Effect of Fuel Injection Timing on The Performance And Emission Characteristics of HCCI Engine – A CFD Study

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Abstract*- Homogeneous charge compression ignition (HCCI) is a form of internal combustion engine in which homogeneously mixed fuel and oxidizer are compressed to the point of auto ignition. Controlling HCCI requires microprocessor control and physical understanding of the ignition process. HCCI engine achieves gasoline engine like emissions and diesel engine like efficiency.*

HCCI operation is affected by fuel injection timings; different injection timings will have significant effects in case of HCCI combustion. Variety of injection timing cases are studied and implemented in this study to investigate the heat release rate, combustion duration, and IMEP and emission characteristics.

A 3D CFD model is to be developed using CONVERGE CFD software with different fuel injection timings to understand the effects on theHCCI operation. The study considers a single cylinder light duty diesel engine based on a four-stroke, water-cooled, single-cylinder direct injection diesel engine. The CFD models used in the study are validated with available data from the literature. The pressure-velocity coupling is solved using PISO algorithm and in-cylinder turbulence is analyzed using RNG k-ε model. The combustion analysis is carried by a detailed chemical kinetics using SAGE model.

From the results it is clear that the injection timing of 320CAD and 270CAD are seems like conventional diesel engine combustion and leads to knocking. The cases of 220CAD and 170CAD injection timings results in good HCCI operation. The injection timing of 120CAD is not suitable for HCCI combustion because of poor combustion.

Keywords- HCCI engine, combustion, fuel injection strategy, emissions.

I. INTRODUCTION

Internal combustion [IC] engines are the leading source of power generation in automobile as well as industrial sectors. IC Engine converts thermal energy of combustion products into mechanical energy; on the other hand it also produces harmful emissions. Such as carbon monoxide (CO), carbon dioxide (CO_2), sulphur oxide (SO_2), un-burnt hydrocarbons (UHC), non-regulated hydrocarbons, oxides of nitrogen (NO_X) etc. [1-3]. Also, efficiency of conventional IC engines is very less (about 30%). Major part of thermal energy is wasted as heat. Thus main focus of today's IC engine research is towards achieving fuel economy and improving emission characteristics.

In this regards researchers has found advanced mode of combustion such as homogeneous charge compression ignition (HCCI), stratified charge compression ignition (SCCI), low temperature combustion (LTC) [1]. Among these HCCI engine is proved to have superior thermal efficiencies and ultra-low emissions of NOx and soot. It has potential to meet regulation of emission standards (EURO VI).HCCI engines use lean, premixed and homogeneous charge. This results in comparatively lower peak temperatures and pressure which gives less emissions and high efficiency. Due to low bulk temperatures NO_X emissions are low or negligible in compared with SI and CI engines. Unlike CI engines it uses premixed and homogeneous charge, hence simultaneous reduction in soot and particulate matter (PM) is possible.

II. LITRATURE REVIEW

Onishi et al., [6] applied the concept of HCCI combustion in a two-stroke gasoline engine using a high quantity of exhaust residual gas by trapping or re-cycling. They observed the ignition of the mixture at many points simultaneously.

Najt and Foster [7] performed experiments with four-stroke HCCI engine. They found that combustion in HCCI mode was kinetically controlled and the effect of turbulence and mixing was minimal.

Samveg et al., [8] reviewed the fundamental phenomenon affecting the low temperature combustion. They explained about chemical kinetics, hydrocarbon breaking, chemical reactions at low and intermediate temperatures, fuel characteristics, single and two-stage ignition; and the influence of molecular structure on fuel evaporation. Also explained about the importance of in-cylinder charge conditions to control combustion timing and strategy to extend the operating range of HCCI engine

Suyin et al., [9] reviewed the implementation of HCCI combustion in direct injection (DI) diesel engines and investigated the effect of design and operating parameters on NOx and soot emissions. Also, various strategies viz., port fuel injection (PFI), early direct injection (DI), late DI and multiple pulse injection were used in HCCI engine operation.
Mathivanan et al., [10] investigated the influence of multiple fuel injection strategies on the performance and combustion characteristics of a diesel fuelled HCCI engine. They adopted five injections using common rail diesel injector (CRDI) and analysed the effect of fuel injection timing and duration on the performance and emission characteristics of the engine. They concluded that, in the diesel HCCI mode, thermal efficiency with multiple fuel injection modes was higher and NOx emissions were lower compared to that of single injection mode.

