETERS

The following engine parameters have large influence on emissions and hence have undergone substantial modifications since the pre-emission control era.

- Engine compression ratio,
- Combustion chamber design – low crevice volume, high turbulence
- Spark timing
- Air-fuel ratio
- Fuel system design: carburetor giving way to fuel injection
- Multivalves and variable valve actuation
- Engine temperature control

Engine Compression Ratio

Engine compression ratio affects

- Surface to volume ratio of the combustion chamber
- Engine combustion temperature
- Thermodynamic efficiency
- Fuel octane number for knock free engine operation

The premium high performance car engines during 1960s employed CR of 10 to 11:1. The engine CR was lowered to 8.5 to 9.0:1 when stringent emission standards were legislated for the first time in 1975.
The combustion chamber with a lower CR has lower surface/volume ratio resulting in a reduction in volume of quench layer on the combustion chamber surface. Typical effect of surface/volume ratio of combustion chamber is shown on Fig, 5.1. Moreover, for a low CR engine the crevice volume would also be proportionately lower. These factors in turn would reduce HC emissions. Higher exhaust temperatures resulting with low CR would promote oxidation of HC and CO in exhaust system.
At low CR the peak combustion temperatures are lower and hence low NOx formation.
Introduction of catalytic converters made the use of unleaded gas necessary. As the petroleum refinery economics dictated the use of unleaded gasoline of a low octane number, engine CR had to be lowered.
The principal disadvantage of low CR engine is that it has a poorer fuel efficiency that also results in higher CO_2 emissions.
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However, due to development of high turbulence engine combustion chambers and use of port fuel injection system it has been possible to use a somewhat higher engine CR. The modern gasoline engines have CR mostly in the range of 9.0 to 9.5:1.

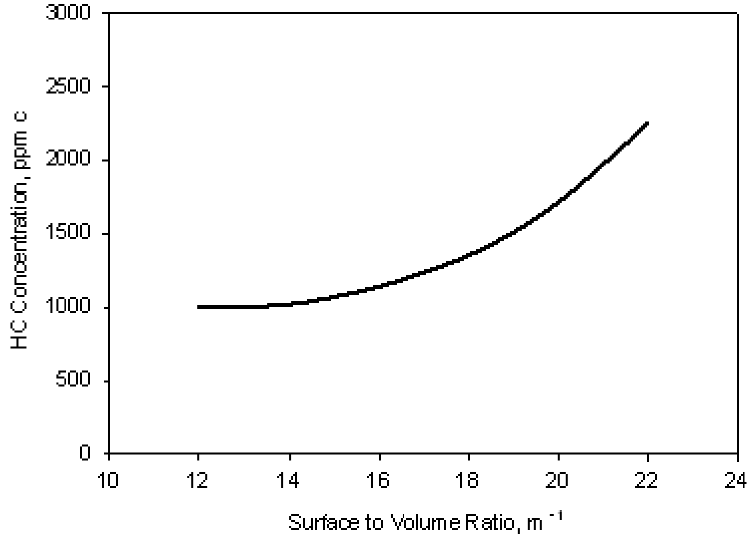

Fig 5.1	Effect of surface/volume ratio of combustion chamber on HC emissions

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High Turbulence Combustion Chambers

Small cylinders with hemispherical and pentroof type combustion chambers are now more commonly used in SI engines.

- Small cylinder engines can be operated at higher speeds whicht increases turbulence and tends to reduce HC emissions..
- Smaller cylinders have smaller amount of burned gases that form the high temperature adiabatic core. More heat transfer takes place from the burned gases as the walls are nearer to the bulk gases. It results in lower NO_x.
- The compact hemispherical combustion chambers shape (Fig 5.2a) provides the lowest surface to volume ratio and minimum tendency to engine knock.

The hemispherical combustion chamber although may employ multiple valves, the two valve configuration is more common as it is difficult to accommodate 4-valves at the necessary valve positioning angles. The valve heads along with the surface of combustion chamber form a profile that looks like a hemisphere. Both the intake and exhaust valves are inclined increasing valve port area that results in higher volumetric efficiency. The chamber has a low surface to volume ratio. The intake ports are provided with a suitably curved geometry to generate high rate of air swirl.

