Applied Energy 88 (2011) 1153–1163

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental investigation on the effect of intake air temperature and air–fuel ratio on cycle-to-cycle variations of HCCI combustion and performance parameters

Rakesh Kumar Maurya, Avinash Kumar Agarwal *

Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

ARTICLE INFO

Article history:
Received 12 May 2010
Received in revised form 8 September 2010
Accepted 29 September 2010
Available online 23 November 2010

Keywords:
Homogeneous charge compression ignition (HCCI)
Coefficient of variation (COV)
Ethanol
Combustion stability
Cycle-to-cycle variation

ABSTRACT

Combustion in HCCI engines is a controlled auto ignition of well-mixed fuel, air and residual gas. Since onset of HCCI combustion depends on the auto ignition of fuel/air mixture, there is no direct control on the start of combustion process. Therefore, HCCI combustion becomes unstable rather easily, especially at lower and higher engine loads. In this study, cycle-to-cycle variations of a HCCI combustion engine fuelled with ethanol were investigated on a modified two-cylinder engine. Port injection technique is used for preparing homogeneous charge for HCCI combustion. The experiments were conducted at varying intake air temperatures and air–fuel ratios at constant engine speed of 1500 rpm and P-θ diagram of 100 consecutive combustion cycles for each test conditions at steady state operation were recorded. Consequently, cycle-to-cycle variations of the main combustion parameters and performance parameters were analyzed. To evaluate the cycle-to-cycle variations of HCCI combustion parameters, coefficient of variation (COV) of every parameter were calculated for every engine operating condition. The critical optimum parameters that can be used to define HCCI operating ranges are ‘maximum rate of pressure rise’ and ‘COV of indicated mean effective pressure (IMEP)’.

1. Introduction

Considering continuously stringent emission regulations, as well as increasing shortage of primary energy resources, the development of new highly efficient and environment friendly combustion systems, associated with alternative fuels has become increasingly important and hence research need to be carried out in this domain. Homogeneous charge compression ignition (HCCI) combustion concept received significant focus in recent years because of the advantages it offers. HCCI was identified as a distinct combustion phenomenon about 30 years ago [1,2]. The Homogeneous charge compression ignition engine concept is has potential to overcome the current fundamental NO_x and particulate emission trade-off limitation of conventional diesel engines. However, HCCI mode engines generate higher amount of unburned hydrocarbons (HC) compared to conventional engines and operate at significantly lower indicated mean effective pressure (IMEP) [3–11]. Also, there are difficulties associated with control of combustion initiation and rate of combustion over the required speed and load range of the engines [12,13]. These factors presently restrict the commercial exploitation of the HCCI combustion concept in the engine applications.

The main problem with the HCCI is that the ignition is completely controlled by chemical kinetics, and is directly affected by the fuel composition, equivalence ratio, and thermodynamic state of the fuel–air mixture [14–16]. There is no external control of initiation of combustion such as the fuel injection or spark timing that are used in traditional CI or SI engines. Achieving the required level of control during transient engine operation is even more challenging since charge temperature has to be correctly matched to the operating condition during rapid transients with a high repeatability when the speed and load are changing. The ignition timing and combustion rates are dominated by physical and chemical properties of fuel/air/residual gas mixtures, boundary conditions including environmental temperature, pressure, and humidity and engine operating conditions such as load, speed, etc. Because of these reasons, wide cycle-to-cycle variations are observed in HCCI combustion engines. Even small changes in ignition timing and combustion rate bring large variation in engine performance and emissions [17]. As a result, wide cycle-to-cycle variations, combustion instability under lean combustion condition and knock combustion constrain operating range of HCCI combustion engines. Cycle-to-cycle variations in combustion process are essential as they play important role in combustion stability and operating limit decision for the HCCI engine operating range. Many researchers reported coefficient of variation of IMEP (COV_{IMEP}) and maximum rate of pressure rise as HCCI operating region criteria [18,19].

---

* Corresponding author. Tel.: +91 512 259 7982; fax: +91 512 259 7408.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

0306-2619/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2010.09.027

Nomenclature

CAD	crank angle degree
CI	compression ignition
COV	coefficient of variation
COV_{IMEP}	coefficient of variation of indicated mean effective pressure
EVO	exhaust valve opening
$dP/d\theta$	rate of pressure rise
HCCI	homogeneous charge compression ignition
IMEP	indicated mean effective pressure
ISFC	indicated specific fuel consumption
IVC	intake valve closing
P	cylinder gas pressure
Q	heat release
ROHR	rate of heat release
SI	spark ignition
TDC	top dead centre
T	mean gas temperature
V	volume of the cylinder

Greek letters

λ	relative air-to-fuel ratio
θ	crank angle
γ	ratio of specific heats
σ	standard deviation