III. METHODOLOGY

In this study CONVERGE CFD is used to analyse the engine operations. Solid works is used for modelling the engine and then it is executed on CONVERGE. The detailed examination of the engine is constructed for the cycle starting from the IVO (-4.5° CAD) to the EVO (504.5° CAD) in the CFD analysis. The CONVERGE uses the modified cut-cell Cartesian grid generation method and generates grid automatically during run time [8]. However, it provides control over meshing through fixed embedding and adaptive mesh refinement. In this complete study, the base grid size is 4mm, in order to determine the effect of turbulence and flow characteristics. The minimum grid size of the fixed embedding used is 0.5mm; depend on velocity, Temperature and species concentration adaptive mesh refinement is used. Computational grid of the engine is shown in Fig1.

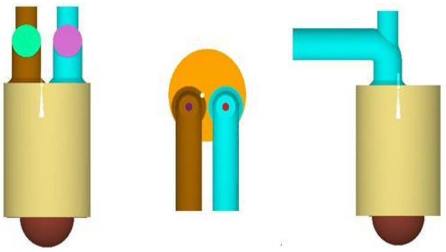


Fig 1: Geometric model of Engine

ENGINE SPECIFICATIONS

A single-cylinder, four-stroke, two-valve, flat cylinder head Engine with different shapes of pistons are used in this study. The comprehensive specifications of engine are given in Table1.and a single-hole type injector is used in the common rail system and is located at an offset distance of 5 mm from the cylinder axis.

BOUNDERY CONDITIONS:

In this present work cylinder, intake and exhaust are the three regions of the computational domain, Depending on valve opening and closing event these regions are connected. The specific details of inlet and outlet pressure and temperature are listed in the Table 2.

Table1. Engine Specifications

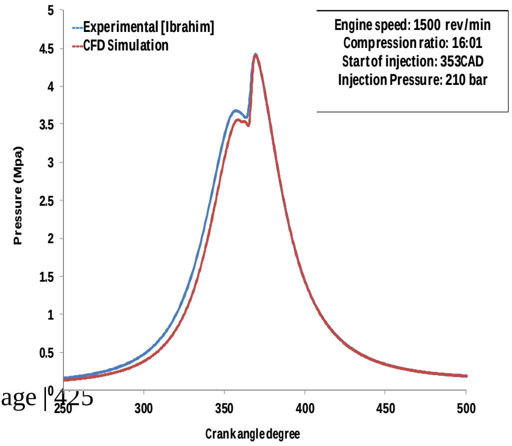
stroke	110mm
bore	80mm
Connecting rod	231mm
Compression ratio	16:1
Rated power	3.7k w
Engine speed	1500rpm
Number of valves	2
Valve Timings:	
Inlet Valve Opens (IVO)	4.5 before TDC
Inlet Valve Close (IVC)	35.5 after BDC
Exhaust Valve Opens (EVO)	35.3 before BDC
Exhaust Valve Close (EVC)	4.5 after TDC

Table2 boundary conditions

Inlet	Temperature 325k and Pressure 0.86 bar
Outlet	Temperature 625k and Pressure 1.01325 bar
Intake, Exhaust and Cylinder	Stationary Boundaries
Valves and piston	Moving Boundaries

Validation of CFD model

The CFD models have already been validated by Gurukiran et al [11] in their study. Validation was done based on the experimental results obtained from Ibrahim et al [9] on the same engine. Comparison of in-cylinder pressure with crank angles obtained from both the CFD and experimental results are shown in Fig 2, from the Fig it is evident that the comparative result is in good arrangement therefore the model in this work is to be considered well, therefore, this model is used in this work confidently.