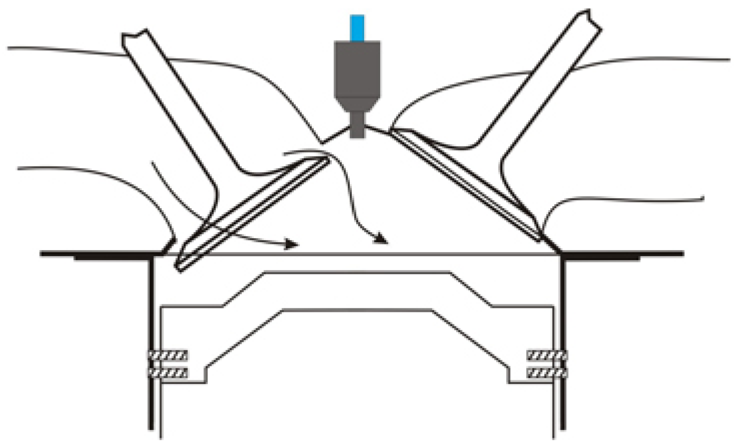

Fig 5.2 (a)	Hemispherical combustion chamber (generally with two valves)

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- A shallow angle pent-roof type combustion chamber (Fig. 5.2b) is a good compromise as it allows use of 4 valves of optimum size and positioning. A higher volumetric efficiency and tumble air motion are obtained in these combustion chambers resulting in higher burning rates. These compact combustion chambers have lower heat transfer losses. Thus, quench layer thickness is minimized lowering HC emissions.

Pentroof combustion chamber being shallow compared to hemispherical combustion chamber it has somewhat higher surface to volume ratio. However the pentroof combustion chamber is a good compromise between compactness of the combustion chamber and use of multiple valves. A shallow angle pentroof type combustion chamber allows optimum valve size and their positioning in multiple-valve engine configuration. Pentroof combustion chambers having 2 and 3 intake valves and total of 3 to 6 valves per cylinder are in use. The 4-valve combustion chambers are the most common The inclination of the intake and exhaust valves to each other tilts the pair of valve heads such that they resemble to an arch and take the shape of a pentroof, hence the name. The spark plug is located close to centre. Mixture from the intake port flows across the cylinder to the walls from where it is deflected downwards direction and rolls perpendicular to the axis of the cylinder in a tumbling motion. This motion is called air 'tumble'.

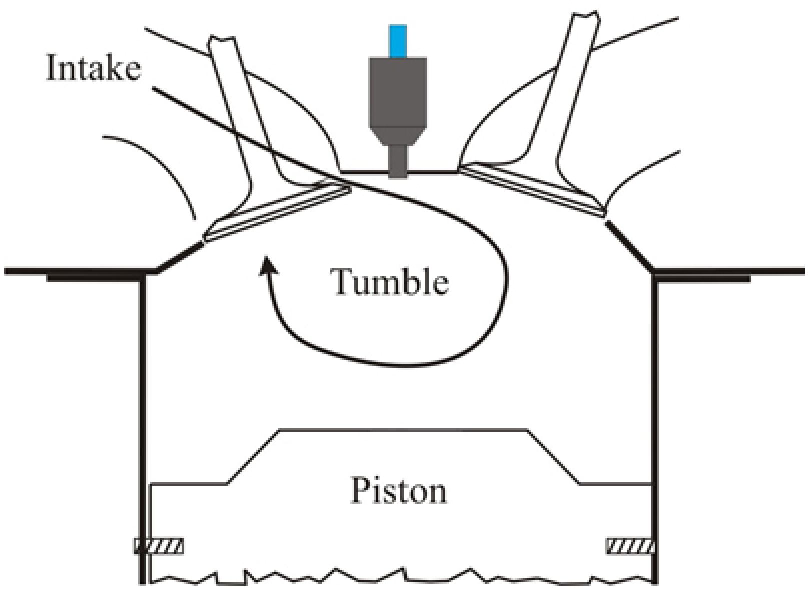

Fig 5.2(b)	Pentroof combustion chamber with 4-valves for modern SI engines

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Fuel System

Trends in development of gasoline engine fuel introduction system are shown in Fig 5.3. Until 1980 practically all gasoline SI engines employed carburettors. Only a few premium model gasoline cars employed electronic fuel injection (EFI) system. Initially, a single point EFI injecting fuel at the throttle body was used. It was also known as throttle body injection (TBI) system and it provided more precise fuel metering than the carburettor. However, from 1990 onwards electronically controlled multi-point port fuel injection (MPFI or PFI) system replaced the carburettor on all the production cars in the USA. Port fuel injection systems require one injector per cylinder that injects fuel into intake port of each cylinder. Some engines use an additional injector to supply extra fuel required during starting and warm-up.

