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Full Length Article

Evaluation of in-cylinder mixture homogeneity in a diesel HCCI engine – A CFD analysis

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ABSTRACT

Performance and emission characteristics of HCCI engines depend on achieving a good in-cylinder homogeneous mixture. The formation of in-cylinder mixture depends on many engine parameters, which need optimization. In addition, as of now, there is no direct way to clearly describe and estimate in-cylinder mixture homogeneity. In the CFD analysis, it is evaluated indirectly using contour plots of equivalence ratio, variation of in-cylinder pressure with crank angles, heat release curves or by the comparison of emissions. In this study, an attempt has been made to develop methods to evaluate the in-cylinder mixture homogeneity by the CFD analysis using AVL-FIRE. Here, global and local in-cylinder fuel distribution and in-cylinder fuel distribution index are used to evaluate the mixture homogeneity. In order to evaluate these methods, mixture homogeneities in two cases of fuel injections with 7- and 10-hole injector are compared. Finally, we found that the global fuel distribution (GFD) plot helps direct quantitative assessment of mixture distribution in various ER range. However, the GFD method cannot explain the spatial variation of fuel distribution and does not provide mixture homogeneity on a simple scale. In the method of plotting fuel distribution index, the overall homogeneity will be evaluated on a scale of 0 to 1 by a simple way. In the method of plotting local fuel distribution (LFD), the spatial variation of mixture homogeneity is well defined in local zones both in radial and axial directions. Further, these proposed methods help us to reduce the computation time significantly.

1. Introduction

Diesel engines constitute a major portion of transportation sector worldwide. But a main problem associated with the diesel engines is of high emissions of smoke, nitric oxides (NOx) and particulate matters (PM). There are many ways to overcome this problem in diesel engines. One of the solutions is homogeneous charge compression ignition (HCCI) concept, which is becoming very popular today.

The HCCI concept mainly involves a low temperature combustion of a homogeneous air–fuel mixture, which leads to simultaneous reduction of smoke, NOx and PM emissions. But the main challenge to the concept of HCCI is that it requires preparation of the homogeneous air–fuel mixture in short time duration. In addition, the homogeneity of air–fuel mixture is also influenced by many engine parameters viz., combustion chamber geometry, fuel injection parameters and engine operating conditions, etc. Therefore, understanding how the mixture homogeneity is affected under different operating conditions in a HCCI engine is very much essential.

Late injection HCCI concept [1–6] is a promising solution that is being explored by many researchers around the world for emission reduction in diesel engines because of the ease of control of the start of combustion and the rate of pressure rise. In order to achieve a good in-cylinder mixture homogeneity, engine parameters viz., compression ratio, piston bowl shape, number of injector holes, swirl ratio, fuel spray cone angle, fuel injector flow rate etc., need to be optimized. At present, even though a good amount of research work is being carried out to optimize the engine parameters to get good in-cylinder mixture homogeneity, there are no direct ways – either experimental or theoretical to evaluate the mixture homogeneity. Generally, the optimization of engine parameters is done by using CFD analysis [7–11]. Some of the current methods used are as follows.

1.1. Contour plots of equivalence ratio (ER)

The contour plots of ER show the variation of ER inside a combustion chamber. It is a widely used method for an assessment of in-cylinder mixture homogeneity [7–10,12,20–22]. In this method,

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the in-cylinder the mixture homogeneity is better and the range of ER in contour plots is better. Rich and lean mixture zones can be assessed by studying ER contour plots at different sections of combustion geometry. However, this method has certain limitations like: (i) it gives only a qualitative assessment and change in mixture homogeneity cannot be quantified, (ii) time consuming and interpretation of results can vary from person to person, and (iii) marginal changes in mixture homogeneity cannot be identified during a parametric study.

1.2. Plots of rate of heat release and in-cylinder pressure

Plots of the variation of rates of heat release and in-cylinder pressure with crank angle are used to indirectly assess the mixture homogeneity [7,9,10,13–15]. In this method, the mixture homogeneity is better, the rate of pressure rise and heat release is higher, and the combustion duration is shorter. However, using this method, one cannot explain the reasons for the change in mixture homogeneity and spatial variation of ER.

1.3. Plots of exhaust emissions

NOx, PM, hydrocarbon (HC) and carbon monoxide (CO) emission levels in the exhaust gas are analyzed to indirectly assess the mixture homogeneity [7,9,10,13–17]. In this method, the mixture homogeneity is better and the engine out PM and NOx emissions are lower. This method also lacks in explaining the reasons for the change in mixture homogeneity and the spatial variation of ER.

