Fuel Processing Technology 152 (2016) 413–420

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Research article

Spark assisted premixed charge compression ignition engine prototype development

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ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 1 July 2016
Accepted 7 July 2016
Available online 15 July 2016

Keywords:
Spark assisted premixed charge compression ignition
Homogeneous charge compression ignition
NOx
Port fuel injection
Gasoline compression ignition

ABSTRACT

Thermal efficiency of compression ignition (CI) engine is higher than spark ignition (SI) engine however heterogeneous fuel-air mixing in CI engine leads to higher NOx and soot formation. Fuel quality is deteriorating with time because of availability of heavier crude reserves. There is a need to use low volatility, low octane number fuels in the engines in an environment friendly manner. To investigate this, gasoline was blended with low volatility fuels such as diesel and kerosene. In order to improve fuel-air mixing, spark ignition of gasoline like fuels blended with low volatility diesel like fuels at higher compression ratio (11) was experimentally investigated in a prototype single cylinder partially premixed charged compression ignition (PCCI) engine. Experiments were conducted at a constant engine speed using five test fuels namely GD5 (5% v/v diesel blended with 95% v/v gasoline), GD15 (15% v/v diesel blended with 85% v/v gasoline), GK5 (5% v/v kerosene blended with 95% v/v gasoline), GK15 (15% v/v kerosene blended with 85% v/v gasoline) and G100 (100% gasoline), which was used as baseline fuel. Relative air-fuel ratio (RAFR) was maintained at 0.95 to avoid misfire at lower engine loads. Mixing and manifold injection of gasoline blended with diesel and kerosene was carried out at low pressure (3 bar) using a customized common rail fuel injection system. Spark plug was used for triggering the start of combustion at a fixed spark timing of 25° bTDC. Compression ratio of spark assisted partially premixed charge compression ignition (SAPCCI) engine was kept lower than conventional CI engine to avoid auto-ignition of test fuels however it was higher than conventional SI engine to achieve greater thermal efficiency. Fuel injection timing and injection duration were controlled by a customized electronic circuit. Engine performance, emissions and combustion characteristics were investigated and compared with baseline gasoline at different engine loads. GK5 and GD5 blends exhibited higher brake thermal efficiency than baseline gasoline in SAPCCI mode, which suggested that low volatility fuels can be used in SAPCCI mode in an engine efficiently.

1. Introduction

Homogeneous charge compression ignition (HCCI) is an emerging and promising technique, which uses homogeneous charge of fuel and air. This air-fuel mixture burns spontaneously and simultaneously throughout the combustion chamber, resulting in a very high heat release rate (HRR), which cannot be controlled easily. HCCI combustion offers substantial benefits such as high thermal efficiency and it resolves PM-NOx trade-off observed in conventional combustion modes. However HCCI combustion remains difficult to control at higher and lower engine loads. Partially premixed charge compression ignition (PCCI) combustion is a very promising combustion concept in tackling the problem of PM-NOx trade-off as well, in which highly advanced fuel injection is used. PCCI and HCCI combustion concepts are also known as low temperature combustion concepts, which are inherently effective in controlling NOx emissions. NOx emissions can be further reduced by using variable EGR, which affects the P-θ and HRR curve shapes. However, in order to tackle the drawbacks of HCCI combustion, researchers used compound HCCI techniques, in which, port fuel injection and in-cylinder direct injection techniques were combined together for using gasoline/diesel blends. In compound HCCI technique, spark assistance was not used, hence compression ratio of the engine was higher (016) than a typical SI engine. Two-stage injection strategy made fuel injection system more complex and this strategy was not able to achieve smooth pressure-crank angle curve. In addition, pure gasoline could not be ignited in this combustion mode. Hence, port fuel injection of premixed gasoline/diesel and gasoline/kerosene blends were considered.

