Energy Conversion and Management 98 (2015) 199–207

Contents lists available at ScienceDirect

Energy Conversion and Management

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

An experimental investigation into combustion and performance characteristics of an HCCI gasoline engine fueled with *n*-heptane, isopropanol and *n*-butanol fuel blends at different inlet air temperatures

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ARTICLE INFO

Article history:
Received 7 December 2014
Accepted 11 March 2015
Available online 10 April 2015

Keywords:
HCCI
Isopropanol
n-Butanol
Alcohol
Performance
Combustion

ABSTRACT

An experimental study was conducted in a single cylinder, four stroke port injection Ricardo Hydra test engine in order to determine the effects of pure *n*-heptane, the blends of *n*-heptane and *n*-butanol fuels B20, B30, B40 (including 20%, 30%, 40% *n*-butanol and 80%, 70%, 60% *n*-heptane by vol. respectively) and the blends of *n*-heptane and isopropanol fuels P20, P30, P40 (including 20%, 30%, 40% isopropanol and 80%, 70%, 60% *n*-heptane by vol. respectively) on HCCI combustion. Combustion and performance characteristics of *n*-heptane, *n*-butanol and isopropanol were investigated at constant engine speed of 1500 rpm and $\lambda = 2$ in a HCCI engine. The effects of inlet air temperature were also examined on HCCI combustion. The test results showed that the start of combustion was advanced with the increasing of inlet air temperature for all test fuels. Start of combustion delayed with increasing percentage of *n*-butanol and isopropanol in the test fuels. Knocking combustion was seen with B20 and *n*-heptane test fuels. Minimum combustion duration was observed in case of using B40. Almost zero NO emissions were measured with test fuels apart from *n*-heptane and B20. The test results also showed that CO and HC emissions decreased with the increase of inlet air temperature for all test fuels. Isopropanol showed stronger resistance for knocking compared to *n*-butanol in HCCI combustion due to its higher octane number. It was determined that *n*-butanol was more advantageous according to isopropanol as thermal efficiency. As a result it was found that the HCCI operation range can be extended using high octane number alcohols away from knocking combustion and autoignition can be controlled.

1. Introduction

Exhaust emissions caused from motor vehicles and decreasing petroleum reserves are main challenges for engine researchers and producers. Exhaust emissions produced by motor vehicles are harmful to people and environment [1–6]. Using alternative fuels and different exhaust gas aftertreatment systems are the most common methods in order to meet exhaust emissions regulations. Furthermore, emissions can be reduced with the increase of thermal efficiency due to increasing the compression ratio in the internal combustion engines. However, the compression ratio of SI engines cannot be increased due to detonation. Although the thermal efficiency of CI engines is higher than SI engines, they emit high NO_x and PM. At this point, HCCI combustion has a big potential due to reducing NO_x and PM emissions simultaneously with a higher thermal efficiency [7–13]. HCCI combustion is highly dependent on the chemical kinetics, mixture composition and the temperature before the auto-ignition [9,10]. However, there are still some difficulties on HCCI combustion in order to be used in the internal combustion engines. First, autoignition occurs simultaneously and spontaneously across the combustion chamber. This spontaneous and sudden combustion causes a rapid heat release rate resulting in knocking. In contrast, misfiring problem is seen at lower engine loads. Secondly, CO and HC emissions increase due to leaner mixture and lower combustion temperature in HCCI engines, because CO emissions are strongly affected by combustion temperature Third one is to control the combustion phasing [10–16]. To eliminate these problems possible solutions such as EGR, variable valve timing and variable compression ratio and high octane number fuels are proposed in order to slow down rapid heat release and control the combustion phasing in HCCI combustion. Thus, considerable attention should be directed in HCCI combustion. Fuel composition effect, which determines the operating range of HCCI, should be understood well. At this point, the chemical properties and the molecule structure of the fuel affect the HCCI combustion substantially [17–19]. So, one common

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http://dx.doi.org/10.1016/j.enconman.2015.03.043
0196-8904/

Nomenclature

ATDC	after top dead center	OH	hydroxyl radical
BTDC	before top dead center	p	cylinder pressure (bar)
CI	compression ignition	PM	particulate matter
CO	carbon monoxide (%)	RCCI	reactivity controlled compression ignition
dp	the variation of cylinder pressure (bar)	SI	spark ignition
dV	the variation of cylinder volume (m^3)	SOC	start of combustion
$d\theta$	the variation of crank angle (°)	TDC	top dead center
EGR	exhaust gas recirculation	UEGO	universal exhaust gas oxygen
HC	hydrocarbon (ppm)	V	cylinder volume (m^3)
HCCI	homogeneous charged compression ignition	V_d	swept volume (m^3)
imep	indicated mean effective pressure (bar)	W_{net}	net work (J)
k	the ratio of specific heat values	dQ	heat release rate (J)
m_{fuel}	consumed fuel per cycle (kg/cycle)	dQ_{heat}	heat transfer to cylinder walls (J)
MTBE	methyl tert-butyl ether	η_T	thermal efficiency
NO_x	nitrogen oxides (ppm)	Q_{LHV}	the heating value of the fuel (kJ/kg)

