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Effects of Fuel Temperature on Injection Process and Combustion of Dimethyl Ether Engine

To investigate the effects of fuel temperature on the injection process in the fuel-injection pipe and the combustion characteristics of compression ignition (CI) engine, tests on a four stroke, direct injection dimethyl ether (DME) engine were conducted. Experimental results show that as the fuel temperature increases from 20 to 40 °C, the sound speed is decreased by 12.2%, the peak line pressure at pump and nozzle sides are decreased by 7.2% and 5.6%, respectively. Meanwhile, the injection timing is retarded by 2.2 °CA and the injection duration is extended by 0.8 °CA. Accordingly, the ignition delay and the combustion duration are extended by 0.7 °CA and 4.0 °CA, respectively. The cylinder peak pressure is decreased by 5.4%. As a result, the effective thermal efficiency is decreased, especially for temperature above 40 °C. Before beginning an experiment, the fuel properties of DME, including the density, the bulk modulus, and the sound speed were calculated by "ThermoData." The calculated result of sound speed is consistent with the experimental results. [DOI: 10.1115/1.4023549]

Keywords: dimethyl ether, engine, injection, combustion, thermal efficiency

1 Introduction

The recent increase of world oil price and the growing awareness of environmental problems associated with the use of petroleum fuels, have led to the renewed interest in alternative fuel [1–5]. DME is one of the most promising alternative fuels for compression ignition engines. DME has a simple molecular structure (CH₃-O-CH₃) with high oxygen content and cetane number, and no C-C bond in its molecule. Therefore, DME engine can achieve a smoke free combustion and lower particulate matter, hydrocarbon, carbon monoxide, and nitrate oxides emissions with high thermal efficiency [6–10]. Though DME has more advantages as one promising alternative fuel, more works still need to be done to further improve DME engine application.

Some previous work and results from studying the effects of fuel properties and conditions on diesel engine fuel injection and combustion were presented by Hsu and co-worker [11,12] and Maeda et al. [13]. Particularly, an investigation of fuel temperature effects on the fuel-injection behavior and engine combustion was conducted and some of results from the investigation were available and reported by Hsu [11] and Gong [14]. The results from their studies indicated that the injection process and the combustion of diesel fuel were significantly affected by the fuel temperature, and further confirmed that the primary fuel temperature effects are due to the changes of bulk modulus and the density.

Compared to diesel fuel, DME has lower density and bulk modulus, and they are more sensitive to temperature. Zhao et al. [15] illustrated the differences of injection parameters at different temperature through the numerical simulations. Meanwhile, Cipolat [16] and Zhang et al. [17] compared the fuel-injection process and the combustion between diesel fuel and DME, and found that there is a striking difference between them. The same reason was obtained from the difference of fuel properties. Meanwhile, the

changes of density and the bulk modulus of DME on the sound speed and compressibility was studied by Teng et al. [18].

The comprehensive studies including the theoretical analysis and the experimental test of fuel temperature effects on the fuel injection and the combustion were rarely reported. In this context, more work is necessary to investigate the temperature dependence of DME engine.

2 Experimental Setup

The DME engine used in this study was retrofitted from a four-stroke, water-cooled, direct-injection diesel engine, and its major specifications are listed in Table 1. To prevent DME from vaporizing, DME in the low pressure supply system was pressurized to 2 MPa approximately by three electronic fuel pumps.

Figure 1 shows the schematic diagram of engine test bench. DME temperature was sensed by a temperature sensor (Pt 100) which was located at the inlet of pump. The cylinder pressure was sensed by a water-cooled piezoelectric pressure transducer (Kistler 7061B), and the signals were amplified by a charge amplifier (Kistler 5011). The signals of crank angle and the piston top dead

Table 1 Comparison of the major specifications of diesel engine and DME engine

Parameter	Unit	Diesel engine	DME engine
Cylinder number	/	2	
Bore × stroke	mm × mm	102 × 115	
Displacement	cm ³	1880	
Combustion chamber	/	ω type	
Compression ratio	/	17.5	
Rated power/speed	kW/r·min ⁻¹	26.1/2700	26.8/2800
Maximum torque/speed	N·m/r·min ⁻¹	110.2/1400	108.9/2000
Plunger diameter	mm	8.5	10.5
Nozzle hole diameter	mm	0.27	0.35
Number of nozzle holes	/	4	5
Needle valve open pressure	MPa	18	14
Fuel delivery advance angle	°CA BTDC	23	19

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Fig. 1 Schematic diagram of the engine test bench

center (TDC) were obtained from an optical rotary encoder (Kistler 2013B). The pressures of injection line were sensed by two high pressure sensors (Kistler 4067A) which were fixed at the two sides of injection line. The injection timing was measured by a needle valve lift sensor (NLM-1). The above signals were recorded by a data acquisition apparatus (YOKOGAWA DL750).

