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Effects of second injection timing on combustion characteristics of a two stage direct injection gasoline–alcohol HCCI engine

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HIGHLIGHTS

- Second fuel injection timing has major effect on combustion and emissions of HCCI engine.
- Alcohol–gasoline fuel blends improved the indicated efficiency and MPRR.
- NO_x emissions were reduced without a major increase in HC and CO emissions with TSDI.

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ABSTRACT

In this study, the effect of second injection timing on the combustion and emissions characteristics of a direct injection HCCI gasoline engine was investigated by using ethanol and methanol blended gasoline fuel. For this aim, a diesel engine was converted to an electronically controlled HCCI gasoline engine. The injection timings and fuel quantity for each injection were adjusted to get desired mixture formation in the cylinder. Five different fuels (gasoline, E10, E20, M10 and M20) were studied at the same energy input condition. The tests were conducted at high and low equivalence ratios and constant engine speed. The test results show that the combustion and emissions characteristics can be directly controlled and HCCI operating range can be extended by the second fuel injection timing. The maximum cylinder gas pressure and rate of heat release significantly decreased and the start of combustion delayed with the retarding of the second fuel injection. Using optimal second fuel injection timings, better combustion characteristics, lower NO_x, UHC and CO emissions, and higher IMEP and indicated efficiency values were obtained for the alcohol–gasoline fuel blends compared to the gasoline case at low equivalence ratio. At the same time, the dilemma between NO_x and smoke emission was controlled with changing of the second fuel injection timing by keeping the IMEP and indicated efficiency almost constant for all test fuels.

1. Introduction

The increasing number of vehicle causes environmental problems such as greenhouse effect and acid rains. These environmental threats bring a must for the vehicle producers to comply with the new emission standards. Because of this obligation, engine manufacturers and researchers have tended to work on the new technology and combustion theories. Homogenous charge compression ignition (HCCI) is a new combustion mode which has advantages such as lower NO_x emissions and higher thermal efficiency compared to conventional diesel and gasoline engines. The mixture preparation before the compression process in HCCI engines is based on spark ignition (SI) engine principle. The ignition of the pre-mixed mixture is similar with compression ignition (CI) engine. In the SI and CI engines, the combustion process is initiated by a spark plug and fuel injection timing, respectively. HCCI combustion is an auto-ignition combustion process which is governed by chemical kinetics of the air–fuel mixture. Therefore, there is no a direct control mechanism in HCCI combustion [1]. Controlling the combustion phases such as initiation and duration of combustion is one of the main challenges in HCCI combustion. Other

Abbreviations: aBDC, after bottom dead center; aTDC, after top dead center; bBDC, before bottom dead center; bTDC, before top dead center; CA50, crank angle at which the mass burn fraction reaches to 50%; CI, compression ignition; COV_{IMEP}, coefficient of variation in the indicated mean effective pressure; DI, direct injection; DISI, direct injection spark ignition; DOI, duration of injection (first DOI_1, second DOI_2); EGR, exhaust gas recirculation; HCCI, homogenous charge compression ignition; IMEP, indicated mean effective pressure; MPRR, maximum pressure rise rate; MRHR, maximum rate of heat release; PFI, port fuel injection; P_{max}, maximum cylinder gas pressure; P_{maxloc}, maximum cylinder gas pressure location; Q_{cyc}, fuel quantity per cycle; SI, spark ignition; SOI_1, start of first injection; SOI_2, start of second injection; TDC, top dead center; TSDI, two stage direct injection.

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challenges include narrow operating range, higher UHC and CO emissions and dynamic control between HCCI and conventional combustion cycle.

In order to control auto-ignition timing and combustion rate in HCCI combustion, two main parameters play important roles. First is time-temperature history, second is auto-ignition characteristic of fuel [2]. General control methods include intake temperature [3,4], intake pressure [5,6], variable compression ratio [7], variable valve timing for adjusting the level of internal exhaust gas recirculation (EGR), external and cooled EGR [8,9] to control time-temperature history. On the other hand, time-temperature history and fuel concentration only can be controlled with two stage direct injection (TSDI) technique after the intake valve closed.

TSDI technique allows desired fuel–air mixture concentration in the cylinder due to more flexible controlling for fuel injection timing and duration [10]. TSDI technique can be used in the engines with higher compression ratio, it has also lower fuel consumption (less heat loses) and higher volumetric efficiency compared with port fuel injection (PFI) technique [11,12]. It is well known that using gasoline direct injection (DI) concept in SI engines produces high NO_x and PM emissions due to high local temperature and equivalence ratio when compared to PFI technique. In the previous studies Mariott [13], and Canakci and Reitz [14] applied double injection technique to a gasoline direct injection HCCI engine and the researchers observed significantly reductions in NO_x and PM emissions as well as high thermal efficiency. Wang et al. [10] compared TSDI and single direct injection at the same amount of fuel conditions. They obtained lower UHC and NO_x emissions, expanded high and low operating conditions, and lower coefficient of variation in the indicated mean effective pressure (COV_{IMEP}) with the TSDI technique and assisted spark. Their experimental and computational studies showed that second fuel injection phase can directly control start and rate of HCCI combustion. The second fuel injection improves combustion stability, suppresses knock tendency and extends HCCI high load range [15]. Hunicz and Kordos [16] investigated the effects of the second fuel injection timing on the combustion and emissions characteristics by using TSDI technique. They confirmed that the second fuel injection timing can control the combustion phases and emissions values.

