ADVANCED COMBUSTION SYSTEMS AND ALTERNATIVE POWERPLANTS

The Lecture Contains:

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DIRECT INJECTION STRATIFIED CHARGE (DISC) ENGINES

Historical Overview

For many decades the researchers have pursued development of direct injection stratified charge SI engines to have overall very lean engine operation for higher fuel efficiency. Charge stratification is a means of ensuring repeatable ignition without misfire and stable combustion while using overall very lean fuel-air ratios that is otherwise not possible with homogeneous mixtures. In the stratified charge engines, the mixture composition is varied within the combustion chamber such that stoichiometric or slightly richer mixture exits near spark plug to provide good ignition characteristics and the mixture gets progressively leaner away from the spark plug. Overall air-fuel ratio in the cylinder is significantly leaner than the stoichiometric.

A typical configuration of DISC engine is shown on Fig 7.1. Liquid fuel is injected in the cylinder. The fuel spray is directed by air motion or by the geometry of piston crown or by combination of the both towards spark plug. By the time fuel spray reaches the spark plug electrodes some fuel gets vaporized and forms combustible mixture with air. The vaporized fuel in spray is then ignited by spark, combustion begins and the flame spreads in the combustion chamber.

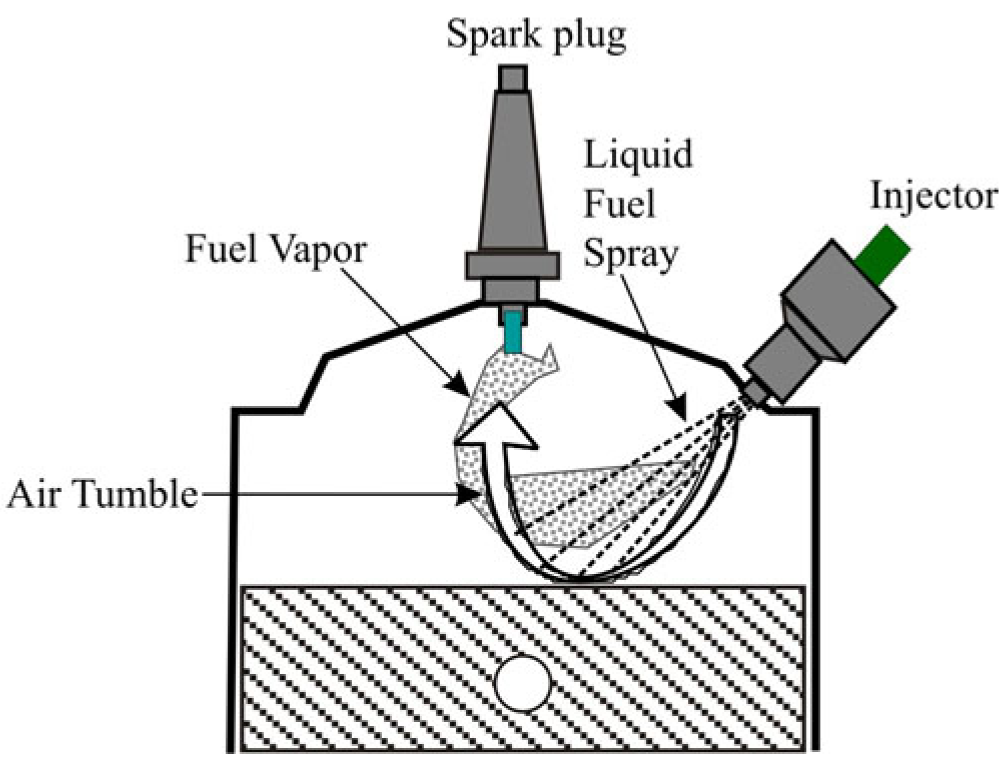

Figure 7.1	Schematic of a direct injection stratified charge (DISC) engine combustion system

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Development of direct injection stratified charge engines started in 1950s when Mercedes Benz developed an engine employing mechanical injection system. It was followed by development of two very widely known DISC engine prototypes during 1960s: Ford Programmed Combustion (PROCO) engine and Texaco's Stratified Charge (TCCS) engine. Both of these engines employed mechanical jerk type fuel injection systems. These engines could not be put into production as maintaining proper charge stratification under all engine loads and speeds was not possible. Moreover, the spray was directed very close to spark plug, which resulted in frequent spark plug fouling and also emission of black smoke at high engine loads.