DME engine operating conditions were set according to electrostatic compatibility (ESC) test cycle and more attention was paid to 1870 r·min⁻¹ operating condition. DME temperature was kept within a stable and small range by setting the target temperature and hysteresis error on the intelligent temperature controller, such as 20 ± 1 °C. In the experiment, the ambient temperature was 17 °C. The experimental data can be collected and shown in Fig. 3. Similarly, another two temperatures, 30 °C and 40 °C, were conducted. In this temperature range, DME is well in its liquid phase because of the pressure in the fuel delivery system.

3 Results and Discussion

3.1 Effects of Temperature on DME Properties. To a CI engine, the fuel must be injected into the cylinder at the right time with a proper duration or rate. The propagation of the pressure wave is a very important parameter in the fuel-injection process. Since DME is in single liquid phase, the pressure wave propagates at the local sound speed. To understand how it changes with the increase of DME temperature, the sound speed, α , is analyzed by the following formula: [18]

$$\alpha = \sqrt{\frac{E}{\rho}} \quad (1)$$

where E is the bulk modulus (Pa) and ρ is the density (kg·m⁻³). The sound speed is determined by the thermodynamic parameters of the bulk modulus and the density. It can be calculated by "ThermoData," established by Thermodynamics Research Group of Xi'an Jiaotong University [19]. In the calculation, the pressure wave propagation in line was seen as isobaric process under the pressure of 5 MPa. That is to say, DME is in the sub cooled state. In the test range of fuel temperature, the calculated results are shown in Fig. 2. As DME temperature increases, both the bulk modulus and the density decrease. And, the descending of bulk modulus is greater than that of density, resulting in the reduction

of sound speed. Also, the compressibility of DME can be calculated. The isothermal compression rates for three testing temperatures are 2.6%/MPa, 3.0%/MPa and 3.5%/MPa, respectively.

3.2 Effects of Fuel Temperature on DME Injection Processes

3.2.1 DME Pressure Fluctuation in Fuel Line. Figure 3 shows the DME pressure fluctuation in the fuel line for three temperatures. As DME temperature increases, the line pressures are reduced while the corresponding crank angles are retarded due to the decrease of sound speed and the increase of compressibility. In the temperature test range, the line pressure initial rising points at pump side are retarded by 1.4 °CA, the peak line pressures are reduced by 1.6 MPa and the corresponding crank angles are retarded by 2.0 °CA. The similar changes at nozzle side are observed. The line pressure initial rising points are retarded by 2.1 °CA, the peak line pressures are reduced by 1.4 MPa and the corresponding crank angles are retarded by 2.3 °CA.

The line pressure fluctuation at nozzle side and 20 °C is used to illustrate the characteristics of DME injection process. The residual line pressure remains constant around 5 MPa. After 11.4 °CA BTDC, the line pressure undergoes a steep and steady rise to the needle valve open pressure 14 MPa at 6 °CA BTDC. The open of needle valve causes a lag of line pressure rise. Since the plunger

Fig. 2 Influence of temperature on DME properties

Fig. 3 DME injection pressures ($n = 1870 \text{ r} \cdot \text{min}^{-1}$, BMEP = 0.5 MPa)

Fig. 4 Measured sound speed at speed of $1870 \text{ r} \cdot \text{min}^{-1}$

speed is high and the needle valve flow area is small, the line pressure goes up to the maximum of 25.2 MPa at 1.2°CA BTDC. Then, the spill port opens the line pressure at pump side decreases sharply. At 12.6°CA ATDC, the needle valve closes followed by a series of pressure oscillations. Finally, the line pressure stays at around 5 MPa.

