Makine Teknolojileri Elektronik Dergisi
Cilt: 12, No: 1, 2015 (49-56)

Electronic Journal of Machine Technologies
Vol: 12, No: 1, 2015 (49-56)

TEKNOLOJİK
ARAŞTIRMALAR

www.teknolojikarastirmalar.com
e-ISSN:1304-4141

Makale
(Article)

The Effects of iso-propanol and n-heptane Fuel Blends on HCCI Combustion Characteristics and Engine Performance

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Abstract

In this study, the effects of iso-propanol fuel blends were investigated on HCCI combustion and engine performance. The variations of cylinder pressure, heat release rate, start of combustion and engine performance were studied in a single cylinder, four stroke, gasoline HCCI engine. The experiments were conducted at different inlet air temperatures at constant air excessive coefficient (λ=2) and engine speed (1500 rpm). The test results showed that cylinder pressure and heat release rate delayed with the addition of iso-propanol in the test fuels. It was also found that the increase of inlet air temperature causes to advance the combustion. Iso-propanol has higher octane number compared to conventional fuels. However, calorific value of iso-propanol is lower than conventional fuels. The aim of this study is to research the usage of iso-propanol in HCCI engines. The experimental findings showed that the tendency of knocking combustion decreased with the increase of the amount of iso-propanol. The start of combustion was delayed with the increase of the amount of iso-propanol. In addition, combustion duration decreased with the addition of iso-propanol in HCCI combustion. As a result, knocking can be prevented using iso-propanol in HCCI engines. This effect also led to extend the HCCI operating range.

Keywords : HCCI Engine, Iso-Propanol, Air Excessive Coefficient, Calorific Value

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1. INTRODUCTION

Many researches have been performed to reduce exhaust emissions and improve the efficiency in the internal combustion engines. Because oil reserves are consumed rapidly and the earth is polluted with harmful exhaust gases produced from motor vehicles. So, researchers and engine manufacturers have directed considerable attention improving engine efficiency and reducing exhaust emissions in the internal combustion engines. At this point, HCCI combustion seems to be one of the most attractive combustion modes due to reducing exhaust emissions and improving efficiency. In HCCI combustion, auto-ignition occurs without spark plug and fuel injector unlike SI and CI engines. Charge mixture is compressed at higher compression pressure and temperature via increasing compression ratio or heating inlet air [1-4]. In addition, air inlet temperature or variable valve timing are altered to achieve auto-ignition. Combustion occurs across the combustion chamber spontaneously and simultaneously without forming richer mixture zones. HCCI combustion is strongly dependent on the pressure-temperature history during the compression stroke. Richer mixture zones are formed in CI engines resulting in soot emissions. Moreover, very lean charge mixture can be ignited in HCCI combustion. It results very low emissions. In-cylinder temperature decreases as the lean mixture is ignited in HCCI combustion. Thus, lower in-cylinder temperature cause to decrease in NOx emissions. NOx and soot emissions can be decreased simultaneously with higher thermal efficiency which is the most important advantages of HCCI combustion. However, HCCI engines suffer from some difficulties such as narrow operating range, rapid heat release rate and uncontrolling combustion phasing. These difficulties restrict the usage of HCCI engines in today’s cars [5-9]. On the other hand, there is no direct control mechanism on HCCI combustion phasing and auto-ignition occurs suddenly in the combustion chamber resulting in higher pressure rise rate hence knocking. For this purpose, high octane number alcohols should be used in order to prevent knocking via slowing down the rapid heat release rate in HCCI combustion [5-10]. Isopropanol can be used in spark ignition and HCCI engines as an additive fuel [10-15]. High octane number alcohols include more oxygen resulting in lower exhaust emissions and improving combustion. However, there are very few experimental studies related to iso-propanol in HCCI engines. Lu et al. [16] investigated the effects of i-propanol and n-heptane fuel blends on emissions of HCCI engines. The addition of i-propanol caused to incomplete combustion. Gong et al. [14] performed an experimental study in order to see the effects of isopropanol-gasoline blends on emissions of spark ignition engines. They showed that HC emissions increased when EGR rate was up to 5 % with pure isopropanol. Keskin and Gürü [15] studied the effects of ethanol-gasoline blends and propanol-gasoline blends on exhaust and noise emissions of a spark ignition engines. They implied that HC and CO emissions decreased with ethanol-gasoline blends and propanol-gasoline blends by about by 65.56 and 33.92%, respectively. Beeckmann et al. [17] experimented laminar burning velocities in a spherical combustion vessel at an unburnt temperature of 373 K and a pressure of 10 bar. Numerical studies were also conducted to identify the combustion characteristics of iso-propanol [2,3,18]. Frassoldati et al. [19] developed kinetic model to describe the combustion of n-propanol and iso-propanol. They have determined an agreement between kinetic model and experimental data. Lü et al. [20] observed the inhibition effects of MTBE, isopropanol, ethanol and methanol in HCCI engine. The lowest suppression effect was determined with MTBE. He et al. [21] performed an experimental study to see the effects of n-butanol in HCCI engine. Vuilleumier et al. [22] examined the intermediate temperature heat release in HCCI engines fueled with ethanol/n-heptane mixtures. Good agreement was found between experimental and modeling results. In this study, experimental study was conducted in order to determine the effects of iso-propanol on HCCI combustion. For this purpose, a single cylinder, four stroke, port injection spark ignition engine was converted to HCCI engine. The tests were performed at constant lambda value of 2 at wide open throttle with n-heptane isopropanol fuel blends. The influence of inlet air temperature was also observed on HCCI combustion at 1500 rpm engine speed.

