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An Investigation of the Performance of a Gasoline Spark Ignition Engine Fuelled with Hot Ethanol Direct Injection

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Abstract

Ethanol direct injection (EDI) is a promising technology to address the issue of knock in downsized spark ignition (SI) engines due to the strong cooling effect of EDI and ethanol's large octane number. However, the evaporation rate of ethanol is lower than that of gasoline fuel because of its low volatility (saturation vapour pressure) in low temperature conditions and large enthalpy of vaporization. This might have caused the increased HC and CO emissions in an ethanol direct injection plus gasoline port injection (EDI+GPI) engine when EDI was applied. To address this issue, the combustion and emission performance of an EDI+GPI engine fuelled with hot ethanol fuel was experimentally investigated in the present study. The experiments were conducted on a 249 cc single cylinder SI engine at medium load (IMEP 6.0-6.3 bar) and stoichiometric fuel/air ratio condition. The injected ethanol fuel temperature ranged from 45 ℃ (no fuel heating) to 105 ℃ (flash-boiling spray) with an increment of 15 ℃. Experimental results showed that the IMEP decreased slightly with the increase of ethanol fuel temperature. However, the ISCO and ISHC emissions decreased significantly and ISNO increased moderately with the increase ethanol fuel temperature.

Keywords: Ethanol direct injection, Fuel temperature, Flash-boiling, Spark ignition, Combustion performance.

1. Introduction

Ethanol fuel is considered promising as an alternative transportation fuel because it can be produced from bio-mass via established and new processes [1]. Comparing with gasoline fuel, ethanol fuel has many advantages including greater enthalpy of vaporization, larger octane number, faster laminar flame speed and smaller air/fuel ratio. Recently, ethanol direct injection (EDI) has been developed as a new technology to address the issue of knock in downsized spark ignition (SI) engines due to the strong cooling effect of EDI and ethanol's large octane number.

However, as neat fuel, EDI may be not suitable to power SI engines in some conditions because of its low volatility, low heating value and high enthalpy of evaporation, especially under cold conditions [2, 3]. It was reported that gasoline-fuelled engine could be started at ambient temperature as low as -40 ℃, while ethanol fuelled engine could not be started at temperature lower than 13 ℃ without an auxiliary cold start system [2]. Therefore, ethanol direct injection plus gasoline port injection engine (EDI+GPI) needs to be investigated to address this issue. As reported, EDI+GPI utilizes ethanol fuel more efficiently and flexibly in SI engines than the E10 or E85 in the current market [4]. It integrates the advantages of both port injection and direct injection fuel systems. Dual-injection concept offers the flexibility to change the gasoline-ethanol blending ratios online in terms of engine loads. The GPI can be used to address the cold start issue of ethanol fuel. The EDI can be started once the engine is warmed up and the percentage of ethanol fuel can be increased when engine load is increased to suppress the knock propensity.

To exploit the potential of the dual-injection concept, a single cylinder SI engine equipped with EDI+GPI has been developed at the University of Technology Sydney. Experimental results showed that the engine thermal efficiency was increased and knock propensity was reduced when EDI was applied [4, 5]. On the other hand, the HC and CO emissions of the engine were increased with the increase of ethanol ratio [4, 5]. It was found from the numerical modelling of the EDI+GPI engine that the low evaporation rate of ethanol fuel might have resulted in the poor mixing and increased HC and CO emissions [6].

The mixing and evaporating processes of a spray can be affected by a number of factors. The fuel temperature is an important factor that determines the saturation vapor pressure and thus the evaporation rate of a liquid fuel. The effect of fuel temperature on the EDI spray characteristics was investigated experimentally in a constant volume chamber [7]. The results showed that the ethanol evaporation rate did not increase much and could be considered as non-evaporating spray when the fuel temperature was increased from 275 K to 325 K, but increased significantly with further increase of fuel temperature. The cold start and mixing can be big issues for engines fuelled with neat ethanol or high percentage of ethanol/gasoline blends. Increasing the fuel temperature is an effective way to reduce the viscosity and increase the vapor pressure of the fuel, and consequently increase the break-up and evaporation rates. Studies were conducted to investigate the cold start

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and emission characteristics of engines fuelled with heated ethanol fuel [2, 8-12]. Experimental results showed that the cold-start time was shortened and emissions were reduced with the heated ethanol fuel.