During early 1970s, Honda developed a divided chamber stratified charge engine using two carburettor. A small carburettor provided rich mixture to the auxiliary small chamber where spark plug ignited the mixture. The lean carburettor supplied mixture to the main chamber and the overall mixture in the engine was significantly leaner than stoichiometric. The burning mixture from the small chamber flowed via a small throat into the main chamber like in the divided chamber diesel engines. This engine was called Honda CVCC (compound vortex combustion chamber) engine. The Honda CVCC engine had high fluid dynamic and heat transfer losses, and it also required catalytic aftertreatment for the medium size and bigger cars to comply with the then US emission standards. The production of this engine did not continue much longer.

During 1990s, fuel economy improvement to reduce emissions of CO_2, a greenhouse gas became a major thrust of research. As the DISC engine has the potential to give high fuel efficiency at part loads, it resulted into a renewed interest in DISC engine development. Mitsubishi and Toyota Motors introduced DISC engine powered cars during mid 1990s. These engines operate in stratified mode at part loads and in stoichiometric mode at high loads.

Potential Advantages of DISC Engines

The direct injection stratified charge SI engines have the potential to provide following advantages over the premixed homogeneous charge engines;

- The mixture being rich near spark plug good ignition characteristics without misfire are obtained.
- High combustion temperatures obtained as a result of initial burning of rich mixtures near spark plug produce high flame speeds that burn the lean mixtures in the cylinder away from spark plug.
- The overall air-fuel ratio can be very lean reaching 40:1 to 50:1giving high fuel efficiency.
- An unthrottled engine operation is possible such that the engine power may be controlled by varying only the fuel flow. It would reduce pumping losses.
- The end gases being very fuel lean, precombustion reactions would be very slow leading to reduced knocking tendency. Hence, a higher compression ratio can be used further improving the fuel efficiency.
- Presence of rich mixture near spark plug keeps the formation of NO_x at low levels. The mixture that burns early is deficient in oxygen although it attains high combustion temperatures.

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- Overall mixture being lean very low CO is produced as the CO produced early in combustion can be oxidized within the cylinder itself by the excess oxygen available.
- The mixture in piston ring crevice region being very lean the contribution of crevices to HC emissions would also be very low.
- The direct injection of fuel in the cylinder can decrease HC emissions during warm-up after cold start as liquid fuel film is not formed in the intake manifold and port. Also, a smaller fuel quantity needs to be injected during cold start compared to PFI engines.
- With direct injection of gasoline a faster dynamic response is possible hence a flatter air-fuel ratio curve during acceleration can be used that provides lower HC emissions.
- The DISC engines can tolerate higher EGR rates than the homogeneous charge SI engines and hence larger reductions in NO_x

DISC Engine Combustion Requirements

For stratified charge engine operation the following main requirements are to be met to obtain good combustion:

- Combustible mixture must form quickly.
- The liquid fuel and fuel over-rich zones should be minimum at the time of ignition
- Suitable air motion is to be provided during compression stroke and at the time of fuel injection to accomplish charge stratification and transport mixture to the spark plug in a reproducible manner cycle after cycle. Air motion may be aided by a suitably designed cavity on the piston crown.
- Wetting of piston crown and spark plug by excessive liquid fuel deposition is to be prevented.
- Over mixed zones having excessively lean mixtures beyond flammability limits as well as under mixed over-rich zones are to be avoided.

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Methods of Charge Stratification and Combustion

The methods of charge stratification and combustion that have been studied and some of these employed in production engines may be grouped in the following three types. These are also shown on Fig. 7.2.

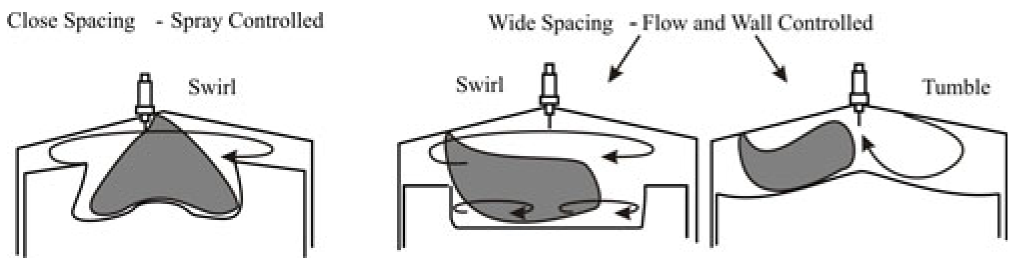

Figure 7.2	Spray, flow and wall controlled DISC engine combustion.