2. EXPERIMENTAL SETUP AND PROCEDURES

A 0.54 L, single cylinder, port injection Ricardo Hydra spark ignition test engine was used in the experiments. The technical specifications of the test engine are given in Table 1. The test engine was coupled with DC dynamometer which absorbs 30 kW power at 6500 rpm. The schematic view of the experimental setup is seen in Figure 1. The engine oil and coolant temperatures were kept constant during the experiments. Engine torque, fuel injection pulses, inlet air temperature and throttle valve position can be controlled from the dynamometer control panel.

Table 1. The technical specifications of the test engine

Model	Ricardo-Hydra
Cylinder number	1
Cylinder bore & stroke [mm]	80.26 & 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°BTDC/56° ABDC EVO/EVC 56° BBDC/12° BTDC
Valve lift	Intake/Exhaust 5.5/3.5

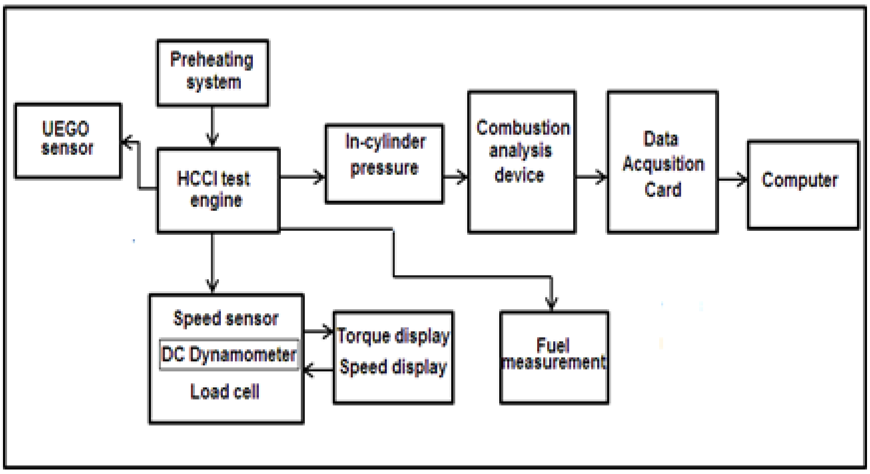


Figure 1. The schematic view of the experimental setup

Preheating system was placed in the suction line to warm up the inlet air temperature. K type thermocouple was mounted in the inlet line in order to measure the inlet air temperature. Inlet air temperature was controlled using close-loop circuit. Lambda was also held constant at 2 using fuel injection potentiometer in the control panel. UEGO sensor mounted in the exhaust line was utilized to measure lambda.