First diesel HCCI engine was experimentally demonstrated by Najt and Foster [1] in 1983, however HCCI combustion concept in any IC engines was first demonstrated in a two-stroke engine by Onishi et al. [2] in 1979. Gray et al. [3] concluded that for effective homogeneous mixture preparation, avoiding fuel-wall interaction was crucial. This was helpful in achieving high thermal efficiency and reducing emissions in

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http://dx.doi.org/10.1016/j.fuproc.2016.07.006
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HCCI combustion mode. In order to overcome drawbacks and limitations of HCCI combustion, researchers employed techniques such as variable EGR and variable intake air temperatures. Hyvönen et al. [4] used a modified variable compression ratio (VCR) engine for investigating spark assisted HCCI combustion and compared it with baseline HCCI combustion. Combustion phasing was controlled by varying the compression ratio. They mainly emphasized on intermediate engine cycles during mode switching, and experienced higher fluctuations in lean combustion mode. Higher intake air temperature increased coefficient of variation (COV) for intermediate cycles. Raw NOx emission levels ranging from 4–8 ppm for spark assisted HCCI mode and 1–2 ppm for conventional HCCI mode were recorded. Lower compression ratio was the main reason for ultra-low NOx and PM emissions in diesel HCCI combustion mode [5]. Ward [6] carried out experiments on a direct injection CI engine having low compression ratio (11 − 13) using twin spark plugs. The ignition system was successful in reducing NOx and PM emission, but the issue of persistent spark plug fouling due to short-circuiting by injected liquid fuel could not be resolved. The reason was that diesel is a non-volatile fuel, which needs high latent heat for evaporation and insufficient heat is available in the combustion chamber due to lower compression ratio of the engine, which is unable to evaporate all diesel droplets at the time of spark ignition. Enright et al. [7] optimized the spark timings for both 2-stroke and 4-stroke engines for direct injection of diesel. Weinrotter et al. [8] compared laser assisted HCCI and spark assisted HCCI combustion in a 2 L single cylinder optical research engine with a compression ratio of 11.2, which was operated at constant engine speed of 1200 rpm. Test fuel used was a mixture of isooctane and n-heptane (80:20), which was introduced in the engine via a port fuel injection (PFI) system. Wang et al. [9] investigated the effect of spark ignition and stratified charge on gasoline HCCI combustion. Ignition timing could be controlled by using two-stage gasoline direct injection. In-cylinder mixture formation was controlled by multiple injections and ignition was controlled by varying the spark timing. Spark assistance to the HCCI combustion improved its stability. HCCI mode operating range was 1–5 bar IMEP, and conventional SI mode operating range was 1–8 bar IMEP. Possible reason for excessive cyclic variations may be failure of auto-ignition of charge in few engine cycles in HCCI mode [10,11]. Wagner et al. [12] suggested that the reasons for cyclic variations in SIHCCI mode could be non-random and non-linear combustion process. Price et al. [13] investigated PM emissions from spray-guided DISI engines and concluded that PM composition was dominated by volatile components of the fuel. Wang et al. [14] argued that PM emissions from DISI engine become complicated when different fuel properties and fuel qualities are involved. Aromatic content, vapor pressure, volatility, and oxygen content were the main fuel properties investigated by these researchers. Herreros [15] suggested that soot with smaller primary particles and smaller agglomerated particles have a tendency to oxidize rather easily. Smaller particles have higher surface-to-volume ratio, therefore they oxidize easily. Itoh et al. [16] performed experiments on a modified high speed engine and were able to achieve stable stratified charge combustion with an overall air-fuel ratio of 40:1. They used EGR to further reduce NOx emissions and improve fuel economy. Richter et al. [17] compared the combustion of (i) poorly mixed fuel delivered by port fuel injection and (ii) well-mixed fuel prepared in a mixing tank. They noted differences in fuel distribution prior to combustion but no significant difference in combustion was observed. Koopmans et al. [18] performed experiments in a multi-cylinder camless engine and concluded that mode change in a multi-cylinder engine from SI to HCCI was more difficult than from HCCI to SI. Singh et al. [19] reported that homogenous charge preparation using less volatile fuels was far more challenging than highly volatile fuels. Diesel-like fuels required higher intake air temperature for HCCI engine operation, when the fuel was injected in the intake port. They developed a fuel vaporizer for fuel-air mixture preparation outside the engine, which was successful in diesel HCCI combustion because diesel was evaporated in this vaporizer. They observed two-stage heat release, which was due to low and high temperature chemistry of diesel HCCI combustion. Christensen et al. [20] reported that average in-cylinder A/F ratio was always lean in HCCI mode but combustion could never be 100% complete. This suggested that for reducing NOx and PM emissions significantly, one needs to adequately mix fuel and air before introducing them into the combustion chamber. Main benefit of HCCI combustion was its capability to reduce NOx emissions by 90–98% compared to conventional diesel combustion [21,22]. Yadav et al. [23] investigated the physical properties of Kerosene-diesel blends and reported noticeable reduction in kinematic viscosity and minor reduction in density compared to mineral diesel. These properties made kerosene-diesel blend suitable for deployment with external mixture formation technique in HCCI combustion. Patil et al. [24] performed experiments using kerosene, and di-ethyl ether (DEE) blended with diesel and faced issues such as high smoke at full load. They reported lower BTE and higher BSFC. Lu et al. [25] performed experiments using compound HCCI technique with the help of premixed gasoline/diesel blends in order to reduce HC and CO emissions.

