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Statistical analysis of the cyclic variations of heat release parameters in HCCI combustion of methanol and gasoline

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ABSTRACT

Combustion instability and cyclic variations lead to the requirement of closed loop control for use of homogeneous charge compression ignition (HCCI) engine technology for automotive applications. The closed loop control of HCCI combustion requires robust combustion timing parameters with a systematic and detailed study of its variations vis-à-vis engine operating conditions. An experimental study is conducted to provide insight into cyclic variations of HCCI combustion phasing for two fuels (gasoline and methanol) using statistical techniques. In this study, cycle-to-cycle variations of heat release parameters such as Maximum Rate of Heat Release ($ROHR_{max}$), 10% Mass Burn Fraction (MBF), 50% MBF, 90% MBF and Indicated Mean Effective Pressure (IMEP) of HCCI combustion engine fueled with methanol and gasoline were investigated using a modified two-cylinder, four-stroke engine. The experiments were conducted with different engine operating conditions at constant intake air temperature (140 °C) and different air–fuel ratios at constant engine speed (1500 rpm). To evaluate the cycle-to-cycle variations of combustion parameters at different test conditions, coefficient of variation (COV) and standard deviation of parameters were used. The results showed that CA_{50} (crank angle position of 50% MBF) is a robust parameter for the closed loop control of HCCI combustion.

1. Introduction

Internal combustion (IC) engines are mainly used for automotive and stationary applications. Stricter emission legislations, demand for increasing power density, and reduced fuel consumption are driving forces to explore the technical feasibility of different combustion concepts in IC engines. The most widely used combustion concepts are direct injection compression ignition (DICI) and spark ignition (SI). HCCI combustion is newly devised combustion concept, which is receiving increased attention of researchers worldwide for its potential to improve the thermal efficiency and drastically reduce the engine out emissions. HCCI combustion concept combines the best features of conventional spark ignition (SI) and compression ignition (CI) engine concepts. The HCCI combustion engines offer extremely high thermodynamic efficiency, low throttling losses and very low emissions. However limited operating range in HCCI combustion mode makes it an alternative to SI engine at part load conditions so as to improve the overall efficiency of the engine [1]. In conventional diesel engines, soot is formed in the fuel-rich regions and NOx in the high temperature regions therefore it is difficult to reduce both NOx and soot simultaneously. HCCI combustion has been proposed to eliminate the twin problem of fuel-rich regions and high temperature regions thus reducing soot and NOx simultaneously.

The fundamental principle of HCCI combustion is using a very lean fuel/air mixture in order to achieve low emissions of nitric oxides and high thermal efficiency. HCCI combustion engine operation can be described as a combination of a SI engine and a DICI engine. A homogeneous charge is prepared in the inlet manifold, wherein fuel and air are mixed before intake to the engine, just like in a SI engine. Following intake stroke, both the valves are closed and the initiation of combustion is governed by compression of the pre-mixed charge, just like in a CI engine [2].

In order to auto-ignite the lean mixtures, temperature of combustion chamber must be sufficiently high towards the end of compression stroke. Depending on the fuel quality, the temperature requirements are different for different fuels. High octane-number fuels do not auto-ignite easily (such as gasoline or ethanol) therefore it is required to (i) preheat the air/fuel mixture before the intake, or (ii) use high levels of internal residuals gases (hot gases retained in cylinder from one cycle to the next). With low octane-number fuels (such as diesel), attaining sufficiently high temperature for auto-ignition at the end of compression stroke may not be an issue however the temperature must still be high enough for the fuel to vaporize and form a homogeneous mixture during the intake stroke. Very rapid heat release rate resulting from auto-ignition of dilute

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fuel/air mixture may potentially causes high in-cylinder pressures and rapid pressure changes which may cause structural damage to the engine and may also lead to unacceptable noise levels. Therefore another key aspect in making HCCI combustion technically feasible is to control the heat release rate during combustion. Heat release rate depends on combustion phasing i.e. the time during the engine cycle, where combustion occurs, and the dilution of the mixture. Unlike SI and CI engines, there is no direct combustion timing control for the HCCI combustion engines. Ignition of homogeneous charge occurs when the temperature of combustion chamber reaches auto-ignition temperature of fuel-air mixture and the ignition delay period has elapsed after this. Therefore in HCCI combustion, the start of combustion is primarily governed by the chemical kinetics of auto-ignition. Thus, controlling the combustion timing requires the tuning of the auto-ignition kinetics, which is affected by in-cylinder charge composition and pressure and temperature histories of the reactants during the compression process [3,4]. Variety of techniques have been investigated for the control of combustion timing such as variable valve timing [5,6], variable compression ratio [7,8], hot exhaust gas recirculation [9] and intake air heating [4,10–14]. Mainly all these techniques adjust the temperature of the combustion chamber gases such that fuel-air mixture auto-ignite at the desired crank angle position in the combustion cycle. Control system readjusts the mixture temperature with the change in engine operating condition such as load and speed [3]. All these techniques are not equally suitable for closed loop control due to their slow response. Since HCCI combustion is highly sensitive to the temperature, unstable engine operation has been observed at some engine operating conditions. At high loads, due to relatively higher temperature of residual gases and cylinder walls, early combustion and faster combustion velocity may lead to pressure oscillation in the combustion chamber, and the resultant knocking may damage the engine. At light loads, lower initial in-cylinder temperature and leaner fuel/air mixture often results in large cyclic variations leading to misfire and partial combustion [15]. Cyclic variations in combustion process parameters have key role in combustion stability and operating range definition for the HCCI combustion engine [14]. Many studies are conducted to understand and control the cyclic variations in combustion parameters of SI engines [16–20]. However, little work has been reported on investigation of cyclic variations of parameters in HCCI combustion as compared to other conventional combustion modes. Some of the researchers have investigated the cyclic variations of different combustion parameters in different engine operating conditions using primary reference fuels and conventional fuels [14,21–25].