In-cylinder pressure was measured using Kistler 6121 pressure transducer mounted in the cylinder head of test engine. Encoder was also mounted in the crankshaft to measure engine speed. Cylinder pressure data were amplified using Cussons combustion analysis device and recorded in the computer. For this purpose, National Instrument data acquisition card was used to convert analog signals to digital signals with the interval of 0.36 crank angle degrees. Averaged of 50 consecutive cycles was used for in-cylinder pressure to eliminate the cyclic variations. The compression ratio of the test engine was increased to 13:1 achieving HCCI combustion. Thus, the test engine was first operated at spark ignition mode to warm up the engine and then HCCI combustion switching off the spark plug.

The experiments were conducted with n-heptane and isopropanol fuel blends at different inlet air temperatures. P20 and P30 define the fuel blends which include 20% isopropanol, 80% n-heptane and 30% isopropanol, 70% n-heptane by vol. respectively. Chemical properties of the test fuels are given in Table 2.

Table 2.The chemical properties of the test fuels [23, 24]

	n-heptane	Iso-propanol
Chemical formula	C_7H_{16}	$(CH_3)_2CHOH$
Density [kg/m^3]	679.5	809
Octane number	-	107
Lower heating value [MJ/kg]	44.56	30.447
Boiling point [$^{\circ}$C]	98	82
Molar mass [g/mol]	100.16	60.10

Cylinder pressure, heat release rate were determined using program developed with MATLAB. The first law of the thermodynamic was used to determine heat release rate. Heat transfer was also considered calculating heat release rate. Charge mixture was assumed to be ideal gas during the calculations [12,13].

3. RESULTS AND DISCUSSION

Fuel properties affect HCCI combustion significantly. One way to prevent rapid heat release rate in HCCI combustion is to use high octane number fuels. High octane number fuels not also improving combustion but also preventing higher pressure rise rate resulting in knocking. Moreover, HCCI combustion operating range can also be extended at knocking boundaries. Figure 2 shows the effects of isopropanol and n-heptane fuel blends and n-heptane on cylinder pressure and heat release rate at different inlet air temperatures. Two-stage combustion is seen on HCCI combustion as seen in Figure 2 which called low and high temperature reactions. It was concluded from Figure 2 that the addition of isopropanol caused to HCCI combustion to retard due to high octane number of isopropanol. When inlet air temperature was examined, there was no remarkable variation on maximum cylinder pressure with P20 and P30. However, combustion occurred earlier with the increase of inlet air temperature. Because, HCCI combustion dependent strongly on the temperature and pressure history during the compression stroke. Higher inlet air temperature led to advance HCCI combustion due to improvement of auto-ignition chemical reactions. Figure 2 also illustrated that isopropanol showed important resistance to knocking. Knocking combustion occurred when pure n-heptane was used as seen in Figure 2. In addition, it is possible to say that maximum cylinder pressure decreased with the increase of inlet air temperature. It can be explained that higher inlet air temperature increased the tendency of knocking with n-heptane. Chemical kinetics is influenced by inlet air temperature. Auto-ignition chemical reactions occur easily at higher inlet temperatures resulting in higher cylinder pressure.

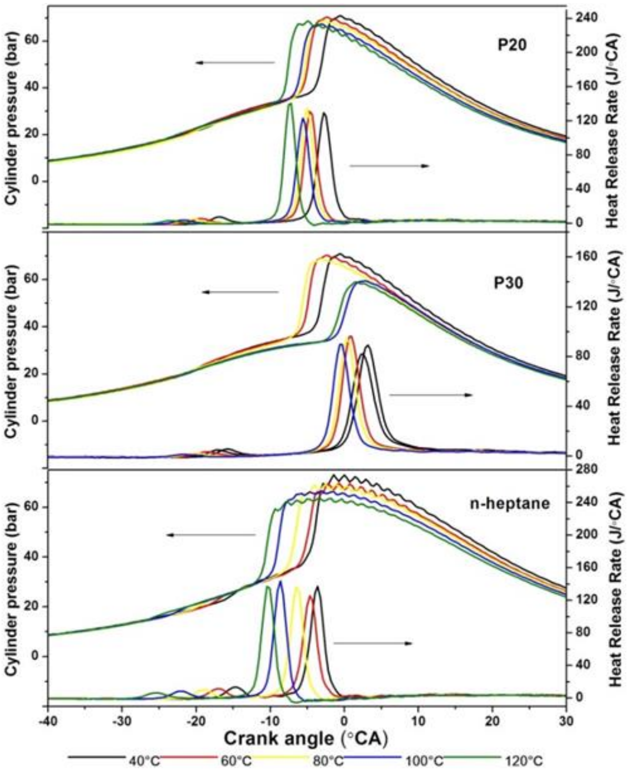


Figure 2. The effects of isopropanol on cylinder pressure and heat release rate at different inlet air temperatures

