CHAPTER 2

LITERATURE SURVEY

The literature survey regarding use of additive with fuel in-cylinder turbulence inducement aspect investigated are reviewed and discussed in this chapter.

2.1 ADDITIVE WITH FUEL

The increase in demand for petroleum fuels and consequent depletion of their reserves has given rise to the need for investigating new energy resources or finding the optimum way of using the present resources. In this regard, two approaches are pursued

a) Improving refining processes for producing better quality fuel from different crude oils, that is, tailoring fuel at the refining stage, and

b) Using some additives for improving the quality of existing fuels to a desired level, which is, improving performance of available fuel.

The effects of fuel quality variations on diesel engine emissions is complicated by the wide variation of the engine response to the fuel quality changes and the extent of inter-correlation of the various fuel variables. In engine literature, many investigators have reported. Betroli et al. (1993) suggest that the particulate emission reduction could be attained using the ash less additive technology. The different fuel characteristics are given in Table 2.1. They found that it is necessary to use a conditioning period prior to emission tests.

Kouremenous et al. (1999) examined the effect of the fuel composition and physical properties on the mechanism of combustion and pollutant formation. A number of fuels having different density, viscosity, chemical composition, (especially aromatics type), are used in their investigation and found that the fuel properties namely density and viscosity are more important than fuel composition (aromatics) in respect of engine
performance and emissions. The total aromatic content, however, has more influence on engine performance and emissions rather than the individual aromatics.

Hajdukovic et al. (2000) reported that the toxicity of diesel fuel is generally attributed to soluble aromatic compounds. Alkyl derivatives of benzene and polycyclic aromatic hydrocarbons are considered as most harmful. New oxygen and nitrogen derivatives of hydrocarbons are formed as a result of oxidative and pyrolytic processes during combustion.

The diesel fuel being heavier and having higher carbon content has some problems when used in an engine. Due to its high freezing point, it is known to cause blockage of filters and nozzles especially under cold conditions. The routine use of fuel additive in diesel began in 1960's in Europe as cold flow improvers. The additives added in parts per millions (ppm) levels achieve a specific objective of either improving the physical or chemical characteristics of the fuel or improving the combustion characteristics. There are many other functions of additives. Based on the function and additive concept, they are reported to be classified (Owen Kieth et al, 1990) as antioxidants and stabilizers, metal deactivators, cetane improvers, combustion improvers, detergents, corrosion inhibitors, anti static additives, dehazers and demulsifiers, anti-icers, biocides, anti-foamants, odor masks and odorants, dyers and markers and drag reducers.

Kidoguchi et al. (2000) in their investigations reported that in fuels with higher aromatics content, the pyrolysis of fuel will not be satisfactory and therefore there are local high temperature regions on account of higher adiabatic flame temperature capability of ring structure hydrocarbons. The aromatic compounds are very compact with very less surface to volume ratio compared to long chain normal polymers. They have higher C/H ratio and also cm ratio per unit volume. They are also more reactive because of lower C-C bond strength compared to C-H bonds.
Hence, in the absence of air, they are prone to higher cracking, pyrolysis and agglomeration with other aromatic molecules nearby during the initial stages of combustion. Their adiabatic flame temperatures are also very high and as a result, soot formation increases (Hirao et al., 1988). Due to higher bond strength of O-H bonds compared to C-H and C-C bonds, O-H bonds break up in presence of high local temperatures and bring the local temperatures down. This decreases the possibility of formation of NO\textsubscript{x}. The O-H bonds are reformed as the temperatures decrease and the absorbed energy is given back.

Jensen et al (1983) observed that the concentrations of alkyl homologues of PAH and oxy-PAH in the particulates were found to decrease with increasing cylinder exhaust temperatures. The degree of alkylation for the most abundant homologue of these compounds increased by one to two carbons as the cylinder exhaust temperature decreased. The inverse relationship between engine temperature and production of extractable organics suggests one possible emission control strategy. The post combustion reactor might achieve reduction of PM associated with organics. To evaluate the feasibility of such an engine modification, both particulate and vapour emissions need to be collected simultaneously. This will allow proper correlation of particulate vapour with the engine conditions. Alkyl homologue analysis of diesel emissions provides information which may lead to selection of engine operating conditions that will reduce the environmental impact of diesel emissions.

