Fuel 219 (2018) 50–61

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Numerical and experimental investigations of the effects of the second injection timing and alcohol-gasoline fuel blends on combustion and emissions of an HCCI-DI engine

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ARTICLE INFO

Keywords:
HCCI-DI
Second injection
CFD simulation
Ethanol
Methanol

ABSTRACT

In this study, experimental and numerical investigations of a homogeneous charge compression ignition (HCCI) combustion engine were performed using alcohol-gasoline fuel blends and two-stage direct injection (TSDI) strategy. A diesel engine was modified to operate as an electronically controlled HCCI-DI engine. TSDI strategy was applied by fixing the first injection timing in intake stroke and varying the second injection timing close to the compression top dead center (TDC). The selected fuels were pure gasoline and four different blends of ethanol and methanol with gasoline, namely E10, E20, M10 and M20. The effects of the second injection timing and alcohol-gasoline fuel blends on the HCCI combustion and emissions were investigated at constant engine speed and high equivalence ratio for the same energy input. CFD simulations were performed using AVL Fire code and CFD results were compared with the experimental results of the HCCI-DI engine. Cylinder gas pressure, rate of heat release (ROHR), maximum cylinder gas temperature, CO and NO_x emissions were investigated numerically. Visual information about the in-cylinder temperature distribution and NO_x emissions were provided from images taken from the CFD model. It can be understood from both experimental and CFD studies that combustion phase can be most effectively controlled by changing the second fuel injection timing for all fuel blends. Adding alcohol to gasoline helped to decrease NO_x emissions while keeping the maximum cylinder gas pressure stable compared to pure gasoline.

1. Introduction

Today's transportation sector is still dependent on internal combustion engines. The most known characteristics of internal combustion engines are their harmful emissions emitted to atmosphere as a result of combustion of petroleum-based fuels. Harmful exhaust gases emitted to the atmosphere as a result of using petroleum-based fuels cause greenhouse effect and critical human health problems. Many researchers have been working to reduce emissions without sacrificing the power demand. HCCI combustion, which is intensively being researched, is a candidate of being amongst the future's new engine technologies due to its low NO_x emissions and high thermal efficiency in comparison to conventional gasoline and diesel combustion.

HCCI combustion has characteristics in common with both SI and CI combustion modes. In conventional HCCI engines, homogeneous air-fuel charge is prepared as in an SI engine by injecting the fuel in the intake stroke and the pre-mixed air-fuel charge is auto-ignited by compression as in a CI engine. Therefore, there is not a direct control mechanism, such as fuel injector or spark plug, to precisely change the ignition timing of HCCI combustion. Reactions leading to ignition and combustion depend on the chemical kinetics of air-fuel mixture and the combustion starts when sufficient energy is supplied to start the auto-ignition of time-temperature history [1,2]. Time-temperature history of the air-fuel mixture can be controlled by changing intake temperature [3], intake pressure [4], valve timing (to make use of residual-affected HCCI with rebreathing, re-induction and retention methods) [5] and using variable compression ratio, external EGR and direct injection timing [6]. After the intake valve closes, time-temperature history and fuel concentration can be controlled by changing fuel injection timing and/or dividing injections into two or more partitions. In addition,

Abbreviations: aBDC, After bottom dead center; aTDC, After top dead center; bBDC, Before bottom dead center; bTDC, Before top dead center; CI, Compression ignition; DI, Direct injection; GDI, Gasoline direct injection; EGR, Exhaust gas recirculation; HCCI, Homogenous charge compression ignition; IR, Injection ratio; LHV, Lower heating value; MPRR, Maximum pressure rise rate; MRHR, Maximum rate of heat release; NVO, Negative valve overlap; P_{max}, Maximum cylinder gas pressure; PPC, Partially premixed combustion; Q_{cyc}, Fuel quantity per cycle; ROHR, Rate of heat release; SI, Spark ignition; SOC, Start of combustion; TDC, Top dead center; T_{max}, Maximum cylinder gas mean temperature; TSDI, Two stage direct injection

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https://doi.org/10.1016/j.fuel.2018.01.061
Received 19 August 2017; Received in revised form 3 January 2018; Accepted 16 January 2018

mixture reactivity can be controlled by blending two or more fuels [7], changing air-fuel equivalence ratio, using fuel additives and fuel preconditioning.

Marriott and Reitz [8] investigated the effects of direct injection timing of gasoline by using high intake air temperature without spark assist on a heavy duty diesel engine which has high compression ratio. They were able to control combustion phasing by changing injection timing from early intake stroke towards the end of compression. Combustion phasing can be adjusted properly and emissions can be optimized by changing number of injections (single or double), injection timing and ratio of the fuel amount in sequential injections. By means of flexible controlling of injection timing, ratio and duration, it is possible to obtain required air-fuel mixture concentration in the cylinder by applying TSDI technique in DI engines. Wang et al. [9] performed experimental and simulation studies of different injection timings and injection ratios on a GDI engine using TSDI technique. They discovered that the first injection timing can be optimized to enhance evaporation process to build homogeneous charge and better engine performance can be achieved. Woo et al. [10] also applied double injection strategy by changing second injection timing, first injection timing and first injection proportion for ethanol combustion in a single-cylinder diesel engine. They found that second injection timing can control combustion phasing and impacts smoke and NO_x emissions vitally. They achieved higher net indicated efficiency, lower NO_x emissions while keeping combustion efficiency close to baseline diesel condition in optimized conditions. They also observed that increasing first injection proportion benefited charge premixing level and impacts smoke emissions while the first injection timing contributed mixture homogeneity and thus improving NO_x emissions as it can be found in the study of Hunicz and Kordos [11] where split injection strategy was used with negative valve overlap (NVO). Tang et al. [12] observed that combustion process initiated by multipoint auto-ignition and flame fronts of the ignition kernels developed from the region with higher fuel concentration to lower concentration with the usage of double injection strategy.

