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Original Research Article

Experimental investigations of combustion, performance and emission characterization of biodiesel fuelled HCCI engine using external mixture formation technique

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ABSTRACT

In the present research, effect of biodiesel content on homogeneous charge compression ignition (HCCI) engine combustion, performance and emission characteristics has been investigated experimentally. Experiments were performed in a modified two cylinder engine, in which, one cylinder was operated in HCCI mode while other was operated in conventional CI mode. HCCI engine can be operated with a wide variety of fuels starting from mineral diesel to various blends of biodiesel (B20 and B40). The basic requirement of the HCCI engines is homogeneous mixing of fuel and air, which is done by using port fuel injection strategy in this study. An external device was used for fuel vaporization and mixture formation. For controlling HCCI combustion, different EGR conditions (0%, 15% and 30%) were also applied. In the experiments, combustion results were found to be more stable for biodiesel HCCI compared to diesel HCCI due to lower rate of heat release (RoHR) for biodiesel. A reduction in power output and an increase in ISFC were observed upon increasing the biodiesel content in the test fuel. A small increase in CO, HC and smoke emissions was observed with increasing biodiesel content due to slower evaporation rate of biodiesel. A significant reduction in NOx emissions was also observed with for biodiesel blends.

Introduction

Demand for petroleum products is increasing day-by-day however the resources are fairly limited. Beside this, there are grave concerns over environmental pollution specially pollution from the automotive/engine exhaust. Therefore it is necessary to develop a technology, which could overcome both issues. HCCI is a technology, which is highly efficient as well as less polluting. HCCI is a hybrid of both spark ignition (SI) and compression ignition (CI) combustion concepts. In HCCI, a homogeneous charge of air and fuel is created during the intake stroke. This homogeneous charge attains auto ignition conditions and explodes spontaneously without any flame at the end of compression stroke/beginning of expansion stroke.

HCCI combustion was first developed for a gasoline-fueled engine by Onishi et al. [1] with an objective of increasing combustion stability of two-stroke engines in 1979. This technology continues to be strongly pursued even today and is named Active Thermo-Atmosphere Combustion (ATAC). After Onishi, a large number of researchers focused on this novel technology and developed a broad scope for HCCI [2–16]. After successfully achieving HCCI in gasoline engines, research efforts were aimed towards attaining diesel HCCI in 1990's. Initially, early fuel injection and late fuel injection strategies were attempted for obtaining diesel HCCI however these techniques resulted in poor mixture quality and inferior combustion. Basic problems related to design and operational parameters of diesel HCCI were evaluated by Gan et al. [17]. In this investigation, experiments were performed under varying operational conditions such as different injection strategies, injection pressures, injection timings, intake air temperatures etc. along with varying design parameters such as piston geometries, compression ratios, swirl etc. Low volatility of diesel was found to be main obstacle in achieving diesel HCCI. To resolve this issue, several researchers developed external mixture preparation

Abbreviations: HCCI, homogeneous charge compression ignition; NOx, oxides of nitrogen; PM, particulate matter; DEE, di-ethyl ether; B20, 20% biodiesel and 80% diesel; EGR, exhaust gas recirculation; CO, carbon mono oxide; HC, hydrocarbons; EOI, end of injection; SoC, start of combustion; DME, di-methyl ether; TDC, top dead center; ATDC, after top dead center; BTDC, before top dead center; ISFC, indicated specific fuel consumption; ITE, indicated thermal efficiency; EGT, exhaust gas temperature.

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technique, in which, fuel was injected in the intake manifold and mixed with hot air to provide premixed homogeneous charge. Ryan and Callahan [18] applied external mixture preparation technique and used port fuel injection to supply diesel into the intake air stream. An intake air heater was installed upstream of fuel injector in order to preheat the air. External mixture formation was further developed by Gray and Ryan [19]. Requirement of high temperature for fuel vaporization and higher emissions of CO and HC were found to be two most critical issues in achieving diesel HCCI. However they reported dramatic reduction in NOx emission. Similar experiments were also continued by Maurya and Agarwal [20] using gasoline, alcohols and their blends with gasoline. External mixture formation technique was successfully employed in a high compression ratio (16.5) engine. In most of the recent research efforts related to diesel HCCI, mixture preparation is achieved by using in-cylinder fuel–air mixing techniques, such as very early fuel injection and late fuel injection, leading to formation of partially homogeneous mixture [17,21,22]. Benajes et al. [23] carried out experimental and numerical study to explain the mixing and auto-ignition processes in PCCI combustion using diesel and gasoline. They used a high speed direct injection (HSDI) diesel engine using varying EGR, injection timings, and different fuel types. They reported that use of gasoline has higher impact on air/fuel mixing process and auto-ignition delay than any other engine parameters. Finally they concluded that increasing the ignition delay by advancing the injection in addition to high EGR extends the mixing time. Significant cool-combustion chemistry of diesel was the other challenge for diesel HCCI because it leads to rapid auto-ignition once compression temperatures exceeds 800 K [24,25].