It is reported that

a) Iso-propyl nitrate reduces both aldehyde and CO level without much effect on NO\textsubscript{x}.

b) Iso and Iso-amyl nitrate and di-tertiary butyl peroxide reduce NO\textsubscript{x} by generating alkoxy radical.
Stage de Caro et al. (2001) studied the effect of two organic additives for their properties and to investigate their effect on diesel - ethanol mixture they tested them in the DI and IDI engines. Additives bring stability to the diesel ethanol mixture. Cetane number decreased in the presence of alcohol and also the dynamic viscosity, and heat content increases the volatility. Diesel / ethanol blends with low ethanol content have little effect on the contents of the pollutant gases from the indirect injection engines whereas a reduction is observed with DI engines. DI engines are more sensitive than IDI engines to the fuel cetane number. Adding ethanol leads to a reduction in the smoke and particulates levels emitted in the exhaust. In the presence of additive, the cycle-to-cycle variation of IMEP was reduced.

Kulinowski et al. (1993) in his review suggested that diesel fuel additives such as cetane improvers, combustion improvers, diesel detergents, low aromatic and sulphur content in fuel and lubricity additives can give a desirable effect. They concluded that a properly formulated diesel additive with the above measures will result in desirable changes in the emissions and performance of the engine.

2.2 IN-CYLINDER TURBULENCE INDUCEMENT

2.2.1 Importance of fuel-air mixing

The role of air motion in diesel engines is well recognized for the purpose of fuel-air mixing which is central to the engine combustion and emission characteristics. The effect of organized or unorganized air motion in the engine combustion chamber is generally considered responsible to set in a particular flow field influencing the fuel-air mixing pattern. In general, the air motion responsible for mixing can be considered to affect the in-cylinder turbulence prior to the fuel-air mixing. The generation of in-cylinder
turbulence has been a widely investigated aspect in the context of internal combustion engine context, particularly diesel engines, where mixing process assumes primary importance. From the vast literature that exists in this area, the present discussion is so organized that the state of the art concerning generation or inducement of turbulence is generally covered.

These aspects include:

a) Combustion System

b) Combustion Chamber geometry shapes
   i) Piston cavity
   ii) Cylinder head

c) Injection process
   i) High pressure injection
   ii) Auxiliary gas / Air injection

d) Bluff bodies

e) CFD analysis for turbulence

**a) Combustion System**

In diesel engines, fuel is injected and mixed with hot and compressed air in the cylinder. The presence of air movement generally termed as turbulence is considered necessary to enhance fuel-air mixing for better combustion. There are several techniques used for creating turbulence in the engine. These techniques use either processes like injection, precombustion etc., or hardware modifications such as air cells etc. Fuel is distributed in the cylinders of a diesel engine by injection nozzles, which atomize the fuel and direct it to the desired portions of the combustion space.
Fuel injection itself creates some turbulence, but not enough for efficient combustion. This conditioning, called pre-combustion, involves a partial burning of the fuel before it enters the main combustion space. Precombustion helps to create the turbulence needed for the fuel and air to be properly mix. Because of differences in designs, the manner in which precombustion aids in creating turbulence differs from one type of auxiliary combustion chamber to another. A spherical precombustion chamber is shown in Fig. 2.1. The precombustion chamber is located in the cylinder head and is connected to the main combustion space of the cylinder by a multiple orifice called a burner. During the compression event, a relatively small volume of compression-heated air is forced through the burner into the precombustion chamber. Heat stored by the burner increases the temperature of the compressed air and facilitates initial ignition. Fuel is atomized and sprayed into the hot air in the precombustion chamber and combustion begins. Only a small part of the fuel is burned in the precombustion chamber because of the limited amount of oxygen.