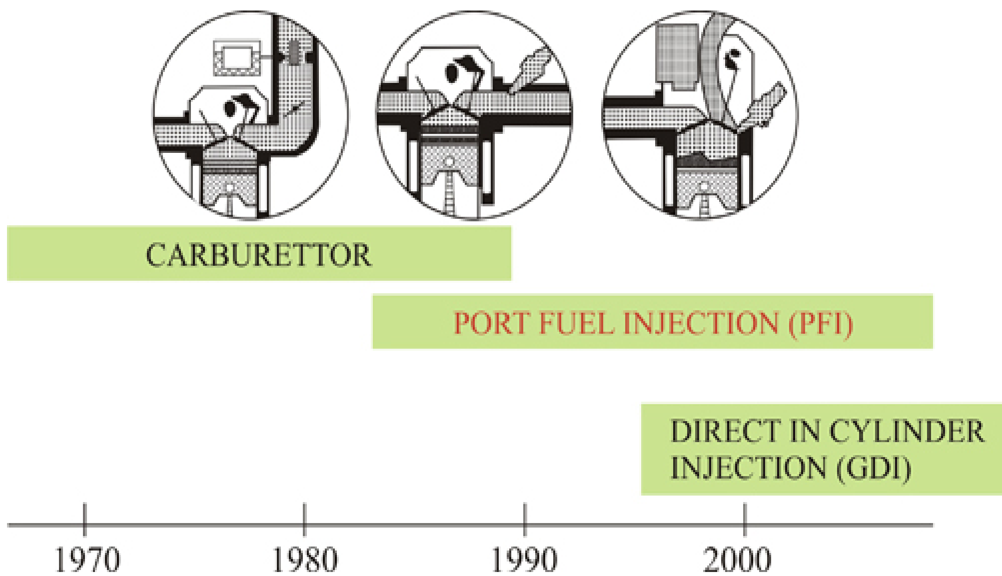

Figure 5.3	Trends in development of fuel system technology for SI (gasoline) engines

The PFI has the following advantages over the carburettor and TBI system;

- Increased power and torque due to improved volumetric efficiency: the venturi system needed for carburettor is eliminated and less fuel vaporizes in the intake manifold, which increase the volumetric efficiency
- Faster fuel evaporation*:* Improved fuel atomization leads to smaller droplets and a faster fuel evaporation.
- More uniform fuel distribution*:* for each cylinder the fuel is metered separately by the corresponding port fuel injector
- More rapid dynamic response to changes in throttle position and hence transient operation: Faster fuel evaporation leads to rapid mixture formation and faster dynamic response. Hence, less fuel enrichment is required during acceleration.
- More precise control of air-fuel ratio: use of closed loop feedback control system that employs exhaust oxygen sensor very precise control of air-fuel ratio is obtained so the unnecessary fuel enrichment of the engine can be prevented
- More precise control of air-fuel ratio cold-start and warm up: less extra fuel compared to carburettor is necessary during cold start and warm up.

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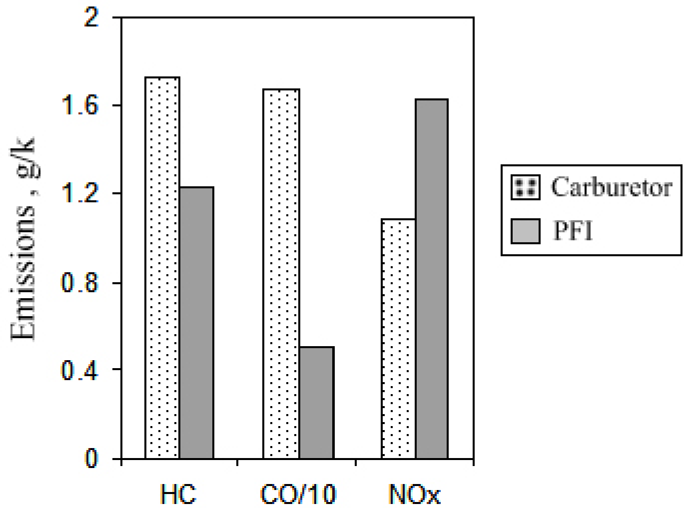

Figure 5.4	Comparison of engine-out emissions from carburettor and open loop PFI engine passenger cars.

In the EFI systems, for control of fuel injection rate and in turn the air-fuel ratio, airflow to the engine is measured by a hot-wire or hot-film anemometer. Air-fuel ratio is more precise. Use of measured air flow rate data by the engine fuel management system results in an automatic compensation for changes in air flow resulting from variations in engine speed, load, exhaust back pressure or change in volumetric efficiency due to valve adjustments, engine wear, deposit build-up etc.

The typical emissions from a car equipped with carburettor and open loop PFI systems are compared in Fig. 5.4. Use of port fuel injection alone provided 20- 30 % reduction in HC and 50 to 60% reduction in CO compared to carburettor when tested over the urban driving cycle. The NO_x however, increased by about 45% as for smooth engine operation overall a leaner mixture was used with PFI. In the closed loop controlled stoichiometric operation of the engine, the effect of PFI on NO_x would not be very significant, while lower CO and HC are obtained due to more uniform fuel distribution among the different engine cylinders.