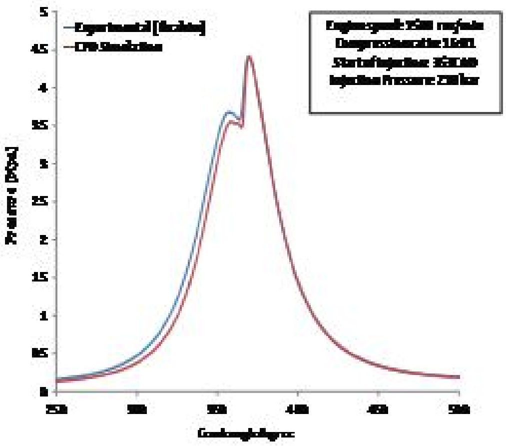


Fig 2: Validation of the model

IV. RESULTS

In this case, all the CFD simulations are carried out at the fuel injection pressure of 800 bars with equal fuel mass at different injection timings. It is interesting to compare the influences of injection timing on the in-cylinder pressure.

In-cylinder pressure

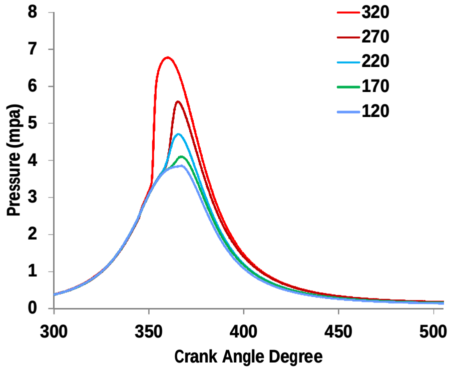


Fig 3: Comparison of in-cylinder pressure

Too higher and too lower in-cylinder pressure is not feasible because higher cylinder pressure causes knocking and lower cylinder pressure because of poor combustion. So injection timing of 120CAD and 320CAD are not suitable for better engine operation. Injection timing of 220CAD makes smooth pressure v/s crank angle curve so this injection timing can be confidently used for low load engines.

Mean temperature

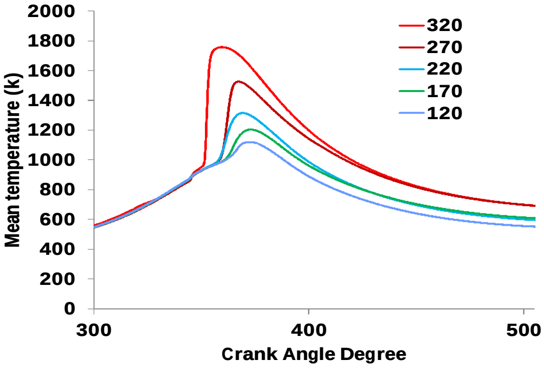


Fig 4: Comparison of mean temperature

Fig 3 shows the comparison of in-cylinder pressures of various injection timings. From the Fig it is clear that the in-cylinder pressure increases with increasing in the injection timings Fig 4 shows the comparison of mean temperature of various fuel injection timings at constant injection pressure of 800bar. From the Fig it is clear that the cylinder mean temperature of 320CAD injection timing is very high and it seems like a conventional diesel engine and the case of 270CAD injection timing also has higher mean temperature. Higher in-cylinder temperature leads to auto ignition and knocking hence injection timings of 320CAD and 270CAD are not feasible for HCCI operation. Injection of 220CAD and 170CAD are maintaining a minimum mean temperature and these injection timings can be used for light duty HCCI engines. Too low mean temperature is also not suitable for HCCI operation because HC and CO emissions will be more for lower mean temperature.

Heat release rate (HRR)

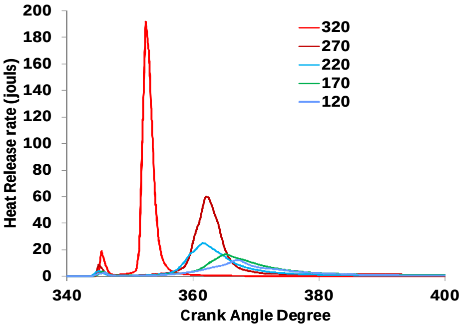


Fig 5: Comparison of heat release rate

Fig 5 shows the comparison of HRR for different fuel injection timings, from these Figs, it is generally seen that, the HRR curves have two peaks, representing two stages of heat release. First, there is a small rise in HRR curve like a small hump at about 345 CAD. This is called as cool flame stage. The cool flame releases a small amount of heat, because of certain intermediate radicals which disappear later. Then, there is a major heat release called as main combustion. The occurrence of the main combustion depends on the occurrence of the cool flame. From these Figs, it is also seen that, in all the cases considered, the occurrence of the cool flame has a slight difference. Therefore, it shows that, the fuel injection timing do not have much impact on the occurrence of the cool flame.