The aim of the present study is to investigate the potential of increasing ethanol fuel temperature on improving the emission performance of an EDI+GPI engine.

2. Experimental Setup

The experiments were conducted on a four-stroke single-cylinder SI engine equipped with an EDI+GPI dual-injection fuel system. Table 1 shows the specifications of the engine. The original engine was an SI engine with gasoline port injection. It was modified to EDI+GPI engine by adding an EDI fuel system. Both GPI and EDI injectors were controlled by an engine control unit (ECU). More details about the engine modification and test rig can be found in [4].

Table 1. Engine specifications.

Engine type	Single cylinder, air cooled, four-stroke, Spark ignition
Displacement	249.0 cc
Stroke × Bore	58.0 mm × 74.0 mm
Connecting rod	102.0 mm
Compression ratio	9.8:1
Valve timings	IVO: 22.20° BTDC; IVC: 53.80° ABDC EVO: 54.60° BBDC; EVC: 19.30° ATDC
Ethanol delivery system	Direct injection
Gasoline delivery system	Port injection

Figure 1 is the schematic of the fuel heating system. An electronic resistance heater made of Kanthal A1 heating resistance wire was used to heat the ethanol fuel in the high pressure rail. The heater was wrapped on the fuel rail upstream the injector. A T-type thermocouple was attached to the surface of the fuel rail at the entrance of the EDI injector. The temperature was fed to a 2132 Eurotherm PID temperature controller, which controlled the relay of the heating system, so that the heating process stopped when the fuel temperature reached the preset value. Therefore, the fuel rail temperature at the injector entrance was regarded as the fuel temperature in the present study. The accuracy of the temperature control was within ±3 ℃. The power required for EDI heating is dependent on the fuel flow rate and the heating temperature. The maximum heating power is 150W which is about 3% of the engine output power.

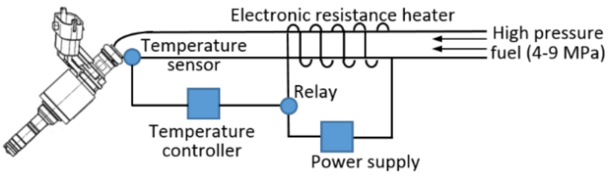

Fig. 1. Schematic of the EDI fuel heating system.

The ethanol fuel mixed with 0.1% gasoline fuel was provided by the Manildra Group. The gasoline fuel was the Unleaded Petrol from the Caltex Australia with an Octane number of 91. The experiments were conducted at medium load (6.0-6.3 bar IMEP) and engine speeds of 3500 rpm or 4000 rpm. The lambda was maintained around one during the experiments. A MEXA-584L gas analyzer was used to measure the lambda of EDI+GPI dual-fuelled conditions by setting the atomic ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) in the blended fuel. The GPI pressure was 0.25 MPa and the EDI pressure was 4 MPa. The spark timing was 15 CAD BTDC. The GPI timing was 410 CAD BTDC and EDI timing was 300 CAD BTDC. The ethanol volume ratio was fixed at 50% (8.0 mg GPI plus 8.8 mg EDI). The investigated ethanol temperature varied from 45 ℃ (no fuel heating applied) to 105 ℃ (flash-boiling spray) with an internal of 15 ℃.

3. Results and Discussion

This section presents and discusses the experimental results in two sub-sections, the effect of ethanol fuel temperature on the engine combustion and emissions characteristics.

3.1 Combustion characteristics

To understand the effect of ethanol fuel temperature on the combustion characteristics of the EDI+GPI engine, the in-cylinder pressure, heat release rate (HRR), mass fraction burnt (MFB), indicated mean effective pressure (IMEP) and indicated thermal efficiency are discussed in this section.

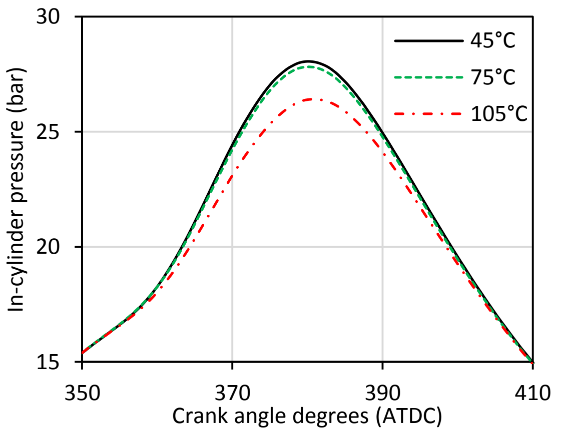

Fig. 2. In-cylinder pressure of different ethanol fuel temperatures at 3500 rpm.