Gasoline direct injection (GDI) system has been employed for the direct injection stratified charge (DISC) engines. During mid 1990s, Mitsubishi and Toyota introduced DISC engines on the production cars. The DISC engine operates as lean as 40: 1 air-fuel ratio and provides large reductions in engine-out emissions. Now however, stoichiometric GDI engines are also being considered for production. These engines are discussed in detail later in the section on advanced engines.

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Valve Gear Design

Multiple Valves:

Four valves (2 intake and two exhaust valves) per cylinder are now common on the SI engines. The use of multiple valves:

- Increases valve flow area compared to two valves
- Spark plug can be placed centrally reducing the maximum flame travel distance hence faster and less knocking tendency combustion,
- Only one intake valve may be used at low speeds and low loads to obtain high intake mixture velocity giving high turbulence and swirl that improves combustion at light loads. At high speeds and high loads both valves are open.
- The two intake valves may be provided with different valve timings and different valve lifts to obtain higher volumetric efficiency.
- The two valves may use different port designs to obtain the desired fluid motion in the cyliunder

Variable Valve Timings and Lift

- A large valve overlap is required to obtain high volumetric efficiency at high engine speeds to make use of the ram effect
- At low engine speeds due to backflow of residual gases in the intake system a low valve overlap is desired.
- With increase in valve overlap, residual gas fraction at low speeds increases giving lower NO_x emissions, but HC emissions increase.
- Ideally the valve timings should vary with the engine speed.
- The intake gas flow velocity through the valves governs the air motion and turbulence in the engine cylinder and hence the rate of combustion and performance For fixed intake valve lift, intake airflow and turbulence would be reduced at low engine loads and speeds, which may not be adequate for good combustion. Hence a variable valve lift is required that would depend on engine load and speed for good combustion and engine performance.

Variable valve timing control allows for continuously variable camshaft phasing over the entire power range of the engine. Honda has developed electronically controlled variable valve timing and lift (VTEC) system. Toyota's system is known as VVTi (intelligently controlled variable valve timing). Other manufacturers have developed their own designs of varable valve actuation. The NO_x emissions with fixed and typically with variable valve timings are compared on Fig. 5.5. Reductions of 30 to 70 % in NOx with variable valve timing are observed. Change in HC emissions between the fixed and variable valve timings is however, small. The CO emissions however, are a function of air-fuel ratio.

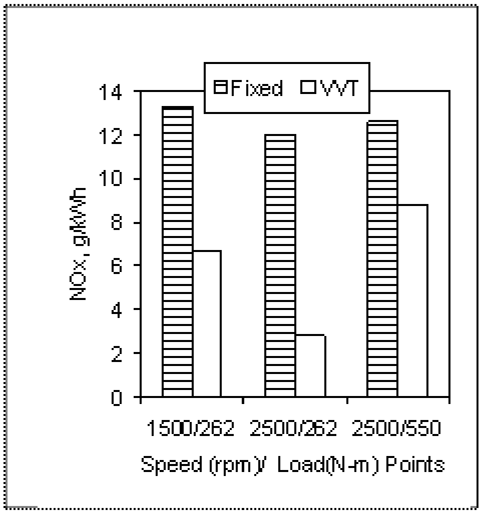

Fig 5.5	Typical emissions with fixed and variable valve timings.

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Variable Swept Volume and Downsizing

The passenger cars during city driving operate at light loads when high pumping losses, poor fuel efficiency and high HC and CO emissions are obtained. Operation of the engine with lower swept volume would be at a higher mean effective pressure which would result in better fuel economy and lower CO and HC emissions. For the 6- and 8-cylinder engines, the effective engine swept volume has been varied by deactivating the valve operation of half of the cylinders during city operation. This technology although has been applied to 4-cylinder engines as well but is better suited for the large engine having 6- and 8-cylinders. On high driving all the cylinders come into operation. The cylinders are electronically switched on and off without the sudden acceleration and deceleration of vehicle being felt. When operating only on half the number of cylinders, friction losses are also reduced as overhead camshafts of the two cylinders are not in operation.

Using a lower displacement engine and develop the required full throttle torque and power by supercharging is another approach to improve fuel economy and reduce emissions particularly the HC. A lower swept volume engine would operate at higher mean effective pressures and would have lower fluid and mechanical friction losses. At part loads, the supercharged and downsized engine can result in fuel economy improvements of upto 25% and accompanied benefits related to lower CO, HC and CO_2 emissions.

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