1.4. Plots of temperature versus ER (T-ϕ)

T-ϕ plot is made at different crank angle during combustion, which helps understand variations of local gas temperature and equivalence ratio. In this method, the mixture homogeneity is better, combustion temperature and ER in each zone will be in the target ER range. Researchers used temperature versus ER plots to understand the combustion process and the mechanism of emissions formation [9,18]. However, with this method, it is difficult to quantify the spatial variation of ER and changes in mixture homogeneity.

1.5. Uniformity index (UI)

In this method, a non-dimensional parameter called uniformity index is used [19]. It is defined as,

$$UI = 1 - \frac{1}{2n}\sum_{i=1}^{n}\frac{\sqrt{(w_i - w)^2}}{w_i} \quad (1)$$

where, n is the total number of cells; w and w_i are the average and local fuel mass fraction in the domain respectively. UI equal to 1 indicates that the fuel distribution is homogeneous, whereas UI equal to zero indicates that the fuel is completely unmixed with the air. It is a simple way of defining the in-cylinder mixture homogeneity.

From the above discussion, we understand that, at present, there are no direct methods available to assess the in-cylinder mixture homogeneity. However, it is important to establish a direct method to evaluate the in-cylinder mixture homogeneity especially for HCCI engines. Therefore, in this study, we have developed direct methods to evaluate the mixture homogeneity.

2. The CFD analysis

2.1. The geometric modelling and meshing

In this study, three-cylinder, water-cooled, direct injection (DI) diesel engine is considered for the CFD analysis. The detailed specifications of the engine considered are given in Table A1 of the Appendix. The AVL-FIRE, a commercial CFD code, is used for this purpose. An engine cycle simulation including combustion has been performed between intake-valve-closure (IVC) to exhaust-valve-opening (EVO) period, i.e., the closed part of the cycle. A diesel engine simulation environment (ESE) tool is used to model and mesh the combustion geometry as shown in Fig. 1. Mesh size and number are selected based on the work carried out by Juttu [10]. The base engine results from the CFD are validated with experimental results as shown in Fig. 2.

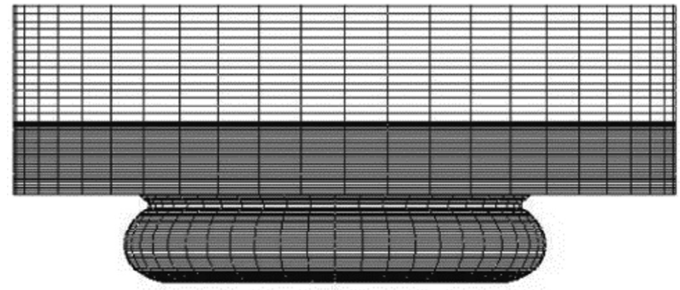

Fig. 1. Computational grid of the combustion chamber used for the CFD study.

Fig. 3 shows the dimensions of the combustion chamber shape and injector inclinations of the base engine used for CFD study. Re-entrant type piston bowl with two different injector configuration is used for the study.

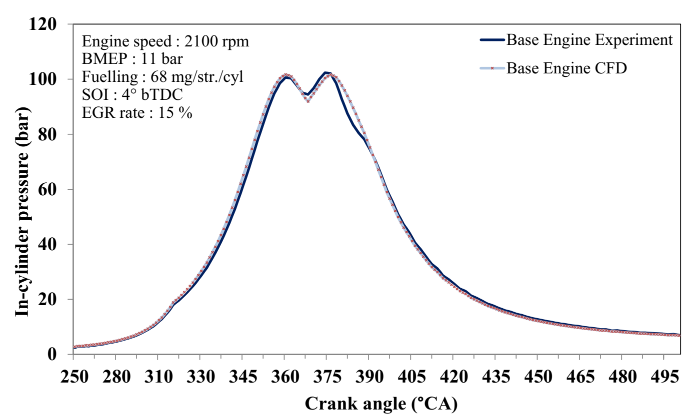

Fig. 2. Comparison of in-cylinder pressures of the base engine.

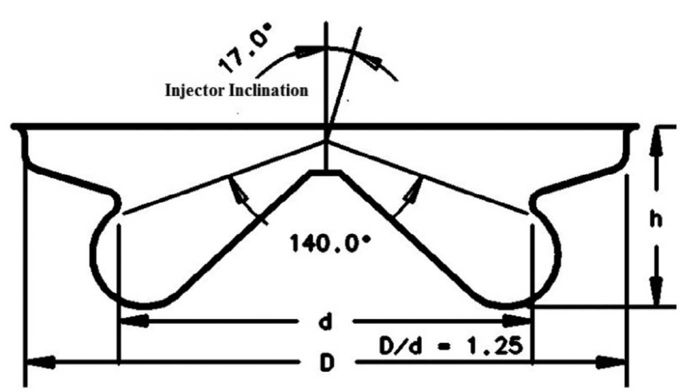

Fig. 3. Combustion chamber dimensions with injector inclination.