Spray Controlled: The fuel spray characteristics primarily controls the charge stratification in this strategy. Ignitable mixture is formed at the boundaries of the fuel spray. The spark plug is placed close to the spray as it is there that the ignitable mixture is present at the time of ignition. Formation of good quality mixture becomes difficult at high engine loads. The combustion being highly sensitive to spray characteristics smoke formation is often observed at high loads. Wetting of the spark plug by liquid fuel causes frequent spark plug fouling.

Wall Controlled: In the wall-controlled concept, fuel injection is directed towards a specially designed piston cavity. The piston cavity is off centre. The spark plug is located away from the fuel injector on the side of combustion chamber. Fuel impinges on the piston cavity walls where it evaporates and mixes with air. An intense reverse tumble charge motion transports the mixture to spark plug electrodes.

Flow Controlled: Mixture is formed by interaction between fuel spray and suitably directed air motion like swirl or tumble. The spark plug and injector are generally widely spaced in these configurations. The air motion transports mixture to the spark plug such that the ignitable mixture is present at spark plug electrodes at the time of spark. When air motion is well organized, the combustion chamber walls do not get wetted by liquid fuel and a stable stratified charge operation is obtained over a wide range of engine operation.

The characteristics of combustion process obtained with the three charge stratification and combustion methods are compared in Table 7.1

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Table 7.1

Comparison of DISC engine combustion process parameters with Spray, Wall and Flow controlled approaches, 2000 rpm, imep =2.8 bar

	Combustion parameter	Spray controlled	Wall controlled	Flow controlled
1	Injection timing, °btdc (approx.)	60	50 -55	40
2	Ignition timing after injection ends, ° CA	3 to 5°	35 -40	10 -15
3	Combustion duration, ° CA 0 -5% heat release 0- 50% 0- 85% 85-90 %	 20 – 25 45 75-80 10	 10 30 50-55 30	 10 25 50-55 5

In the spray controlled method formation of mixture takes longer hence initial heat release rates are small and the combustion duration corresponding to 0 -5% heat release is much longer compared to the other two methods. . On the other hand in the wall controlled approach, although the fuel initially evaporates quite rapidly due to hot walls, but it takes longer to evaporate all the injected fuel Thus, the end of combustion is significantly delayed with the wall controlled method compared to other methods. The flow controlled method has the shortest combustion duration due to better mixture preparation and high intensity of fluid motion and turbulence. In practice, the production DISC engines use a combination of both the wall and air flow controlled strategies to obtain good ignition and combustion characteristics. Mitsubishi engine uses a specially designed piston cavity and tumble air motion while Toyota engine employs a specially designed piston cavity and air swirl.

Modes of DISC Engine Operation

The early DISC engines such as Ford PROCO and TCCS attempted to operate in stratified charge mode throughout the engine operation range but it proved to be unsuccessful and acceptable engine performance and emissions over the entire speed-load range could not be obtained. With mechanical injection system precise control of injection timing also could not be maintained. The current direct injection gasoline engines operate in the stratified charge mode at part loads and up to medium speeds while at high engine loads the engine are made to operate as stoichiometric homogeneous charge engines. This is controlled by fuel injection timing.

Stratified Charge Operation: Fuel is injected late in the compression stroke There is not enough time for fuel to fully mix with air and a stable charge stratification at part loads at the time of ignition is obtained. Engine operates unthrottled and very lean overall air-fuel ratios reaching up to 50:1 are used.

Homogeneous Stoichiometric Operation: Fuel is injected early in the intake stroke to allow adequate time before ignition for fuel evaporation, mixing and formation of homogeneous mixture At high loads, early fuel injection timing is used to operate the engine in stoichiometric homogeneous mode.

Homogeneous Lean Operation: Engine operates homogeneous lean in the mid-load range. This is the transition zone from stratified mode at low loads to stoichiometric operation at full engine load.