3.2.2 Measurement of DME Sound Speed. As shown in Fig. 3, there is a crank angle interval between the initial rising points of line pressures at pump sides and nozzle sides. The sound speed can be calculated by the following formula [17]:

$$\alpha = 6nL/\Delta\phi \quad (2)$$

where n is the engine speed ($\text{r} \cdot \text{min}^{-1}$), L is the length of line between two pressure pickups (m), and $\Delta\phi$ is the crank angle interval of line pressure starting to rise on the two pressure pickups ($^\circ\text{CA}$). The measured sound speeds at speed of $1870 \text{ r} \cdot \text{min}^{-1}$ are shown in Fig. 4. It is easily seen that the sound speed is decreased with the increase of fuel temperature, however, independent on the engine load. And, the measured results are consistent with the calculated results except the low temperature condition. In theoretical calculation, DME temperature remains constant without considering the change of temperature caused by the DME compression and the heat transfer. There is a slight difference between the measured results and the calculated results.

Fig. 5 Injection delay and duration ($n = 1870 \text{ r} \cdot \text{min}^{-1}$)

That is to say, DME temperature should be taken into account in the research and development of DME engine seriously.

3.2.3 Effects on DME Injection Delay and Duration. In our study, the fuel delivery advance angle was set at 19°CA BTDC. The injection delay is defined as the crank angle interval between the start of fuel delivered and the lift of needle valve. The injection delays and the injection durations at the different fuel temperature were measured, as shown in Fig. 5. As the DME temperature increases by 20°C , the injection delays and the injection durations are extended by about 2.2 and 0.8°CA for the all engine loads. Particularly, the injection timing is near the TDC under the high engine load and the high fuel temperature, as shown in Fig. 5, resulting in more fuel injected into cylinder after the TDC. This also means the combustion characteristics are going to be different. It is inevitable that the DME engine fuel delivery advanced angle should be adjusted according to the fuel temperature in the application.

3.3 Effect of Fuel Temperature on DME Engine Combustion. Based on the cylinder pressure, the heat release rate can be calculated [20]. Therefore, the combustion characteristics of DME engine can be analyzed in terms of the maximum cylinder pressure, the ignition delay (τ_{ig}) and the total combustion duration (ϕ_{tot}). In this study, the start of combustion (SOC) is defined as the peak points of second-phase derivative of cylinder pressure and the end of combustion (EOC) is defined as the accumulative heat release rate reaching 95%. The τ_{ig} is defined as the crank angle interval between the start of injection and the SOC. The ϕ_{tot} is the crank angle interval between the SOC and the EOC.

3.3.1 Effect of Fuel Temperature on Cylinder Pressure and Heat Release Rate. Figure 6 shows the cylinder pressure and the heat release rate for different fuel temperatures. It is observed that the curves are similar in shape, indicating a rapid premixed combustion phase followed by a slower diffusion combustion phase. Compared to 20°C , the peak cylinder pressure decreases and the heat release rate in the premixed combustion phase becomes shorter, while the curves move further away from the TDC with the increase of fuel temperature, indicating there is a delay in the SOC and less heat is released in the premixed phase. At the engine speed of $1870 \text{ r} \cdot \text{min}^{-1}$ and the brake mean effective pressure (BMEP) = 0.501 MPa, the peak cylinder pressure is decreased by 0.4 MPa and the occurrence of peak cylinder pressure is retarded by 1°CA , while the SOC is retarded by 2°CA when the fuel temperature increases by 20°C . The reasons are evident that as the temperature increases, the fuel delivery per cylinder is reduced

Fig. 6 Influence of fuel temperature on the cylinder pressure and heat release rate ($n = 1870 \text{ r} \cdot \text{min}^{-1}$, BMEP = 0.5 MPa)

Fig. 7 Influence of fuel temperature on τ_{ig} ($n = 1870 \text{ r} \cdot \text{min}^{-1}$)

and the injection timing is retarded, resulting in the decrease in peak cylinder pressure and the retarded SOC.