Some researchers explored advanced techniques of combustible mixture formation in the intake manifold. Shawn et al. [26] atomized the fuel in a diesel atomizer and then mixed it with air to prepare a homogeneous mixture. The effects of various parameters such as EGR, air–fuel ratio, intake air temperature, engine speed etc. on HCCI combustion was investigated and EGR was found to be the most promising solution to control the rate of combustion hence NOx formation. Singh and Agarwal [27] developed a dedicated device 'Diesel Vaporizer' for diesel HCCI. They reported that external mixture preparation gives superior quality homogeneous charge of diesel and air. They reported that EGR is the most effective parameter for controlling the rate of combustion. EGR reduces the combustion temperature and dilutes the air–fuel mixture. Dilution of intake charge increases the ignition delay and delays the SoC resulting in lower maximum cylinder pressure. Application of EGR results in lower RoHR, which affects both low temperature reactions (LTR) and high temperature reactions (HTR). They concluded that EGR can retard HTR longer than LTR because higher heat capacity of exhaust gas absorbs more energy released by the LTR.

Effect of EGR was further investigated by Ghazikhani et al. [28]. They reported that EGR results in dilution of mixture and leads to insufficient availability of oxygen, which reduces the combustion temperature. However this increases CO emissions. Lack of oxygen also leads to incomplete combustion, which results in higher HC emissions. Shi et al. [29] reported identical trend for CO, HC and NOx emissions with varying EGR. They reported an increase in smoke opacity with increase in EGR. In another research carried out by Agarwal et al. [30], they concluded that EGR is an excellent approach to reduce NOx emissions however it leads to fuel penalty. EGR also degrades the lubricating oil due to higher soot contamination, further resulting in higher engine wear [31]. Singh and Agarwal [32] carried out the diesel HCCI experiments for performance and emission characterization and found that diesel HCCI works well for medium load conditions; while at higher loads, EGR controls the NO formation at the cost of slight increase in CO and HC emissions. Indicated specific fuel consumption (ISFC) and indicated thermal efficiency (ITE) were comparable to conventional CI combustion.

HCCI is a flexible fuel technology however fuel properties have a substantial effect on combustion. Recently this technology was extended to non-conventional fuels such as natural gas, hydrogen. Starck et al. [33] conducted experiments to find the impact of fuel properties on HCCI combustion and reported that fuels with lower cetane number are superior HCCI fuels. They found that lower cetane number along with optimum RoHR can improve the HCCI operating range because it enhances the time available for homogenization of charge which improves HCCI combustion. Tanaka et al. [34] investigated the effect of fuel additives on HCCI and reported that fuels with saturated constituents result in two-stage combustion and fuels with unsaturated constituents undergo single-stage combustion.

Biodiesel HCCI is a new area of research because it combines advantages of both biodiesel and HCCI combustion. Main advantage of burning biodiesel in HCCI combustion mode is simultaneous reduction of NOx and soot, as well as reduction of fossil CO_2 emissions. In HCCI mode, biodiesel combustion happens at significantly lower in-cylinder temperature, therefore it reduces NOx emissions. Use of EGR further reduces the NOx to ultra low levels. Biodiesel HCCI also enhances the fuel efficiency because of combustion of ultra-lean mixtures, which brings the actual thermodynamic combustion cycle closer to the theoretical Otto cycle [35]. Low volatility and high vaporization temperatures are the two properties of biodiesel, which are major impediments in formation of homogeneous fuel–air mixture. Biodiesel also has high flash point, which affects its auto-ignition in the combustion chamber. Relatively lower calorific value of biodiesel is another important factor, which increases volumetric fuel consumption. Biodiesel has higher viscosity and ash content than mineral diesel, which might possibly choke the fuel injector upon long-term usage. It has shorter ignition delay and higher bulk modulus of compressibility, due to which, ignition control may become difficult. Higher bulk modulus shortens the response time of injectors, which lead to relatively earlier fuel injection than expected [36]. Brakora and Reitz [37] performed a numerical study to compare the formation of NOx from biodiesel and diesel combustion. Combustion of test fuels was simulated using Senkin code, for both, as an adiabatic constant volume reactor, and as an adiabatic single-zone HCCI engine model. The results showed that biodiesel surrogate can cause higher NOx, when compared with diesel surrogate, but the relative increase was small (<3%) for most equivalence ratios. Zhong et al. [38] performed biodiesel HCCI experiments to investigate the factors influencing formation of formaldehyde and they also carried out sensitivity analysis. They concluded that formaldehyde emissions can be reduced by improving intake air temperature and pressure. They suggested that higher EGR ratio would improve the quality of mixture to achieve HCCI combustion hence improve performance and emission characteristics of HCCI combustion. Zhang et al. [39] emphasized on accurate numerical study of biodiesel combustion and detailed chemistry of large biodiesel surrogates representing realistic biodiesel fuels. In the simulations, lower CO and NOx emissions and lower engine power were observed for biodiesel surrogates as compared to diesel surrogates. Espadafor et al. [40] developed a methodology for HCCI combustion using biodiesel mixtures. In the experiments, high swirl ratio, high EGR and late fuel injection strategy were adapted for HCCI combustion. This strategy reduced fuel wall impingement when early injection was used. In the experiments, high injection delay was seen with biodiesel, which allowed smooth HCCI combustion, when a high swirl level and EGR rate were applied simultaneously. NOx emissions reduced as EGR increased however a small increase in NOx emissions was observed, when biodiesel percentage in the