way to achieve stable autoignition and extend the HCCI operating range is to use the high octane number alcohol fuels based on renewable energy source. The temperature and the production of the radicals can also be increased when high octane number fuels are used as suppression additive fuel in HCCI combustion [17,19–22]. Furthermore, alcohols contain more oxygen resulting improved combustion and less pollution [23,24]. Cooling effect is also observed on charge mixture as the vaporization heat of alcohols is higher than that of gasoline. In this way, higher pressure rise rate may be also prevented when alcohols are used in HCCI engines. In this regard, *n*-butanol and isopropanol have a big attractiveness on the usage in HCCI engines due to knocking resistance, controlling rapid heat release rate [25–31]. But there is not enough study regarding two fuels on HCCI combustion. A few studies have been applied and discussed on the effects of alcohols in HCCI combustion in recent publications [10,17,26–28]. Lü et al. [22] investigated the effectiveness of inhibition of HCCI combustion using additive fuels (MTBE, isopropanol, ethanol and methanol). They determined that methanol has shown the most suppression effect among the other test fuels (isopropanol, ethanol and methanol). Minimum suppression effect was obtained with MTBE. However, they determined that ethanol was the best additive when the operating range, thermal efficiency and emissions were considered. Saisirirat et al. [17] evaluated the effects of 1-butanol and compared to pure *n*-heptane and *n*-heptane/ethanol mixture fuels on HCCI combustion. They performed the modeling of constant volume combustion in order to discuss engine results. Yao et al. [10] studied the effects of the blends of *n*-butanol and diesel with EGR on combustion, efficiency and exhaust emissions in a direct injection diesel engine. They showed that peak cylinder pressure and heat release rate increased with the increase of amount of butanol at low EGR rates. He et al. [32] conducted an experimental study in order to determine the effects of *n*-butanol in HCCI engine equipped with variable valve timing and lift mechanisms. The test results showed that the start of autoignition was advanced with engine speed. He et al. [33] presented an another study in order to investigate the effects of gasoline, 30% *n*-butanol and 70% gasoline by vol., and pure *n*-butanol in HCCI combustion using negative overlap and variable valve timing. Numerical studies were also conducted in order to observe HCCI combustion. Neshat and Saray [34] developed a new chemical kinetic mechanism for HCCI combustion using multi zone model in order to predict cylinder pressure and emissions. In [35], numerical study was performed in order to examine the role of fuel reactivity gradient in RCCI using Kiva4-Chemkin code. It was shown that fuel reactivity gradient retarded the ignition timing and reduced the heat release rate. Vuilleumier et al. [36] aimed to examine the intermediate temperature heat release in HCCI engines using ethanol/*n*-heptane mixtures. They also modeled the combustion process using single zone HCCI model. They used the simulation results in order to identify the dominant reaction pathways contributing to intermediate temperature heat release. They found good agreement with pre-ignition pressure rise and heat release rate between experimental and modeling results. They also found that H-atom abstraction contributed reaction pathways to intermediate temperature heat release.

In this study, the effects of pure *n*-heptane, and isopropanol/*n*-heptane mixtures and *n*-butanol/*n*-heptane mixtures were investigated on HCCI combustion, performance and emissions of a single cylinder, four stroke, port injection Ricardo Hydra gasoline HCCI engine. *N*-heptane percentages used in the isopropanol and *n*-butanol mixtures were chosen 60%, 70% and 80% by volume. Experimental study was performed at 1500 rpm engine speed and constant lambda $\lambda = 2$ at different inlet air temperatures of 313 K, 333 K, 353 K, 373 K and 393 K in order to observe the controlling of HCCI combustion. The variation of cylinder pressures, heat release rates, the starts of combustion and combustion durations was investigated in case of HCCI combustion with isopropanol/*n*-heptane mixtures, *n*-butanol/*n*-heptane mixtures and pure *n*-heptane.

2. Experimental setup and procedures

A single cylinder, four stroke, port injection gasoline HCCI engine was used in the experiments. The technical specifications of the test engine are seen in Table 1. The test engine was coupled

Table 1
The technical specifications of the test engine.

Model	Ricardo-Hydra
Cylinder number	1
Cylinder bore (mm)	80.26
Stroke (mm)	88.90
Swept volume (cc)	540
Compression ratio	13:1
Maximum power output (kW)	15
Maximum engine speed (rpm)	5400
Valve timing	IVO/EVC 12° before top dead center/56° After bottom dead center
Valve lift	Intake/exhaust 5.5/3.5