From these studies, it is clear that researchers have carried out experiments using direct injection of diesel like fuels and port fuel injection of gasoline like fuels in the engine for attaining HCCI combustion. For diesel HCCI, EGR, higher intake air temperature and water injection emerged to be feasible for controlling combustion phasing. For gasoline HCCI, spark assistance was effective at higher compression ratios. Researchers also used spark assisted direct injection diesel HCCI, but faced problem of persistent spark plug fouling due to presence of diesel droplets in the combustion chamber at the time of spark. Kerosene was also investigated because of its relatively higher volatility, higher calorific value, and relatively easier mixing characteristics with air to form homogeneous charge compared to diesel. Kerosene blending was helpful in improving diesel properties for HCCI/PCCI combustion.

Because of these observations from the previous studies, it was decided to investigate a host of lower volatility blended fuels in spark assisted partially premixed charge compression ignition (SAPCCI) mode such as blends of gasoline, kerosene, and diesel. For these experiments, an engine was customized to operate on PFI of low octane fuels. The compression ratio of the engine was lowered from 17 (as in a diesel engine) to 11 (as in SAPCCI engine) and PFI was used to prepare partially premixed charge.

2. Experimental setup

Test engine used was customized from a water-cooled single cylinder direct injection diesel engine to operate in SAPCCI mode. Specifications of the test engine before and after the hardware modifications are given in Table 1.

Test engine was coupled to a regenerative DC dynamometer (22 kW). Test fuels were injected into the intake port using a PFI gasoline injector, with start of injection (SoI) timing of 364.5° bTDC at 3 bar fuel injection pressure. Conventional spark ignition system with optimized spark timing of 25° bTDC was used. For customization of

Table 1
Technical specifications of the test engine before and after modifications.

Specifications	Before modifications	After modifications
Model/Make	DAF-10/Kirloskar	GA-1/ERL
Ignition type	CI	SAPCCI
Bore × stroke (mm)	102 × 116	102 × 116
No. of cylinders	1	1
Displacement (cc)	948	948
Compression ratio	17.5	11
Lubricating oil	15W40	15W40
Fuel injection	Direct injection	Port injection
Fuel injection pressure (bar)	220	3
Rated power	7.4 kW @ 1500 rpm	6.28 kW @ 1500 rpm
Rated speed (fly-up speed)	1500 rpm	2800 rpm