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Fuel suitability for homogeneous charge compression ignition combustion

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ABSTRACT

The main focus of this paper is to investigate the impact of fuel type on HCCI combustion under different engine loads. A coupled chemical kinetics-computational fluid dynamic (CFD) model is developed to investigate the combustion performance and emissions characteristics of a HCCI engine with pre-combustion chamber fueled with natural gas, natural gas/10% dimethyl ether (DME) mixtures, or methanol. The simulation results indicate that the probability of partial combustion increases when using natural gas under low engine load. However, methanol and natural gas/DME experience complete combustion under low engine load. In contrast, for both methanol and natural gas/DME the rate of pressure rise and heat release at high engine load is very high which induces engine knock. At leaner mixtures (ER < 0.26), natural gas/DME attains the highest indicated mean effective pressure (IMEP) compared to that of methanol and natural gas. However, natural gas fueled HCCI engine has the highest IMEP under rich mixture conditions (ER > 0.26). NO_x emissions of natural gas fueled HCCI engine are much lower than that of methanol and natural gas/DME, especially at high engine loads. However, natural gas/DME and methanol offer superior combustion control and NO_x, carbon monoxide (CO), and unburned hydrocarbon (UHC) emissions under low to moderate engine loads. However, the use of natural gas in HCCI combustion is suitable for moderate to high engine loads.

1. Introduction

The ever increasing energy demand associated with limited reserve of fossil fuels and stringent emissions regulations create a real opportunity and also a challenge for engine researchers and manufacturers to improve vehicle/engine fuel efficiency and implement alternative fuels in conventional internal combustion (IC) engines. The latest emissions regulations are expected to be achieved using after-treatment devices [1]. However, the widespread adoption of after-treatment technologies is impeded by higher economic cost, durability issues, and fuel economy penalties [1]. Consequently, combination of both in-cylinder strategies and using alternative fuels to improve fuel efficiency and to further reduce the engine-out emissions and thereby lessen the after-treatment burden are of great interest.

Reduction of NO_x emissions is a significant challenge for diesel exhaust gas after-treatment; hence, in-cylinder strategies to address NO_x emissions have been widely investigated [2]. Recent studies of NO_x emissions reduction have largely focused on strategies to reduce in-cylinder combustion temperature. HCCI combustion technology has a significant potential owing to its ability of reducing combustion temperature and hence NO_x and particulate matter (PM) emissions while simultaneously achieving high thermal efficiency [3–5]. HCCI combustion typically employs long in-cylinder mixing times prior to combustion to produce relatively lean fuel–air mixture throughout the combustion chamber [1]. However, several technical barriers must be overcome before HCCI combustion can be implemented in practical IC engines. Since, ignition timing is kinetically controlled and is therefore decoupled from the timing of fuel injection event, control of combustion phasing and expanding operating range are the major obstacle of HCCI combustion [6–10]. Moreover, auto-ignition occurs simultaneously throughout the combustion chamber which leads to rapid heat release rate (HRR) resulting in engine knock. On the other hand, partial combustion or misfiring process occurs at low engine loads which causes an increase in UHC and CO emissions. Several research studies and development endeavors have focused on overcoming the difficulties of controlling ignition timing in HCCI engines. Thus, controlling the combustion timing requires careful tuning of the auto-ignition kinetics, which affects in-cylinder charge composition and pressure along with temperature histories of the reactants during the compression process [11]. To eliminate these problems, viable solutions such as exhaust gas

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Nomenclature

ATDC	after top dead center
BDC	bottom dead center
AFR	air fuel ratio
CA10	crank angle for 10% burnt fuel
CA90	crank angle for 90% burnt fuel
CI	compression ignition
CO	carbon monoxide
CFD	computational fluid dynamic
CNG	compressed natural gas
DI	direct injection
DME	dimethyl ether
EGR	exhaust gas recirculation
ER	equivalence ratio
HCCI	homogeneous charge compression ignition
HRR	heat release rate
HTHR	high-temperature heat release
IC	internal combustion
IDI	indirect injection
IMEP	indicated mean effective pressure
LPG	liquid petroleum gas
LTHR	low-temperature heat release
NO_x	nitrogen oxide
PM	particulate matter
rpm	revolution per minute
TDC	top dead center
UHC	unburned hydrocarbon
VCR	variable compression ratio
VVA	variable valve actuation