3.3.2 Effect of Fuel Temperature on τ_{ig} . Figure 7 shows the influence of fuel temperature on the τ_{ig} . It is evident that the τ_{ig} is prolonged with the increase of fuel temperature. However, it can be found that the combustion all start after the TDC for 30 and 40°C operations due to the retarded injection timing, as shown in Fig. 6. That means the atomization and oxidation processes of part of DME are completed after the TDC. At the moment, both the cylinder temperature and pressure decrease with the piston going downward. Besides, with the increase of fuel temperature, the penetration is shorter which deteriorates the formation of mixture. As a result, the τ_{ig} is prolonged by 0.7°CA with the fuel temperature increases by 20°C for BMEP = 0.501 MPa operation. On the contrary, with the increase of engine load, the cylinder pressure and temperature are both increased which improve the atomization and oxidation of DME, resulting in short τ_{ig} .

3.3.3 Effect of Fuel Temperature on ϕ_{tot} . Figure 8 shows the influence of fuel temperature on the ϕ_{tot} . It is evident that the ϕ_{tot} is prolonged with the increase of fuel temperature and engine load. For a specific fuel temperature in the test range, the ϕ_{tot} is prolonged fundamentally with the increase of engine load because more fuel is injected into cylinder which needs more time to burn completely. For a specific engine load in the test range, the ϕ_{tot} is

Fig. 8 Influence of fuel temperature on ϕ_{tot} ($n = 1870 \text{ r} \cdot \text{min}^{-1}$)

Fig. 9 Influence of fuel temperature on η_{et} ($n = 1870 \text{ r} \cdot \text{min}^{-1}$)

also prolonged with the increase of fuel temperature due to the deteriorated mixture formation, especially under the high engine load. In general, higher fuel temperature results in smaller size of fuel droplets and improves the mixture formation process fuelling with diesel fuel on engine. But, in the case of DME, its spray characteristics are different from that of diesel fuel. In general, the spray angle of DME is bigger than diesel fuel, and the spray penetration of DME is shorter than diesel fuel. When the fuel temperature increases, the trends will be more obvious. In this study, the injection pressure of DME is lower than diesel fuel. As the fuel temperature increases, when the fuel is injected into cylinder more fuel congregates on the point of injector, resulting in the mixture formation of DME deteriorating. As shown in Fig. 8, with the increase of temperature from 20 to 40°C, the ϕ_{tot} is extended by 3.6°CA for BMEP = 0.167 MPa operation and extended by 4.0°CA for BMEP = 0.501 MPa operation.

3.3.4 Effect of Fuel Temperature on Brake Thermal Efficiency. Figure 9 shows the influence of DME temperature on the brake thermal efficiency at engine speed of 1870 r·min⁻¹. In this study, the brake thermal efficiency, η_{et} , is defined as

$$\eta_{et} = \frac{3.6 \times 10^3 P}{BQ_{HV}} \quad (3)$$

where P is the brake power of DME engine (kW), B is the DME consumption ($\text{kg}\cdot\text{h}^{-1}$) and Q_{HV} is the DME low heating value ($\text{kJ}\cdot\text{kg}^{-1}$). It is evident that the η_{et} decreases with the increase of temperature and the trend is more obvious under the high engine loads. As discussed above, with the increase of temperature, the τ_{ig} increases, and the ϕ_{tot} is also prolonged. Though, DME has high oxygen content and excellent spray characteristics. With the increase of temperature from 20 to 40 °C, the η_{et} is reduced by 1.8% for BMEP = 0.167 MPa operation and reduced by 5.0% for BMEP = 0.501 MPa operation. The fuel temperature should be lower than 40 °C to prevent the quick reduction of DME engine thermal efficiency.

4 Conclusion

In this study, the effects of DME temperature on the injection process and the combustion characteristics of a DME engine were investigated. The following conclusions can be drawn. (1) As the DME temperature increases, the measured and calculated sound velocities are decreased and the essential reason is the descending of bulk modulus is faster than the increase in density. (2) Due to the changes of fuel properties, the injection timing is retarded, the peak line pressure is decreased and the injection duration is extended. (3) Corresponding to the changes of injection parameters, the start of combustion (ignition) and the occurrence of maximum cylinder pressure are both retarded, while the total combustion duration is extended and the maximum cylinder pressure is reduced. (4) For the changes of combustion characteristics, the effective thermal efficiency is reduced, especially when the DME temperature is above 40 °C. (5) To overcome the adverse effects on the injection and the combustion process caused by the increase of temperature, the advanced injection or delivery timing is necessary. With the increase of DME temperature to 40 °C, 2 °CA advances in injection timing is suitable.

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