![Fig. 2.1. Precombustion chamber (Maleev, 1987)](image)

The fuel that does burn in the chamber creates enough heat and pressure to force the fuel, as injection continues, into the cylinder at higher velocity. The velocity of the fuel entering the main combustion space and the shape of the piston crown help creating
the necessary turbulence within the cylinder. Engines that have precombustion chambers
do not require high fuel injection pressures as great as engines that have open-type
configurations. Also, the spray of injected fuel can be coarser, since the precombustion
chamber functions to atomize the fuel further before the fuel enters the cylinder. The
engines have auxiliary combustion chambers, which differ from precombustion chambers
such that almost all of the air supplied to the cylinder during the intake event is forced
into the auxiliary chamber during the compression stroke. Auxiliary chambers in which
this occurs are sometimes referred to as Turbulence chambers as shown in Fig 2.2.

The turbulence is created in the auxiliary chamber in compression, injection and
combustion periods. In engines with turbulence chambers, there is very little clearance
between the top of the piston and the head when the piston reaches TDC. For this reason,
a high percentage of the air in the cylinder is forced into the turbulence chamber during
the compression event. The shape of the chamber (usually spherical) and the size of the
opening through which the air must pass help to create turbulence.
The Lanova cell is the energy cell divided chamber type. Fig. 2.3 shows cross-sectional top and side views of a divided auxiliary combustion chamber. This design employs a combustion chamber consisting of two rounded spaces cast in the cylinder head. The inlet and exhaust valves open into the main combustion chamber. The fuel-injection nozzle lies horizontally pointing across the narrow section where the lobes join.

Fig.2.3 Energy cell combustion chamber (Maleev, 1987)

Opposite to the nozzle is the two-part energy cell, which contains less than 20 percent of the main-chamber volume. During the compression stroke, the piston forces air into the energy cell. Near the end of the stroke, the nozzle sprays fuel across the main chamber in the direction of the mouth of the energy cell. While the fuel charge is traveling across the center of the main chamber, between a third and a half of the fuel mixes with the hot air and burns at once. The remainder of the fuel enters the energy cell and starts to burn there, being ignited from the fuel already burning in the main chamber. At this point, the cell pressure rises sharply, causing the products of combustion to flow at
high velocity back into the main combustion space. This sets up a rapid swirling movement of fuel and air in each lobe of the main chamber, promoting the final fuel-air mixing and ensuring complete combustion. The two restricted openings of the energy cell control the time and rate of expulsion of the turbulence-creating blast from the energy cell into the main combustion space. Therefore, the rate of pressure rise on the piston is gradual, resulting in smooth engine operation. However, turbulence in a divided combustion chamber is dependent on thermal expansion caused by combustion in the energy cell and not on engine speed as in other types of auxiliary combustion chambers.

b. Combustion Chamber geometry shapes

i) Combustion chambers having cavity in piston

Shigemori et al. (1983) developed a combustion chamber (refer Fig. 2.4) with turbulence induced intake port and optimum fuel injection equipment. They reported that the HMMS-III has the superior performance with a 3 mm nozzle protrusion at all speeds due to short combustion period & active reactions in the second stage of combustion.

![Fig. 2.4 Different combustion cavity shapes (Shigemori et al. 1983)](image)

Saito et al (1986) investigated the effect of the combustion geometry on combustion with special emphasis focused on the re-entrant combustion chamber. They compared the conventional combustion chambers and the reentrant in terms of
combustion process, engine performance and NO\textsubscript{x} and smoke emissions. They found that the reentrant chamber reduces ignition lag and provides better fuel economy with delayed injection timing, which is attributed to the effect produced by the hotter surface of the re-entrant chamber. Also combustion is enhanced with reduced smoke emission due to higher velocities induced around TDC accompanying much turbulence.