recirculation (EGR) [12,13], variable valve actuation (VVA) [14,15], and variable compression ratio (VCR) [16] are proposed in order to slow down rapid heat release and to control the combustion phasing in HCCI combustion. Since, controlling the ignition timing and extending the operational range in HCCI engines can be obtained through the fuel flexibility feature of HCCI combustion, the impact of type of fuel and its composition should be thoroughly examined [17]. Various fuels exhibit different extent of reactions within certain temperature ranges and consequently cause different behaviors of fuels under the same conditions in HCCI combustion. Several fuels combinations such as hydrocarbons, alcohols and reformer gas were used in HCCI combustion engines. For instance, Yeom and Bae [18] compared the combustion characteristics of liquefied petroleum gas (LPG)-DME and gasoline–DME HCCI engines at different valve timings. LPG and gasoline were injected at the intake port using port fuel equipment and DME as an ignition promoter was injected directly into the cylinder during the intake stroke. Their results revealed that the LPG–DME HCCI combustion engine has a wider operating range compared to that of the gasoline–DME due to of its higher octane number and higher latent heat of vaporization. At richer mixtures, the IMEP of both gasoline–DME and LPG–DME fueled HCCI engines was drastically reduced caused by early combustion. Shibata and Ogawa [19] reported that adjusting the proportions of DME and ethanol is an effective technique for extending the operational range and controlling HCCI combustion. With the increase of ethanol ratio, the start of low temperature heat release (LTHR) and high temperature heat release (HTHR) crank angle positions were delayed. Ethanol was considered as a strong LTHR inhibitor and DME showed its strong HTHR properties. By increasing ethanol ratio, IMEP and indicated thermal efficiency were increased and a maximum pressure rise rate was decreased. All experiments revealed that a broadening of the HCCI operational range by the fuel would be possible. Yan et al. [20] modified a single cylinder diesel engine to HCCI combustion engine fueled with methanol and DME. They showed that by adjusting DME and methanol proportions, stable and significantly expanded HCCI operation over a broad speed and load region can be achieved. Li et al. [21] examined combustion performance and emissions characteristics of HCCI engine fueled with ethanol and methanol vis-a-vis gasoline. They found that ethanol and methanol have higher IMEP for combustion phasing corresponding to the best thermal efficiency at any constant air fuel ratio (AFR).

The present study aims at exploring the fuel suitability for various loads of HCCI engine at high compression ratio (17.2) engine. The effect of three types of fuels, namely natural gas, natural gas/10%DME mixture, and methanol on HCCI combustion performance and emissions will be examined using a single cylinder, four stroke and indirect injection (IDI) Ricardo E6/MS diesel engine. It is important to mention that IDI system in diesel engine is an old technology as it has higher fuel consumption and lower thermal efficiency compared with direct injection (DI) system [22]. However, several diesel passenger cars and off-road IC engines are still equipped with pre-combustion chamber diesel engines rather than diesel injection engines because they have a better compromise between efficiency, noise, and emissions [23]. IDI diesel engine, when fitted with a simple pre-combustion chamber in addition to the main combustion chamber, can offer several advantages [22]. Its power concentration becomes high since it has lower ignition delay, greater air utilization and faster combustion. Its PM emissions are in most cases comparable to, or even lower than, that of DI engine. Its NO_x emissions level is relatively low [22]. Owing to these advantages of IDI diesel engine, it is worthwhile examining the pre-combustion chamber for new combustion concept, i.e. HCCI combustion mode, and also testing alternative fuels to further reduce emissions. However, our recent study [7] demonstrated the importance of using pre-combustion chamber of diesel engines in HCCI mode, where rapid pressure rise and fast heat release of HCCI combustion can be damped and hence engine knock phenomenon may be eliminated. Reviewed literature revealed that there is still lack of information on the effect of different fuel types on HCCI combustion in IDI diesel engine. Thus, the ultimate objective of this paper is to analyze numerically the combustion performance and emissions of HCCI engine with pre-combustion chamber operating on three different fuels. In our previous study [7], the model predictions were validated against experimental data obtained from IDI Ricardo engine, which was modified accordingly to operate on natural gas fueled HCCI engine. However, to ensure that the model produces reasonably accurate predictions of the combustion process of methanol, or natural gas/DME, the model predictions were compared with published experimental data of methanol and natural gas/DME fueled HCCI engines [24,25]. The results reported here concern the in-cylinder pressure, released heat, start of combustion, combustion duration, in-cylinder mean temperature contours, IMEP, and emissions for three different fuels. In numerical simulations, a homogeneous combustible mixture is compressed during the compression stroke to enable HCCI type of combustion. The numerical results are analyzed to evaluate the suitability of these fuels for the various loads of HCCI combustion by examining combustion performance and emissions.