JFUE 9414
9 July 2015

ARTICLE IN PRESS

No. of Pages 10, Model 5G

Fuel xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel

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

Control of combustion process in an HCCI-DI combustion engine using dual injection strategy with EGR

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HIGHLIGHTS

- HCCI-DI combustion phasing can be controlled by varying premixed ratio and EGR.
- Peak pressure varies within a narrow range of 2 deg (5–7 deg BTDC).
- Peak HRR varies within a narrow range of 3 deg (1–4 deg BTDC).
- A reduction of 76% NO_X and 40% smoke emissions are achieved.

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form 17 May 2015
Accepted 2 July 2015
Available online xxxx

Keywords:
Homogeneous charge compression ignition
Dual injection
Premixed equivalence ratio
Premixed ratio
Two phase heat release

ABSTRACT

The objective of this study was to achieve a controlled HCCI-DI combustion using in-cylinder dual injection technique and to study the effect of premixed ratio and EGR on combustion, performance and emission characteristics of the engine. Studies were carried out up to 67% (0–67%) of the full load and a constant speed of 1500 rev/min. The premixed ratio was varied from zero to a maximum of 80% of the total fuel by mass. At 50% load condition, occurrences of peak pressure, peak PRR and peak HRR varied within 5–7 deg BTDC, 1.5–5 deg BTDC and 1–4 deg BTDC respectively. It was observed that diesel homogeneous combustion showed a two phase heat release pattern at higher premixed ratios and all combustion parameters advanced dramatically with increasing premixed ratio. The results showed that a reduction of 76% in NO_X and 40% in smoke opacity were achieved using 80% premixed ratio with 30% EGR. As the premixed ratio was increased, there was an improvement in IMEP, ISFC and smoke opacity with penalties in HC and CO emissions.

1. Introduction

Homogeneous Charge Compression Ignition (HCCI) combustion is a promising alternative to existing internal combustion engine operating modes and combines the benefits of conventional SI and CI engines [1]. Combustion occurs simultaneously throughout the whole combustion chamber in an HCCI combustion engine unlike conventional CI or SI engines. Different types of combustion systems have been proposed by several researchers; nevertheless all these systems demonstrate the auto-ignition characteristics of a homogeneous mixture. The HCCI combustion concept was first introduced by Onishi et al. [2] and Noguchi et al. [3] named as Active Thermo-Atmospheric Combustion (ATAC) and Toyota-Sokhen (TS) combustion respectively. Najt and Foster [4] investigated the Compression-Ignited Homogeneous Charge (CIHC) combustion in a 4-stroke engine and reported a very low cyclic variation and lower HC emissions at low load conditions.

A lot of advancements have been achieved in gasoline HCCI combustion engine. To name a few Lund Institute of Technology [5,6]; Shell Global Solution [7–9]; GM R&D [4,10]; ERC, Wisconsin University [11,12]; and Sloan Automotive research lab, MIT [13] are the most significant. Now a day, several US research lab mostly funded by U.S. Department of Energy (U.S. DOE) are closely involved in HCCI combustion research [14]. For instance Argonne National Lab (ANL) [11,12], Sandia National Lab (SNL) [15–17], Lawrence Barkley National Lab [LBNL] and Oak Ridge National Lab (ORNL) are among the most significant. All of the

Abbreviations: ATDC, after top dead centre; BDC, bottom dead centre; BTDC, before top dead centre; CI, compression ignition; EGR, exhaust gas recirculation; IMEP, indicated mean effective pressure; ISFC, indicated specific fuel consumption; ITE, brake thermal efficiency; PRR, pressure rise rate; RPM, revolutions per minute; SI, spark ignition; TDC, top dead centre.

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http://dx.doi.org/10.1016/j.fuel.2015.07.009

Nomenclature

r_p	premixed ratio	M_p	mass of the pilot or premixed fuel
F_p	premixed equivalence ratio	M_m	mass of the main fuel

above mentioned research lab are mainly focused on Gasoline fuelled HCCI combustion engine. "Lund Institute of Technology" is one of the pioneers in HCCI combustion technology where gasoline like fuels were used mainly because, highly volatile fuel helps in forming homogeneous mixtures, in addition, higher auto ignition temperature of gasoline like (high octane) fuel helps in extending the high load range of HCCI combustion engine [6]. This is the main advantage of gasoline like fuel over diesel like fuel when HCCI combustion is practised. At the same time achieving auto ignition with gasoline like fuel at low load is extremely difficult which results in misfire and thereby high cycle by cycle variation. Kalghatgi [9] proposed stratification controlled HCCI combustion which can achieve auto ignition even at very low load. He further suggested stratification can help in controlling auto ignition across various load range and hence combustion phasing can be controlled. Recent studies in Sandia National lab [15–17] and Delphi Automotive [18] have shown notable achievements in extending the load range of gasoline HCCI combustion engine using stratification technique. Stratification technique has become a key combustion control strategy for extending the load range of HCCI combustion [18,19]. Ciatti and Subramanian [20] in Argonne National Lab has shown that low octane fuel, stratification and EGR are extremely important to achieve controlled LTC combustion.

