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ORIGINAL ARTICLE

Effective reduction of in-cylinder peak pressures in Homogeneous Charge Compression Ignition Engine – A computational study

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Abstract HCCI mode of combustion is known for simultaneous reduction of NOx and PM emissions besides yielding low specific fuel consumption. The nature of volumetric combustion of HCCI engine leads to the development of high peak pressures inside the combustion chamber. This high peak pressures may damage the engine, limiting the HCCI engine life period and thus demands sturdy designs. In this study an attempt is made to analyze computationally the effect of induction swirl in reducing the peak pressures of a HCCI engine under various operating parameters. For the study, specifications of a single cylinder 1.6 L, reentrant piston bowl diesel engine are chosen. For the computational analysis ECFM-3Z model of STARCD is considered. This model is suitable to analyze the combustion processes in SI and CI engines. As HCCI engine is a hybrid version of SI and CI engines, ECFM-3Z model with necessary modifications is used to analyze the peak pressures inside the combustion chamber. The ECFM-3Z model for HCCI mode of combustion is validated with the existing literature to make sure that the results obtaining are accurate. Numerical experiments are performed to study the effect of compression ratio, equivalence ratio, exhaust gas recirculation and boost pressure under different swirl ratios in reducing the in-cylinder peak pressures. The results showed that swirl ratio has a considerable impact in limiting the peak pressures of HCCI engine. The analysis resulted in achieving about 21% reduction in peak pressures are achieved when a swirl ratio of 4 with 30% EGR is adopted when compared to a swirl ratio of 1 with 0% EGR. The study revealed that out of the four operating parameters selected, lower compression ratios, higher EGR concentrations, lower equivalence ratios, lower boost pressures and higher swirl ratios are favorable in reducing the peak pressures.

1. Introduction

The Homogeneous Charge Compression Ignition (HCCI) is considered to be the principally promising future IC engine combustion concepts. HCCI is a concept of hybrid

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combustion, between conventional combustion concepts of spark ignition engine and compression ignition engine. HCCI concept is however not a modern finding. Already in the early twentieth century hot bulb engines operated with an HCCI-like combustion. They were superior in terms of brake thermal efficiency compared with the contemporary gasoline engines and at the same level as the diesel engines. Research has revealed that high engine efficiencies, ultra low NO emissions and low particulates are the benefits of HCCI engines. Volumetric autoignited combustion of the compressed lean air–fuel mixture is attributed to these benefits. Though HCCI concept is attractive, it suffers from few limitations such as low specific output, narrow operating range, lack of control over the ignition process, long start-up time and high levels of CO and UHC emissions. The CO and UHC emissions can be after treated using catalytic converters [1–3]. Heywood et al. explained the combustion characteristics of HCCI combustion along with the many other fundamental concepts about the combustion in an IC engine. Heywood reported that the problems such as high particulate matter and soot emissions (because of fuel rich and diffusion rich regions) associated with the conventional CI engine can be overcome by HCCI engines. Volumetric combustion and low temperature combustion of HCCI engine resulted in low particulate and soot formations. Also, low specific fuel consumption was the most attractive of HCCI engines when compared with the conventional CI engines [4]. Onishi et al. conducted experiments to visualize the process of combustion on a conventional SI engine in both SI and HCCI modes using schlieren photography method. From their experimental results they reported that very wee defined propagation of flame was found in SI operation mode but no visible propagation of flame was found in HCCI mode of combustion; proving volumetric combustion of HCCI engines [5,6].

Chen et al. numerically investigated the effect of EGR in reducing the pressure rise rate in HCCI engine. They incorporated CHEMKIN and SENKIN code for the analysis. They reported that with increase in EGR fraction retarded the start of combustion and decreased the peak pressure and temperature rise. Under the same conditions with increase in EGR ratio, extension in preparation of thermal ignition and advancement in LTHR timing were observed [7].

Swirl helps in homogeneous mixture formation of the fuel and air [8]. It also helps in NOx emission reduction [9]. The increase in swirl ratio reduces the peak temperatures by increasing the heat transfer to the combustion chamber parts. This leads to a low temperature combustion process resulting in low NOx emissions [10].

Performing these explorations (under different operating parameters with induction induced swirl) solely in the laboratory would be expensive, inefficient and impractical because of the complex interactions of the many variables. Because of this reason, a CFD tool Star-CD is chosen for the analysis. Several modifications were made to Star-CD es-ice module so that it could be used for HCCI engine modeling. Many commercial CFD packages such as Open FOAM, Ricardo Wave, GT Power, AVL FIRE are available to simulate the combustion process in IC engines. In the present work "es-ice" of STAR-CD is used for the analysis. The various models developed for presaging the engine combustion processes are Transient Interactive Flamelets (TIF) model, Digital Analysis of Reaction System-Transient Interactive Flamelets model (DARS-TIF), G-equation model, Extended Coherent Flame Combustion Model-3 Zones [11,12] and the Equilibrium-Limited ECFM (ECFM-CLEH) [13,14]. Each combustion model possesses limitations and advantages and is appropriate for a particular set of problems. In general ECFM-CLEH and ECFM-3Z are suitable for almost all types of combustion regimes, but ECFM-3Z is mainly applicable for premixed homogeneous turbulent combustion with both SI and CI. Table 1 shows the applicabilities of the various combustion models. Due to its vast range of suitability, ECFM-3Z has been used in the present investigation to examine the impact of piston bowl geometry on flow and combustion characteristics. Fig. 1 shows the schematic representation of the three zones of the ECFM-3Z model.

Induction induced swirl has a predominant effect on mixture formation and rapid spreading of the flame front in the conventional combustion process of a CI engine. This has been well documented in the literature. However, it is observed that no work has been done on the effect of swirl in HCCI mode.

The main objective of the present study was to analyze the effect of induction induced swirl in reducing the peak pressures of the HCCI engine under varying operating parameters. Because of the volumetric combustion the development of peak pressures inside the combustion chamber is very high. This is one of the limitations of the HCCI engine which demands the rigid body construction of the engine and reduces the engine life. In this regard a computational attempt is made to control the peak pressures in terms of induction induced swirl along with other parameters.

2. Methodology

A DI single cylinder CI engine with two different piston bowls was considered for the analysis. The specifications of the engine are tabulated in Table 2 have been considered for the analysis. Reentrant and spherical piston bowls are taken. Care was taken to have same clearance volume with all the two piston bowls. To study the parameters such as flame distribution inside the combustion chamber, rates of heat release, temperatures, pressures and emissions of NO and CO a multidimensional CFD package of STAR-CD; ECFM-3Z is used. The model of the piston bowl shaper was prepared and meshed as per the specification without having any variation in the compression ratio. The analysis was started with a starting angle of 680° CA and ending angle of 800° CA.

3. CFD model set-up

A spline was created in the shape of the piston bowl and was transformed into a 2D template. The 2D template was then cut into 3D piston bowl representing 1/6th of the piston bowl. The 1/6 piston bowl computational mesh has around 128,000

Table 1 Combustion model capabilities.

Model	Applicability
G-Equation	Partially premixed SI and CI
DARS-TIF	Compression ignition
ECFM	Non-homogeneous premixed SI
ECFM-3Z	Premixed and nonpremixed SI and CI