SOC is mainly dependent on the chemical kinetics on HCCI combustion. Figure 3 depicts the effects of isopropanol on SOC at different inlet air temperatures. It can be clearly said that SOC was retarded with the increase of the amount of isopropanol in the test fuel. Minimum SOC was determined with P30 due to higher octane number. As it is known, knocking resistance of n-heptane is zero. So, HCCI combustion started earlier. The addition of isopropanol directly affected the HCCI combustion phasing. It can also be concluded from Figure 3 that the increase of inlet air temperature caused HCCI combustion to advance. The temperature at the end of compression stroke increases with the increase of inlet air temperature which varies combustion phasing. Auto-ignition chemical reactions are deteriorated at lower inlet air temperatures.

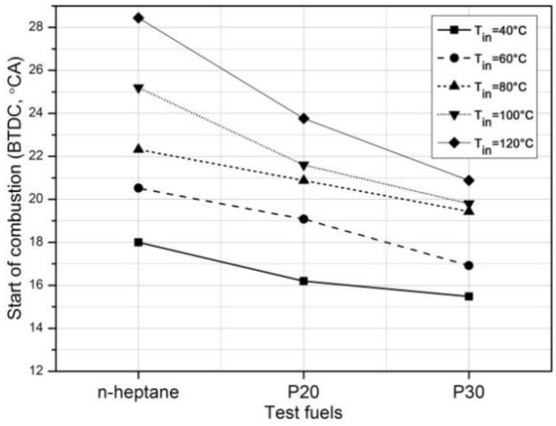
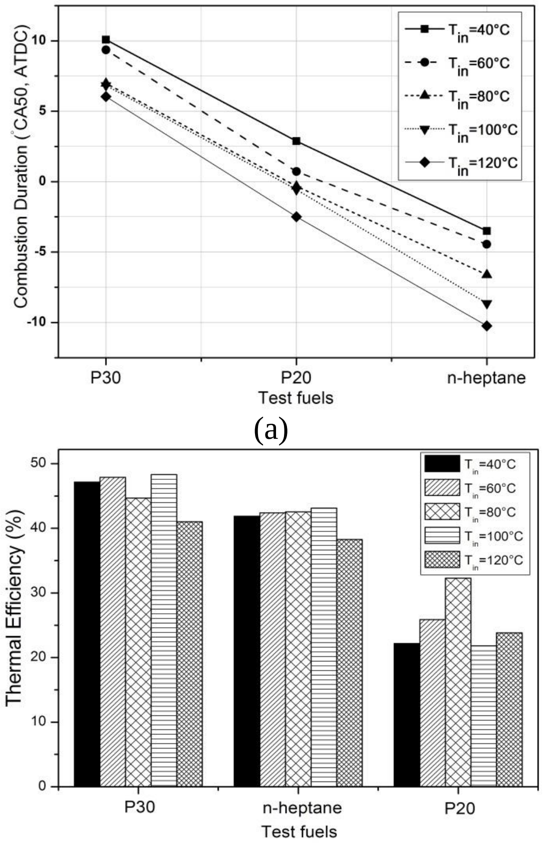


Figure 3. The effects isopropanol on SOC at different inlet air temperatures

Variations of CA50 at different inlet air temperatures are seen in Figure 4-a. CA50 is the point versus crank angle which the half of charge mixture completed to combust. CA50 is important combustion phasing for thermal efficiency. CA50 should be shortly after TDC for better thermal efficiency. As seen in Figure 4-a, CA50 was obtained BTDC with n-heptane owing to earlier combustion. CA50 was obtained later with the addition of isopropanol on HCCI combustion. High octane number isopropanol retarded to HCCI combustion. As mentioned above, CA50 was obtained slightly after TDC with P30. Similarly, the highest thermal efficiency was obtained with P30 as seen in Figure 4-b.