The combustion chamber geometry, the shape of the cavity entrance, bottom corner radius and the position where spray impinges on the wall were varied to investigate their effects on the spray development in the chamber using a common rail injection system (refer Fig. 2.5). In this they have studied the experiments with the focus on the following parameters, that is, the spray spreading area, equivalent wall jet diameter and spray path. They found that the reentrant cavity with round lip produces larger spray volumes and wider spray spreading. For effect on impinging position they stated that the fuel impingement just on the lip corner produces the maximum spreading area. They also concluded that introduction of a bottom corner radius helps to disperse the fuel accumulated at the bottom corner and the spray volume increases.

Rong et al. (2000) developed new combustion system (DSCS) Double Swirls combustion System (DSCS) as shown in Fig.2.6. This combustion chamber is made of two dishes, smaller in the middle of the bigger one. They reported to have reduced fuel consumption by 5-10%. This is attributed to the fact that the fuel jets collides with the ridges of the DSCS combustion chamber and then splits and form double swirl, hence mixing and burning are efficiently carried out.
ii) Combustion chamber having cavity in Cylinder head

Kamimoto et al (1983) studied the effect of air cell fitted on the cylinder head for soot reduction in a DI diesel engine. The air cell fitted engine is as shown in Fig. 2.7. Air is accumulated in the air cell during compression stroke and is injected into the main chamber during the period after the end of the injection. At this instant the air jet stirs the stagnant flame and promotes soot oxidation. They found that the soot emission was lower by 30% in the higher load operation than that of the conventional type of engine. NO concentration is lower in case of air cell system. The air cell fitted engine has higher
specific fuel consumption at low load condition because there is loss in the effective work, which is the air movement between the combustion chamber and the air cell.

![Diagram](image)

Fig. 2.7 Configuration of test engine with an air cell (Kamimoto et al., 1983)

Lin et al (1995) in their investigation designed a multi-impingement wall head at the center of the combustion chamber and attached to the cylinder head as shown in Fig. 2.8. The effects of combustion chamber geometry on combustion characteristics, engine performance and exhaust gases are also investigated. The different multii-impingement wall head and various types of combustion chambers used in the experiments are shown in Fig. 2.9 and 2.10 respectively. They found that the reentrant type of combustion chamber with a projection and cutout has a better fuel consumption and lower harmful emissions. They also found from the photographs that the fuel spray is better diffused and distributed. This is because the engine can obtain a higher squish in the above case. This leads to a higher airflow by the micro turbulence in the compression stroke and the back squish in the power stroke for improved performance.
Fig. 2.8 Concept of MIW head for the NICS-MH engine (Lin et al., 1995)

Fig. 2.9 MIW head used in the experiments (Lin et al., 1995)

Fig. 2.10 Four combustion chambers used in the experiments (Lin et al., 1995)
c. Fuel injection process and combustion chambers

i) High pressure injection

Corcione et al. (1991) in their experiments examined the effects of spray angle, holes diameter and number, compression ratio and the combustion chamber geometry on engine performance and emissions. At high speeds sacless nozzles used in reentrant bowl showed reduction in HC and NO\textsubscript{x} with unchanged BMEP and BSFC under certain condition. But at low engine speed torroidal bowl gave better results.

Takeda et al. (1996) in their study advanced the fuel injection timing and operated the engine with the premixed lean Diesel Combustion (PREDIC) to promote fuel air mixing. They reported that with the PREDIC operation a luminous flame was not observed during the main combustion period due to improved fuel air mixing. They concluded that there was a reduction in NO\textsubscript{x} because the fuel air mixing is made leaner and the stochiometric ratio mixture in the combustion region is reduced. Also, HC and CO levels increased because of the fuel air mixture was over lean.