Mechanism and control of cycle-to-cycle variation in SI engines are systematically investigated by several researchers [20–25]. However, – little work has been reported on cycle-to-cycle variation and combustion stability of HCCI combustion. Xingcai et al. investigated the combustion stabilities and cycle-to-cycle variations of HCCI combustion using n-heptane, primary reference fuels 20 (PRF20), PRF40, PRF50 and PRF60 [17]. Lu et al. also investigated cycle-to-cycle variations under the lean burn limits and rich burn limits in HCCI Combustion using n-heptane [26]. Persson performed preliminary study on the cylinder-to-cylinder and cycle-to-cycle variations of controlled auto ignition (CAI) combustion with trapped residual gas [27]. Koopmans et al. investigated the cycle-to-cycle variations in a camless gasoline fuelled compression ignition engine [28]. Shi et al. investigated combustion stability of diesel fuelled HCCI and effects of engine load, speed and valve overlap [29]. Shahbakhti and Koch performed investigations of cyclic variation of ignition timing using primary reference fuels [30]. These cyclic variations and combustion instabilities lead to necessity of closed loop control of combustion phasing. This motivates the researchers to investigate the cycle-to-cycle variations in HCCI combustion engines. To gain an improved understanding of HCCI combustion, a systematic study of cycle-to-cycle variation of HCCI combustion is essential. The objective of this study is to investigate the effect of intake air temperature and air–fuel ratio on cycle-to-cycle variations in an ethanol fueled port injection HCCI engine operating at constant engine speed (1500 rpm).

2. Experimental conditions

A two cylinder, four stroke, air cooled, naturally aspirated, bowl shaped combustion chamber design; direct injection diesel engine was modified for these experiments. The engine specifications are given in Table 1. One of the two cylinders of the engine is modified to operate in HCCI mode, while the other cylinder operated like a conventional diesel engine at low load, thus motoring the first cylinder for achieving HCCI combustion in this cylinder.

Table 1
Detailed Engine Specifications.

Engine characteristics	Specification
Make/model	Indec/PH2
Injection type	Direct injection
Number of cylinders	Two
Bore/stroke	87.3/110 mm
Power per cylinder	4.85 kW @ 1500 rpm
Compression ratio	16.5
Total displacement	1318 cc
Fuel injection timing	24° before TDC
Fuel injection pressure	210 kg/cm^2 @ 1500 rpm

The fuel (ethanol) was injected into the intake manifold using an electronically controlled fuel injector. The fuel delivery system consists of a solenoid based fuel injector and an injection timing and injection duration control circuit. Fresh air entering the engine is heated by an electric air pre-heater positioned upstream of the intake manifold. The intake air heater is operated by a closed loop controller, which maintains constant intake air temperature at the entry to the intake manifold. The schematic diagram of the experimental setup is shown in Fig. 1. A thermocouple in conjunction with a digital temperature indicator was used to measure the intake and exhaust gas temperatures. An orifice meter and a U-tube manometer were used to measure the air consumption of the engine. A surge tank fixed on the inlet side of the engine maintains a constant airflow through the orifice meter and dampens cyclic fluctuations.

The in-cylinder pressure was measured using a water-cooled piezo-electric pressure transducer (Make: Kistler, Switzerland; Model: 6061B) which is mounted flush in the cylinder head. The pressure transducer minimizes thermal shock error by using a double walled diaphragm and integral water cooling system. In-cylinder pressure-crank angle history of 100 consecutive cycles was recorded for each test conditions using a high-speed data acquisition system. To measure the crank angle position, a precision shaft encoder (Make: Encoders India, Model: ENC58/6-720ABZ/5-24 V) is coupled with the engine crank-shaft using a flexible helical coupling. The in-cylinder pressure – crank angle history data acquisition and combustion analysis is performed using a program based on LabVIEW, which is developed at Engine Research Laboratory, IIT Kanpur for this purpose.

Experiments were conducted at constant engine speed of 1500 rpm and varying intake air temperatures ranging from 120, 140, and 160 °C at different air–fuel ratios for each intake air temperature.

3. Definitions of combustion parameters

To study the cycle-to-cycle variations of typical HCCI combustion and performance characteristics at different engine test conditions, following parameters are analyzed.

- $P_{\max}$: Maximum gas pressure in the cylinder.
- $\theta_{P\max}$: Crank angle corresponding to $P_{\max.}$
- $(dP/d\theta)_{\max}$: Maximum rate of pressure rise.
- $\theta_{(dP/d\theta)_{\max}}$: Crank angle corresponding to maximum rate of pressure rise.
- Rate of heat release (ROHR) rate: Calculated from the acquired data using the zero dimensional heat release model [31]. Consequently, the main combustion parameters were extracted from the heat release and in-cylinder pressure curves.