Fig. 2 shows the in-cylinder pressure at the ethanol fuel temperatures of 45 ℃ (no fuel heating), 75 ℃ and 105 ℃ at the engine speed of 3500 rpm. As shown in Fig. 2, the peak in-cylinder pressure decreases slightly when the ethanol temperature is increased from 45 ℃ to 75 ℃, but decreases noticeably from 75 ℃ to 105 ℃. The corresponding HRR and MFB with different ethanol fuel temperatures at 3500 rpm are depicted in Figs. 3 and 4. Consistently, the HRR and MFB derived from the cylinder pressure shown in Fig. 2 demonstrate no noticeable difference when the fuel temperature is increased from 45 ℃ to 75 ℃. However when the fuel temperature is further increased to 105 ℃, the peak HRR value decreases and the slope of the MFB curve becomes smaller, indicating slower combustion speed.

The decrease of combustion speed with increased ethanol fuel temperature may be caused by the following two reasons. Firstly, the fuel density and viscosity decrease when the fuel temperature is increased, which affect the injection process. Experiments and simulations on the injection process of a compression ignition engine found that the injection timing was retarded, the peak line pressure was decreased and the injection duration was prolonged when the fuel temperature was increased [13, 14]. The fuel mass flow rate also decreased when the fuel temperature was increased due to the decrease of fuel density [15]. These indicate that the mass of ethanol fuel injected into the combustion chamber is reduced with the increase of fuel temperature.

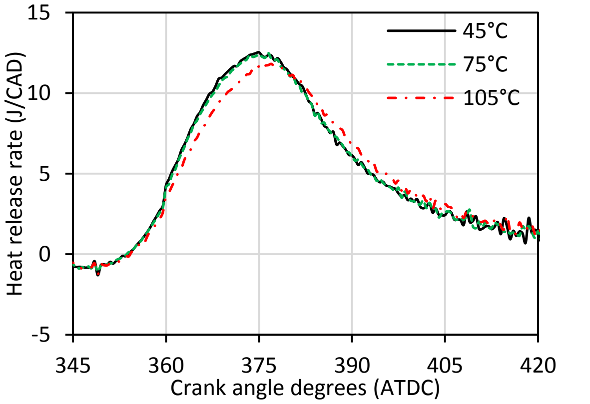

Fig. 3. Heat release rate of different ethanol fuel temperatures at 3500 rpm.

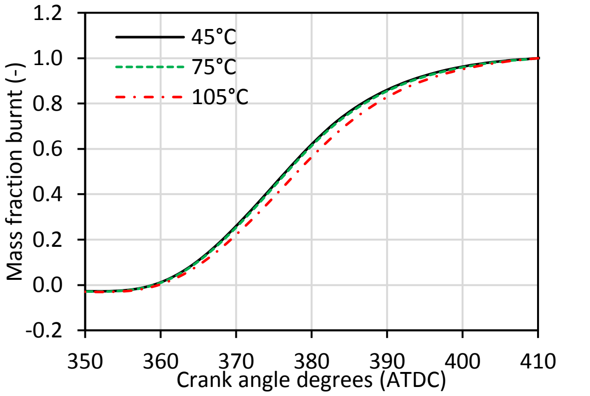

Fig. 4. Mass fraction burnt of different ethanol fuel temperatures at 3500 rpm.

The second reason is that the fuel spray process is affected significantly by the fuel temperature. The direct injection injector used in the engine tests was a six-hole nozzle. Fig. 5 shows the spray structures at 2.0 ms after the start of injection in a constant volume chamber with different fuel temperatures. The injection pressure was 6 MPa and the ambient pressure was 1 bar. More details about the spray experiments in the constant volume chamber can be found in reference [7]. Fig. 5 shows that the two side plumes of the ethanol spray converge towards the middle one when the fuel temperature is increased from 52 °C to 77 °C, and collapse completely when the temperature reaches 102 °C. In the EDI+GPI engine, the EDI injector was installed with the spray plumes bend towards the spark plug to create an ignitable mixture around the plug gap by the time of ignition. However, the results in Fig. 5 indicate that the spray was not collapsed at 45 °C and 75 °C, but collapsed at 105 °C. This may have destroyed the desired fuel distribution in the combustion chamber, and consequently deteriorated the ignition and combustion processes.