From the Fig it is evident that the injection timing of 320CAD has very high steep heat release curve in small crank angle duration, so too high heat release rate is because of abnormal combustion results in knocking; the rate of heat release is taking place before TDC, hence it is clearly indicating the pre-ignition phenomena and pre-ignition makes engine knocking. Therefore the fuel injection timing of 320CAD cannot be used

For better operation of HCCI combustion heat release rate should be minimum, injection timing of 270CAD also makes knocking. Fuel injection timing of 220CAD and 170CAD cases has smooth curve of HRR, it indicates the longer combustion duration. So both these fuel injection timings can be confidently used. And fuel injection timing of 120CAD has too low HRR; it indicates the poor combustion of the mixture.

Indicated mean effective pressure (IMEP)

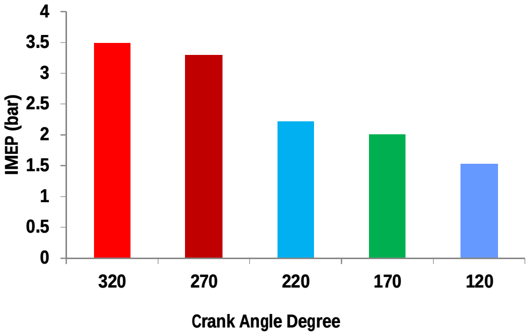


Fig6: Comparison of IMEP

Indicated mean effective pressure is an hypothetical pressure which is acting on piston in the cylinder due to the combustion process or it is an average pressure acting on the piston during different portions of an engine cycle. Fig 6 shows the comparison of Indicated Mean Effective Pressure of different fuel injection timings. IMEP is depending upon the in-cylinder pressure if the in-cylinder pressure is high the IMEP will be higher. from the Fig it is clear that the injection timing of 320CAD and 270CAD has higher IMEP because the in these both cases the fuel is injected just before the TDC so the spontaneous combustion takes place and higher pressure will act on the piston so IMEP is higher.

Injection timings of 220CAD and 170CAD cases produce IMEP of 2.4 and 2.2 bar respectively. In these both cases combustion duration and in-cylinder pressure is gradual and proper ignition will takes place. In case of 120CAD injection timing the IMEP is low of about 1.5bar it is because the poor combustion results in lower in-cylinder pressure as well as lower IMEP.

Soot emission

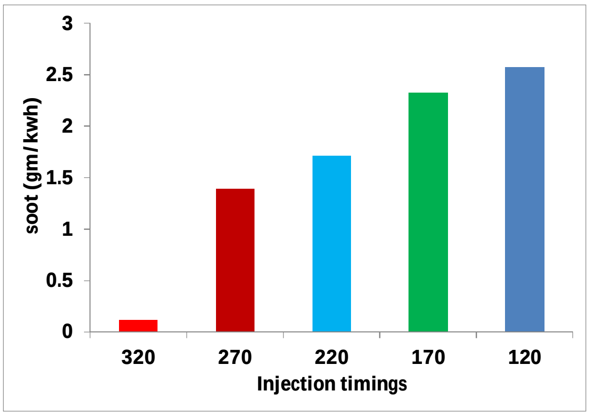


Fig 7: comparison of Soot emissions

Fig 7 shows comparison of soot emissions of various fuel injection timings. Soot is formed because of incomplete combustion occurs when the supply of air or oxygen is poor. Water is still produced, but carbon monoxide and carbon are produced instead of carbon dioxide. The carbon is released as soot. Carbon monoxide is a poisonous gas, which is one reason why complete combustion is preferred to incomplete combustion.