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Injection strategy and typical operation regimes for a DISC engine are shown in Fig. 7.3 and their features are summarized in Table 7.2. The different features of DISC engine operation are summarized in Table 5.2

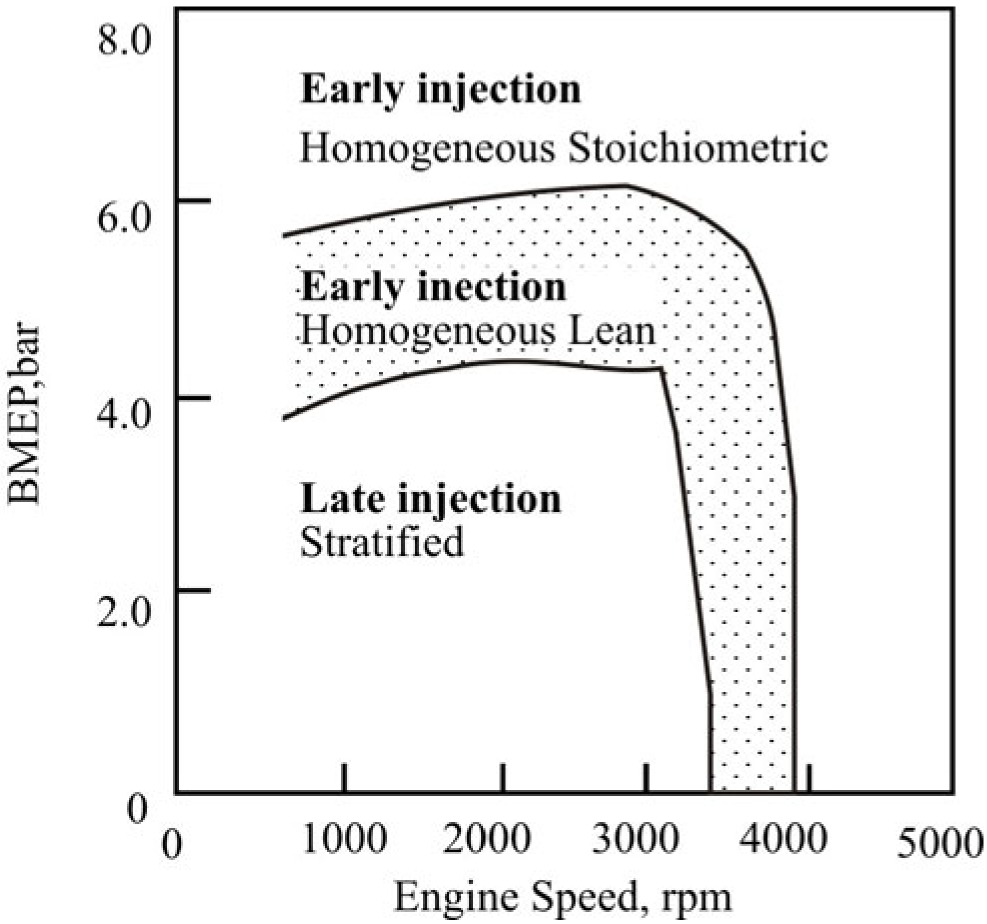

Figure 7.3	Fuel injection and operation strategy for DISC engines

Table 7.2
Features of DISC Engine Operation

	Stratified	**Homogeneous stoichiometric**	**Homogeneous lean**
Injection timing	Compression stroke	Intake stroke	Intake stroke
Air-fuel ratio	24 -50	14.7	24 to 14.7
Intake Throttling	Low	High	Medium

Mitsubishi and Toyota introduced 4-cylinder, DISC engine powered cars for the first time during 1996. Other manufacturers have also developed DISC engines. The DISC engines use 10 to 12:1 compression ratio and fuel is injected at 50 to 120 bar injection pressure. The leanest air-fuel ratio used is more than 40:1 reaching as lean as 55:1.

DISC Engine Performance and Emissions

The performance of a swirl dominated DISC engine is compared to that of a lean burn PFI engine on Fig. 7.4. Main differences observed are;

- The lean limit of homogeneous charge PFI engine was about 25: 1 A/F ratio, while the DISC engine could be operated well beyond A/F ratio of 40:1.
- The specific fuel consumption of DISC engine was lower by up to 20% compared to stoichiometric PFI engine. Other studies also showed 30 percent improvement in BSFC of DISC engines over the conventional PFI engine. Lower SFC results due to less throttling or unthrottled engine operation, and lean air-fuel ratio and higher compression ratio.
- PFI engines exhibit a continuous decrease in NO_x emissions as the mixture is leaned from near stoichiometric mixture. Very low NO_x emissions without EGR are obtained at air-fuel ratios higher than 20:1. DISC engine is seen to give significantly high NO_x levels even at overall air-fuel ratio of 45:1. In the DISC engine considerable amount of charge is contained in the combustion zones with stoichiometric or near stoichiometric mixture. The local burnt gas temperature in these zones is at higher level leading to higher NO_x formation than when the engine is operating in lean homogeneous mode at the same overall air-fuel ratio.
- The DISC engines have a higher tolerance of EGR before the combustion stability and fuel consumption becomes unacceptably poor as the mixture in the vicinity of spark plug in DISC engines is stoichiometric or richer and a stable combustion even with 40% or higher EGR rates is possible.