In a parallel way, stratification controlled diesel fuelled HCCI combustion concept are practised widely among automotive industries and academia all across the globe. Stratification technique has evolved as the most promising technology which is expected to dominate in near future.

Toyota and Nissan Motors have already commercialised diesel fuelled HCCI like combustion concept in Japanese market. Delphi Power train used this stratification technique for achieving HCCI combustion with diesel as fuel [21].

Studies [22–24] have reported that fuel consumptions worsened while running on HCCI mode using diesel fuel, which remained one of the major issues of such HCCI engines. Kimura et al. [25] demonstrated the Modulate Kinetics (MK) combustion concept and ultra low emissions of NO_X and smoke were reported. One of the most successful HCCI combustion technologies [26] using dual injection strategy was successfully implemented by Toyota Motors where early pilot injection was used to form a homogeneous mixture followed by a main injection to trigger the combustion. A detailed review [27] on diesel fuelled HCCI combustion provided the insight and importance of various operating parameters in such combustion systems. Homogeneous charge preparation itself is a major issue in diesel fuelled HCCI combustion engines. Thring. [28] showed that a port injection system could be used to prepare the homogeneous mixture but intake air heating and high EGR would be required to achieve HCCI combustion. Another major concern of HCCI combustion is knocking. This limits the high load operation of HCCI combustion engines [29]. To overcome these difficulties switching to conventional combustion during high load operation is an accepted option for HCCI combustion engines [29]. An interesting observation suggested that transition from conventional to premixed charge compression ignition (PCCI) during high load operation was possible by varying the fuel injection timing [30]. Ganesh et al. [31,32] reported that using external mixture formation they were able to achieve HCCI combustion with ultra low emissions. The Single early injected HCCI combustion [33] would have no control over the identifiable start of combustion and this is recognised as one of the major problems in achieving controlled HCCI combustion. HCCI combustion is governed by operating parameters like intake pressure, temperature, fuel air equivalence ratio, fuel type, engine speed and residual gas fraction. In other words, it is majorly controlled by chemical kinetics. Several studies [34–37] have been reported on dual and multi injection strategies as a means to achieve controlled homogeneous combustion. Double and multi-level injection strategies to achieve HCCI combustion in diesel engines are being investigated these days. An early pilot injection forms a homogeneous mixture and late injection near TDC controls the combustion phasing. It is realised that split injection timing and split injection ratio play significant roles in controlling combustion phasing of HCCI combustion. Several other control strategies have been proposed to control the combustion phasing of an HCCI combustion engine. A few strategies are EGR [37–39], controlling intake air temperature [40,41], reduced CR, retarded main injection timing and retarded single injection timing [42]. Some researchers [43,44] investigated a wide range of early single injection timings and studied their effect on HCCI combustion. They observed that as the mixing time was increased, combustion phasing was retarded thereby reducing NO_X and PM simultaneously but advanced injection also worsened the fuel consumption. Ra et al. [44] proposed that low pressure injection system was better as higher injection pressure would tend to increase the spray tip penetration resulting in wall wetting. Thus a low pressure injection system has been recommended as this would reduce the cost of the HCCI engine. Effect of split ratio on combustion and emission characteristics of HCCI-DI combustion engine using a novel dual injection strategy was presented in an earlier work. These studies showed that a two phase heat release pattern appeared in HCCI-DI combustion when low octane fuel was used [45,46].

From the literature, it is seen that pilot and main injection strategy is one of the most promising HCCI combustion phasing control technique. It is well understood that a second injection or main injection would certainly initiate the combustion and at the same time misfire can be avoided for low load HCCI operation. For HCCI combustion, controlling combustion phasing is extremely difficult. In the recent past, stratification technique has become very popular due to its inherent merits. The prediction of occurrences of peak pressure or the control of combustion phasing is not yet developed as combustion phasing is highly sensitive to variation in operating conditions while running on HCCI combustion mode. The available literature is limited to in-cylinder stratified controlled HCCI combustion. The present study is focused on the roles of premixed ratio and EGR on combustion phasing, performance and emission behaviour of a diesel fuelled HCCI combustion engine using dual in-cylinder injection. Dual injection is used to achieve homogeneous combustion where an early (pilot) injection forms a premixed homogeneous charge and a second (main) injection near the TDC is intended to trigger the combustion and thus a controlled combustion phasing is obtained. Present study covers both extreme low load range and the limiting high load range. Strategies have been identified and discussed how this load range can be extended further. This study also presents the effect of

Please cite this article in press as: Das P et al. Control of combustion process in an HCCI-DI combustion engine using dual injection strategy with EGR. Fuel (2015), http://dx.doi.org/10.1016/j.fuel.2015.07.009