(a) 52 °C (b) 77 °C (c) 102 °C

Fig. 5. Effect fuel temperature on the EDI spray structure.

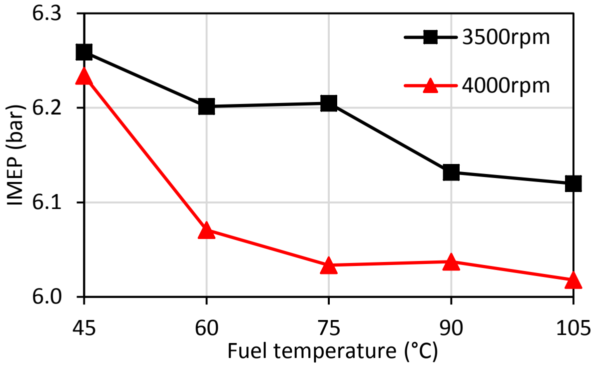

Fig. 6. Effect of ethanol fuel temperature on IMEP.

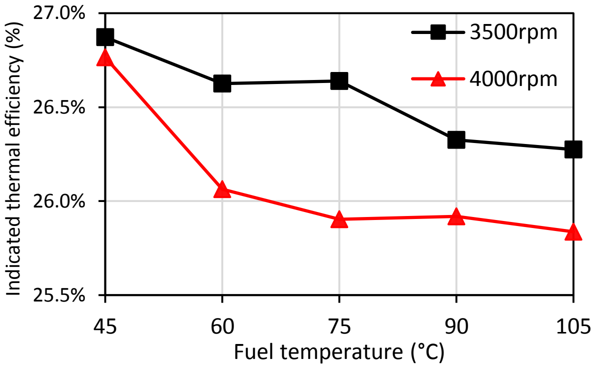

Fig. 7. Effect of ethanol fuel temperature on indicated thermal efficiency.

Fig. 6 shows the effect of ethanol fuel temperature on the IMEP at the engine speeds of 3500 rpm and 4000 rpm. As shown in Fig. 6, the IMEP decreases slightly from 6.26 bar to 6.12 bar at 3500 rpm and from 6.23 bar to 6.02 bar at 4000 rpm when the fuel temperature is increased from 45 °C to 105 °C. The decrease of IMEP with increased fuel temperature is caused by the decreased combustion speed, as discussed in Figs. 3 and 4. Consistently, the indicated thermal efficiency decreases slightly from 26.9% in 45 °C to 26.3% in 105 °C at 3500 rpm, and from 26.8% in 45 °C to 25.8% in 105 °C at 4000 rpm, as shown in Fig. 7. The heating load is not included in the decrease of thermal efficiency.

3.2 Engine emissions

Although increasing ethanol fuel temperature decreases the thermal efficiency slightly, the emission performance of the EDI+GPI engine can be significantly improved with heated ethanol fuel. Figs. 8 and 9 show the effect of ethanol fuel temperature on the indicated specific carbon monoxide (ISCO) and hydrocarbon (ISHC) emissions. As shown in Fig. 8, the ISCO decreases from 24.27 to 15.81 g/kw-h at 3500 rpm and from 38.13 to 14.10 g/kw-h at 4000 rpm when ethanol temperature is increased from 45 °C to 105 °C. The ISHC also decreases from 2.26 to 1.20 g/kw-h at 3500 rpm and from 2.47 to 0.77 g/kw-h at 4000 rpm, as shown in Fig 9. The decrease of ISCO and ISHC emissions are the results of improved evaporation and mixing processes with heated ethanol fuel. Previous CFD simulation on the spray and combustion processes of the EDI+GPI engine showed that the low evaporation rate of ethanol fuel in low temperature environment before combustion led to a large number of liquid droplets not evaporated before the combustion took place, which consequently resulted in incomplete combustion and increased CO and HC emissions when EDI was applied [6]. In the present study, the ethanol fuel temperature is increased, which should increase the spray evaporation of ethanol fuel and thus improve the consequent combustion process and reduce the ISCO and ISHC emissions. Fig. 10 illustrates the effect of fuel temperature on the indicated specific nitric oxide (ISNO) emission. As shown in Fig. 10, the ISNO increases moderately from 13.38 or 10.73 g/kw-h at 45 ℃ to 14.32 or 12.30 g/kw-h at 105 ℃. The ISNO is increased due to the higher combustion temperature which might be resulted from the higher temperature of the ethanol fuel.