Fig. 2.11 Fuel spray location of MULDIC (Hashizume et al., 1998)
ii) Auxiliary Gas / Air Injection Processes

Konno et al (1992) attempted to reduce smoke emitted from direct injection diesel engine by generating strong turbulence during combustion process. For this purpose a small auxiliary chamber and fuel injection nozzle were installed at the cylinder head of the basic engine (refer Fig. 2.12) which is termed as the combustion chamber disturbance (CCD). In CCD a small amount of fuel is injected by using separate injection pump. Four different diameters (2, 4, 6 and 8mm) of the passage connecting the CCO and main chamber were investigated. EGR and water injection into the intake manifold were also examined with the CCO system. They concluded that smoke reduction becomes large with higher jet momentum and a combination of EGR of water injection with CCD is very effective to achieve simultaneous reduction of both NO\textsubscript{x} and also in present system water is injected at high loads and EGR at low loads.

![Fig. 2.12 Cross section of the CCD system (Konno et al., 1992)](image)

Choi et al (1995) investigated the effect of introducing a gas jet. In this case they tried with industrial nitrogen and carbon dioxide with advanced and retarded timing of the fuel injection, at a particular timing in the cylinder during the later part of the diesel combustion. The arrangement of the gaseous injector in the head is as shown in Fig. 2.13.
They concluded that the reduction of particulate was controlled by a combination of the total momentum input and the specific timing at which the momentum was introduced. For both retarded fuel and gaseous injection timing, higher the jet momentum the larger is the soot reduction. When injecting CO$_2$ at retarded timing, the rate of reaction for the carbon-carbon dioxide reaction was too small for any soot oxidation by CO$_2$ to occur. They also reported that the reduction in NO emissions is caused by ceasing the NO formation by creating local lower temperature region.

Kurtz et al (2000) used auxiliary gas injection (AGI) to increase in-cylinder mixing during the latter portion of the combustion in a DI diesel engine in order to reduce soot emissions without affecting NO$_x$. The equipped auxiliary gas injector for injecting either nitrogen or air in three different directions 0, 45 and 90 from the center of the combustion chamber respectively.

d. Bluff bodies

Igarashi (1999) investigated the performance of the vortex shedders as shown in the Table 2.4. They reported that the vortex shedding caused by the circular cylinder with a slit and the triangular-semicircular cylinder is excellent in regularity and intensity as
compared to that of the ordinary trapezoidal cylinder and concluded that the circular cylinder having a slit corresponds to $d/D=0.2-0.267$ and $s/d=.1$ is the most efficient vortex shedder.

Possibly taking clue from role of vortex shedder in engine, Tanabe et al (2001) used bluff body as a vortex generator in the combustion chamber of a DI diesel engine and investigated the engine performance and the exhaust emissions. The also performed a 2-D unsteady computer simulation to classify the effect of the size and shape of the bluff body and compared with the experimental results obtained in the wind tunnel experiments. The bluff bodies were set in the piston cavity as shown in Fig. 2.15. They found that for both bluff body operation unburned emissions CO, THC, NO$_x$ and SOF are lower than non-bluff body operation at low load region.

e. CFD analysis for turbulence

Lisbona et al (2000) studied the process of fuel spray/wall interaction flame propagation and interaction with the piston surfaces and the most relevant mechanisms of soot formation and oxidation through CFD analysis to guide the plan of experiments. They studied two engine operating conditions viz.

a. Maximum power operation and quantified the effect of combustion chamber geometry on efficiency

b. The emission test cycle.

They analytically proposed a new combustion chamber having a small bowl which leads to higher swirl levels during expansion accompanied by more soot oxidation and slightly lower combustion efficiency.
2.3 CLOSURE

For improving performance and emission characteristics of a direct injection diesel engine, the two key aspects identified in this work include using fuel with additive for better combustion and modifying in-cylinder flow field through turbulence inducement providing better mixture formation. The fuel additive is expected to alter the physical and chemical characteristics of the fuel resulting in the reduction of fuel consumption and/or emissions. The literature on fuel additives reveal that use of aromatic, metallic and organic additives is widely reported. Many additives serving specific purposes in the engine on use are found to add to the fuel cost. In certain refinery processes, the availability of polymer based additive as a bye product could eliminate the cost consideration in their production. It is also felt that such additives are not thoroughly investigated.