Systematic study of cycle-to-cycle variations of HCCI combustion parameters is essential for understanding the behavior of HCCI combustion and successful implementation of advanced control algorithms to control the engine. In our previous paper [14], the cyclic variations of different combustion parameters such as maximum cylinder pressure, rate of pressure rise, IMEP, maximum mean gas temperature, etc. were investigated in detail. Present investigation is focused mainly on the understanding of the cyclic nature of the ignition timing parameters to further understand the cycle-to-cycle variations of HCCI combustion in an engine. The objective of this study is to investigate statistical analysis of the cyclic variations of heat release parameters such as maximum rate of heat release (ROHR_{max}), 10% MBF, 50% MBF, and 90% MBF in a port fuel injected HCCI engine operating on methanol and gasoline at a constant engine speed (1500 rpm).

2. Experimental setup details

Our previous papers [12,14] cover the engine specification and experimental set-up explanation in detail, therefore in this section, only brief explanation about engine setup and experimental procedure is given. A two cylinder, four-stroke, naturally aspirated, direct injection diesel engine (Model: Indec PH2) was modified to achieve HCCI combustion in one of the cylinders and the experimental observations are also made on this cylinder. The experimental engine is air-cooled and its compression ratio is 16.5:1. An electronically controlled solenoid operated port fuel injector is used for injecting the fuel in the intake manifold in order to prepare a homogeneous mixture of fuel and air. An electronic driver circuit is designed, and used to control the fuel injection quantity and fuel injection timing. To auto-ignite the fuel-air mixture at the desired crank angle position, it is required to control the intake air temperature. Air temperature is modulated by closed loop controlled electric heater, placed upstream of intake manifold.

Schematic diagram of the experimental setup is shown in Fig. 1. Proper phasing of cylinder pressure data and volume data is required for correct calculations of rate of heat release and IMEP. This requires acquisition of cylinder pressure data with respect of crank angle position of the engine. An optical shaft encoder is used for precise crank angle measurement, which is connected to the engine through a flexible helical coupling. Flush mounted water-cooled piezo-electric pressure transducer is used for cylinder pressure measurement. LabVIEW based high speed data acquisition system developed in our laboratory is used for cylinder pressure data acquisition and analysis. In-cylinder pressure–crank angle history for 100 consecutive cycles was recorded and analyzed to evaluate the combustion parameter for each test condition.

Experiments were conducted at constant engine speed of 1500 rpm and constant intake air temperatures of 140 °C for different air–fuel ratios.

3. Definition of heat release parameters

HCCI combustion parameters are calculated for the study of cyclic variation using thermodynamic relations. Details of the equations used for the calculations of different combustions parameters in this study are given below:

Rate of heat release (ROHR): Calculated from the acquired cylinder pressure data using “zero dimensional heat release model” [26]. Consequently, the main combustion parameters were extracted from the heat release and in-cylinder pressure curves. ROHR was calculated as

$$\frac{dQ(\theta)}{d\theta} = \left(\frac{1}{\gamma - 1}\right)V(\theta)\frac{dP(\theta)}{d\theta} + \left(\frac{\gamma}{\gamma - 1}\right)P(\theta)\frac{dV(\theta)}{d\theta}$$

The following assumptions were made in this calculation.

I. The cylinder charge was considered to behave as an ideal gas.
II. Distributions of thermodynamic properties inside the combustion chamber were considered to be uniform.
III. Dissociation of combustion products was neglected.
IV. No variation in the cylinder mass due to blow-by was considered.
V. Heat transfer from the cylinder is neglected in this model.

The ratio of specific heat is calculated by equation [27]

$$\gamma = \gamma_0 - \frac{k}{100}\frac{T}{1000}$$

γ_0 is the γ value at some reference temperature, usually 300 K. γ_0 is dependent on the gas composition. For pure air, γ_0 is 1.4 and for lean air/fuel mixtures, 1.38 is an usable value. The constant k is usually set to about 8.