HCCI combustion phases depend upon the auto-ignition properties of fuel which can be changed by using different fuel mixing and additives [17–19]. Alcohols such as methanol and ethanol have higher octane number than that of gasoline. Therefore, alcohol–gasoline blends can be used in the engines with higher compression ratio and obtained higher thermal efficiency. At the same time, alcohols have excellent lean burn properties and good combustion characteristics in HCCI combustion [20]. Dale et al. [21] worked on double and single injection techniques at direct injection spark ignition (DISI) gasoline engine fueled with different blending ratio of bioethanol–gasoline at part load and constant engine speed conditions. They found improved combustion stability and efficiency, reduction in CO emissions and COV_{IMEP}, increase in maximum cylinder gas pressure (P_{max}) and engine efficiency with single injection for lower ethanol blends (<30 vol.%). When the double injection and split ratio (50–50%) were used, the combustion stability and efficiency improved, but those advantages were not obtained with higher ethanol blends (>30 vol.%). Yang et al. [22] studied methanol and gasoline stratifications on a single cylinder engine equipped with a dual-fuel injection system for extension of HCCI high load limit. The homogenous charge was prepared with gasoline by using PFI technique while the desired fuel stratification for methanol or gasoline was created by DI technique during the compression stroke. When methanol stratification was used, the cylinder gas temperature, maximum pressure rise rate (MPRR), CO and NO_x emission reduced. It also retarded combustion timing and prolonged combustion duration. They showed that HCCI high load limit could be extended with optimized methanol ratio stratification. However, high load extension was limited due to the dilemma between CO and NO_x emissions when using gasoline stratification.

It is seen that TSDI technique is an important parameter to control combustion in HCCI engine, and alcohols–gasoline fuel blends have also given good combustion characteristics on the HCCI engines. In general, researchers have investigated the effects of alcohols on HCCI combustion in PFI engines or dual fuel engines under different operating conditions. However, there is no enough study about the using of alcohol–gasoline blends, especially with TSDI technique, in high compression ratio DI HCCI gasoline engine without spark ignition and EGR. Therefore, in this study, the effects of different alcohol–gasoline fuel blends and second fuel injection timing on HCCI combustion and emissions characteristics have been investigated by using TSDI technique in the experiments to control the combustion phases and to obtain high efficiency and low emissions.

2. Experimental setup

In this study, a naturally aspirated, water-cooled, single cylinder DI diesel engine was converted to a DI HCCI gasoline engine. The engine specifications are shown in Table 1 and schematic diagram of the test cell is shown in Fig. 1. The test engine is coupled to a DC electrical dynamometer. K types thermocouples with a digital temperature indicator were used to measure intake air, exhaust gas, fuel, oil and cooling water inlet–outlet temperatures. The intake charge temperature, engine coolant temperature and fuel temperature were controlled in closed-loop at 100 ± 2 °C, 75 ± 2 °C and 30 ± 2 °C, respectively, to eliminate their effects on HCCI combustion. During the experiments, an intake surge tank was also used to eliminate cyclic fluctuations, and air consumption was monitored using an orifice-meter and a differential pressure manometer.

The cylinder pressure was measured with a water-cooled pressure transducer (Kistler, model 6061B) which was installed on the engine cylinder head. The charge output from the transducer was converted to an amplified voltage using a charge amplifier (Kistler, model 5011B). A shaft encoder on the engine crankshaft was used to acquire the cylinder pressure and top dead center (TDC) signal. The output of charge amplifier and the TDC signal from the magnetic pick-up were converted to digital signals and recorded by fast data acquisition card (National Instrument, PCIe 6251). To analyze the cylinder gas pressure, a combustion analysis program was written and the cylinder gas pressure data of 50 cycles were averaged to eliminate cycle to cycle variation. Then, the pressure data was used to calculate the heat-release rate and main combustion characteristics.

A swirl type, single-hole gasoline direct injector (Bosch, model HDEV 1.1) was installed on the engine cylinder head. Fuel injection pressure was fixed at 10 MPa with the use of a common rail system. First and second fuel injection timings and fuel quantity per cycle (Q_{cyc}) were controlled by designed electronic control unit,

Table 1
Engine specifications.

Engine	Super star 7716 model diesel engine
Type	DI, natural aspirated, 4 stroke, 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