In this study, mixture reactivity of HCCI combustion was changed by using different blends of ethanol-gasoline and methanol-gasoline fuels. Due to their higher octane rating than gasoline, alcohols such as methanol and ethanol (RON for ethanol and methanol are 108 and 110, respectively) can be used as octane enhancer when they are blended with gasoline fuel [13–15]. As a result, it can be benefited from alcohol-gasoline fuel blends in higher compression ratios and higher thermal efficiencies can be achieved by this way [16–18]. Alcohols can provide great lean burn properties [19,20] and they have great potential for reducing exhaust emissions. Ariello and Zanoelo [21] theoretically investigated NO formation from an ethanol-gasoline HCCI engine by using a detailed kinetic model. They found that it is possible to reduce NO emissions without compromising CO and UHC emissions. They also asserted that ethanol blending could be an alternative to using high EGR rates which can cause high amounts of CO and UHC emissions. Chen et al. [22] investigated the combustion of ethanol-gasoline fuel blends at different ratios in a high-pressure constant volume vessel using single hole injector and spark plug. They discovered that it gets harder to start combustion and flame propagation becomes more dependent on spark energy with ethanol fraction increasing in the fuel blend. Yang et al. [23] experimentally studied fuel stratification of gasoline and methanol on a single cylinder engine. They used a dual fuel injection system in which gasoline fuel was injected into intake port to build homogeneous charge while either gasoline or methanol was injected into the cylinder to create stratification. They observed that methanol direct injection strategy can decrease cylinder temperature, retard combustion and reduce maximum pressure rise rate (MPRR) and NO_x emissions. Furthermore, they observed that oxygen content of methanol can keep combustion efficiency on a high level and they were able to extend the load limit by optimizing stratification amount without exceeding acceptable level of MPRR.

HCCI and other forms of combustion can be examined more comprehensively by using computer simulations including either 0D-codes or more advanced 3D-CFD codes [24,25]. Wang et al. [26] conducted a 3D-CFD study of a gasoline HCCI engine with a detailed chemistry model to investigate two-stage injection strategy. They compared single injection with two-stage (split) injection strategy and observed that retarded injection advances ignition timing and builds a stratified charge in the cylinder which allows controlling ignition timing and combustion rate. Syed et al. [27] analyzed the effects of pressure, temperature, dilution and equivalence ratio on auto-ignition timings of ethanol-gasoline fuel blends by using semi-detailed chemical mechanism. They found that auto-ignition timing retarded at low temperatures and advanced at high temperatures as ethanol fraction increased. They also observed that ethanol's charge cooling effect influenced auto-ignition timing more dominantly compared to kinetic effects in ethanol-gasoline blends.

Various parameters of injection for diesel-HCCI and conventional diesel combustion were investigated using AVL-Fire and satisfactory results were obtained in the previous studies [26,28]. Gasoline compression ignition (GCI) combustion was investigated recently using third-party CFD software [29]. Furthermore, in the previous study, effects of TSDI technique on HCCI combustion of alcohol-gasoline fuel blends were analyzed experimentally [30]. 3D-CFD and 0D-SRM simulations were performed for only gasoline fuel [31,32]. It was seen from literature review that using TSDI technique and alcohol-gasoline fuel blends are effective for controlling HCCI combustion phase and obtaining lower emissions. However, more CFD studies concerning the use of TSDI technique with alcohol-gasoline fuel blends in HCCI-DI engines need to be performed to understand the HCCI combustion. Therefore, the aim of this current study was to investigate the effects of the second injection timing and alcohol-gasoline fuel blends on the HCCI combustion numerically by using CFD simulations and to compare the results with experimental data.

2. Experimental setup

In this study, a naturally aspirated, water-cooled, single cylinder DI diesel engine was converted to HCCI-DI engine fueled with 97 octane gasoline and its blends with ethanol and methanol. Properties of fuels were evaluated in Alternative Fuels R&D Center in Kocaeli University. Engine specifications were given in Table 1 and schematic diagram of the experimental setup is shown in Fig. 1. The engine is coupled to a DC electrical dynamometer. K type thermocouples were used during the experiments to obtain intake air, fuel, oil, exhaust gas and cooling water inlet-outlet temperature data. Intake charge temperature and coolant temperature were controlled in closed-loop at $100 \pm 2\,^{\circ}C$ and $75 \pm 2\,^{\circ}C$, respectively, to provide steady engine operating conditions. Air consumption was measured using an orifice-meter and a differential pressure manometer.

A water-cooled transducer (Kistler, model 6061B) was mounted on cylinder head to obtain cylinder gas pressure data. A swirl type, single-hole gasoline direct injector (Bosch, model HDEV 1.1) was installed on cylinder head to inject the fuel at 10 MPa injection pressure using low pressure common rail system. Fuel injection timings and fuel quantity

Table 1
Engine specifications.

Engine	Super Star 7716 Model Diesel Engine
Type	DI, natural aspirated, water cooled
Cylinder number	1
Volume (cm^3)	770
Compression ratio	17:1
Intake valve open (bTDC)	22
Intake valve close (aBDC)	60
Exhaust valve open (bBDC)	66
Exhaust valve close (aTDC)	16