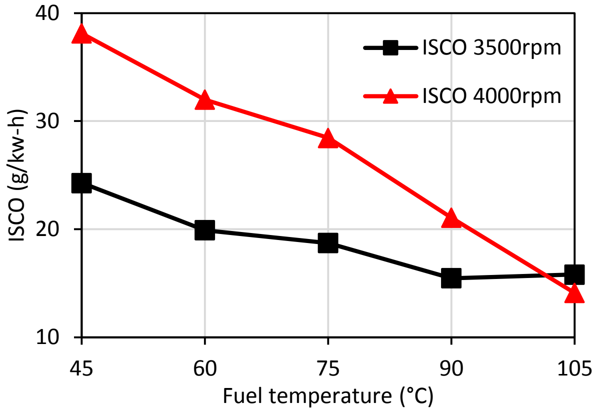

Fig. 8. Effect of ethanol fuel temperature on ISCO.

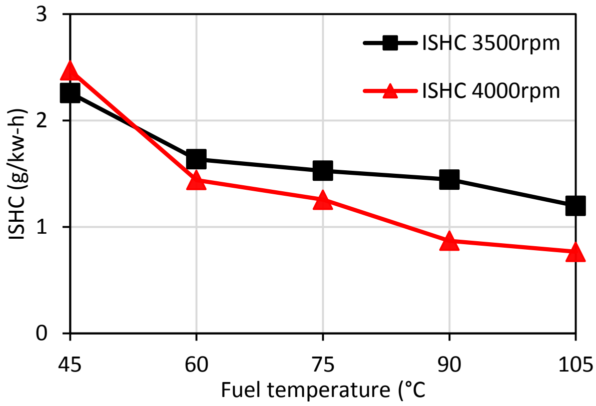

Fig. 9. Effect of ethanol fuel temperature on ISHC.

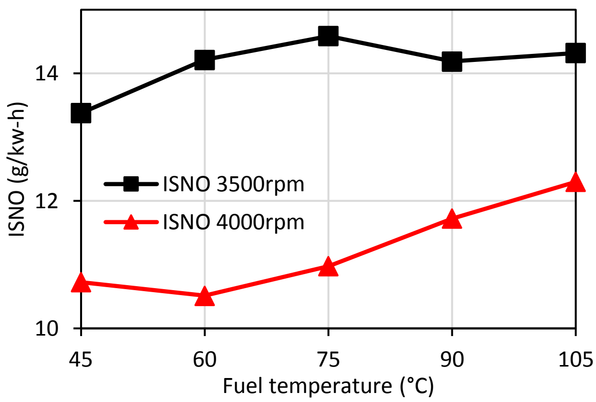

Fig. 10. Effect of ethanol fuel temperature on ISNO.

4. Conclusions

Experiments were conducted to investigate the effect of ethanol fuel temperature on the combustion and emission performance of a single-cylinder SI engine equipped with EDI+GPI dual-injection fuel system. The engine was operated at medium load (IMEP 6.0-6.3 bar) and stoichiometric air/fuel ratio at engine speeds of 3500 rpm or 4000 rpm. The ethanol fuel temperature was increased from 45 ℃ (no fuel heating) to 105 ℃ (flash-boiling spray).

The ISCO emission is decreased by 35% at 3500 rpm and 63% at 4000 rpm and the ISHC is decreased by 47% at 3500 rpm and 69% at 4000 rpm when ethanol temperature is increased from 45 ℃ to 105 ℃. On the other hand, the penalties of heating ethanol fuel are only 2% or 4% of decrease in thermal efficiency, and 7% or 15% of increase in ISNO emission. However even the increased ISNO emission is still smaller than that of GPI only condition due to the lower combustion temperature and stronger cooling effect of EDI. These indicate that increasing fuel temperature can be effective on reducing the CO and HC emissions while keeping the high thermal efficiency of the EDI+GPI engine.

5. Acknowledgments

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