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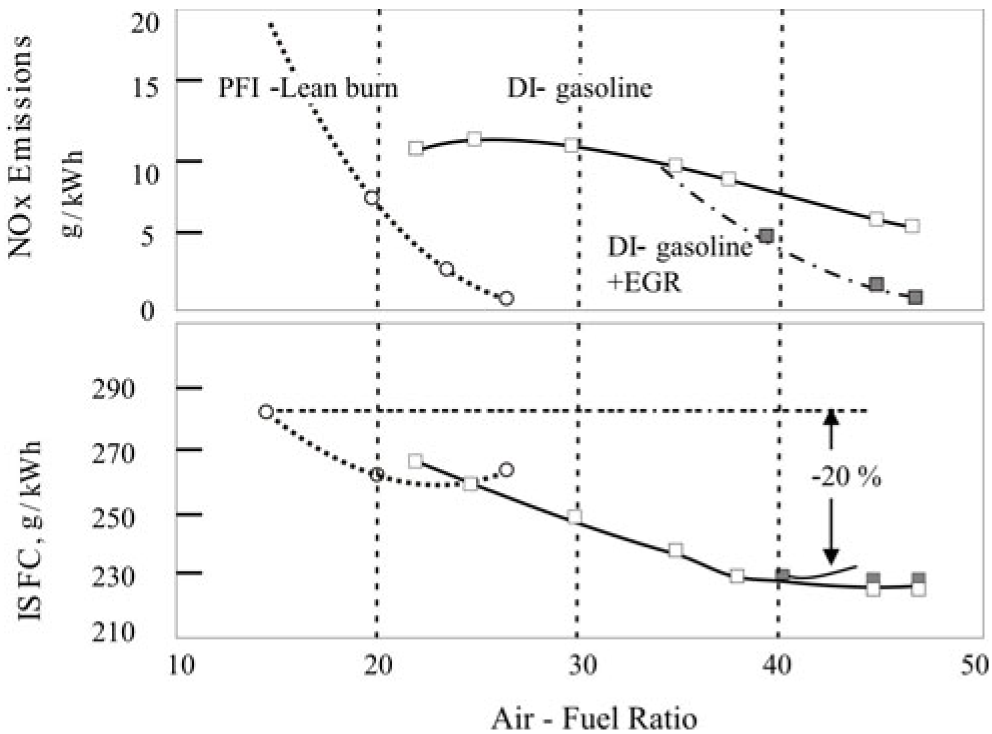

Figure 7.4	Comparison of performance and NO_X emissions of DISC and lean burn PFI engines.

The DISC engine gives much lower HC emissions than the PFI engine during engine cold start, engine warm-up phase and transient conditions. In the PFI engines during cold start and transient conditions, the amount of fuel entering the engine cylinder is not the same as being injected at the port as some fuel gets deposited at the port forming liquid

fuel film. Hence, in the PFI engine very rich mixture is to be supplied to have quick cold start. In DISC engines, as the fuel is directly injected in the cylinder there is no delay of fuel being inducted into the cylinder. The DISC engines on the contrary can be started on stoichiometric or even slightly overall lean mixtures. After engine is switched on, the DISC engine achieves stable combustion in the very first or second cycle while the PFI engine requires about 10 cycles to attain stable combustion. The cold start HC emissions from a DISC engine are nearly 1/4th of that of PFI engine. CO emissions of DISC engines are very low due to overall very lean engine operation.

For the success of DISC engines, catalytic reduction of NO_X under lean engine operation is required. Although with EGR large reductions in engine out NO_X emissions are obtained, but lean operating limit is narrowed with high EGR and during lean homogeneous engine operation high EGR cannot be used. Therefore, lean de-NO_X catalyst technology is essential to meet stringent emission standards in future while maintaining fuel economy benefits of the DISC engines. Mitsubishi and Toyota DISC engines employ a lean de-NO_X catalyst in addition to EGR to reduce nitrogen oxide emissions to the level of Euro 4 and beyond emission standards.

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