From the Fig it is clear that the as the injection timing increases the soot emission decreases so from the case of 120CAD to 320CAD the soot emission is gradually decreasing.

NOx emission

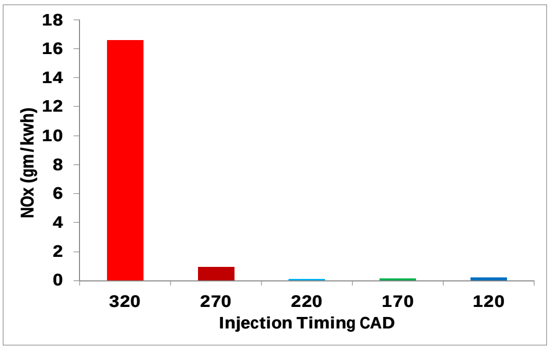


Fig 8: Comparison of NOx emissions

Fig 8 shows the comparison of NOx Emissions of different fuel injection timings. From the above Fig it is known that the earlier injection timing forms lower NOx emissions where as the later fuel injection timings results in higher NOx emissions. NOx emission is temperature dependent product; these emissions directly depending on the combustion temperature. In case of 320CAD injection timing the combustion temperature is high hence the formation of NOx is high.

HC emission

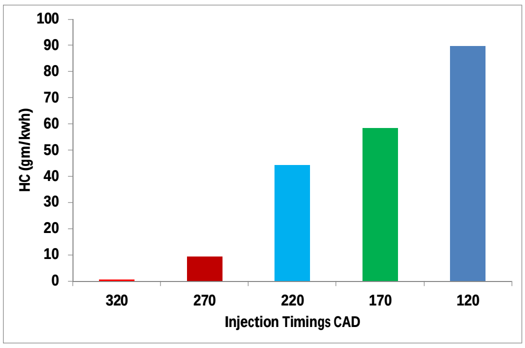


Fig 9: Comparison of HC emissions

Fig9 shows the comparison of HC emissions of various fuel injection timings of HCCI combustion. The above Fig clearly indicating that earlier fuel injection timing forms higher HC emissions where as the later injection timings forms very low HC emissions. From the Fig it is clear that as the fuel injection timing retards the HC emissions gradually decreases. This is because of lean or rich air-fuel ratio, poor ignition performance.

CO emission

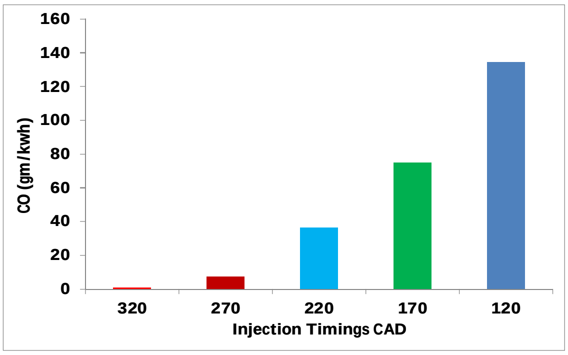


Fig 10: Comparison of CO emissions

Fig 10 shows the comparison of CO emissions of different fuel injection timings of HCCI engine. The causes of CO emission are similar to the causes of HC emissions. TheFig indicating that the earlier fuel injection timings forms higher CO emissions whereas later injection timing results in lower HC formation. The formation of higher HC emissions is mainly depending on the air-fuel (mixture) preparation, homogeneity of the mixture and combustion quality. If the mixture is too lean or too rich the poor combustion takes place hence higher CO emission is formed.

V. CONCLUSION

In this present work fuel injection timing is changed, each injection timing has a difference of 50 CAD. From the results it is known that the performance of an HCCI engine is affected by fuel injection timing. From the analysis of results, the following conclusions are drawn

- Injection at 320 and 270 CAD are not feasible for HCCI engine operation, because it leads to early ignition and tends to knock.
- Fuel injection at 220 and 170 CAD makes better combustion and performance and there is no knocking phenomenon.
- Injection at 120 CAD is not suitable for low load conditions because the mixture became too lean so the combustion efficiency is lower.

VI. ACKNOWLEDGMENTS

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