(a)

(b)

Figure 4-a).Variations of CA50 at different inlet air temperatures b) Variation of thermal efficiency

The increase of inlet air temperature advances HCCI combustion. Minimum thermal efficiency was obtained with P20 at all inlet air temperatures. It is also possible to say that there is decreasing tendency with the increase of inlet air temperature with n-heptane and P30 test fuels. The addition of isopropanol improved thermal efficiency of HCCI combustion. The increase of thermal efficiency with P30 is the result of controlling combustion phasing. Because, higher pressure rise rate was prevented using high octane number isopropanol. It is one of the most important results of the usage of isopropanol on HCCI combustion in the present study.

Indicated mean effective pressure (imep) is one of the most significant parameter indicates engine performance. Imep is the mean pressure exerted on the piston during a cycle. Figure 5 concludes the variations of imep versus test fuels at different inlet air temperatures. Imep decreases with the increase of inlet air temperatures, because combustion is deteriorated. Knocking tendency increased as the inlet air temperature increased. Moreover, HCCI combustion occurred in earlier BTDC. Hence, results in lower imep especially with n-heptane and P20.

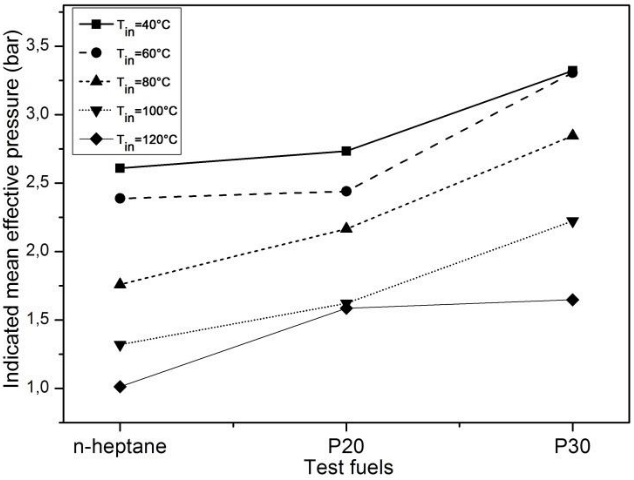


Figure 5. Variations of imep versus test fuels at different inlet air temperatures

The increase of inlet air temperature decreases the charge mass due to lower density. So, lower charge mixture is driven to the cylinder, hence imep decreases. Furthermore, maximum cylinder pressure is obtained BTDC when n-heptane was used as test fuel. It results dramatic decrease on imep. Higher imep was obtained although isopropanol has lower calorific value than n-heptane.

5. CONCLUSIONS

The aim of this study is to investigate the effects of isopropanol on HCCI combustion at different inlet air temperatures experimentally. For this purpose, a single cylinder, spark ignition test engine was converted to HCCI engine increasing compression ratio. Inlet air temperatures were altered from 40°C to 120°C interval of 20°C. The experiments were conducted at 1500 rpm constant engine speed and lambda value of 2. The test results showed that isopropanol has remarkable effect on HCCI combustion. The addition of isopropanol caused HCCI combustion to retard. In addition, knocking occurred with n-heptane for all inlet temperatures. Test results also showed that combustion was advanced with the increase of inlet air temperature. It can be said that P30 gives the best performance and combustion results among the test fuels. Because, isopropanol showed significant resistance to knocking by slowing down the rapid heat release rate due to higher octane number. It is clear to say that HCCI combustion phasing can be controlled and HCCI operating range can be extended using higher octane number alcohols. It is hoped that this study contributes the understanding the effects of isopropanol on HCCI combustion.

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ABBREVIATIONS

ABDC	After bottom dead center
BBDC	Before bottom dead center
BTDC	Before top dead center
CI	Compression ignition
CO	Carbon monoxide
HC	Hydrocarbon
HCCI	Homogeneous charged compression ignition
EGR	Exhaust gas recirculation
MTBE	Methyl tert-butyl ether
NOx	Nitrogen oxides
SI	Spark ignition
SOC	Start of combusiton
UEGO	Universal exhaust gas oxygen