ON-LINE MIXING AND EMISSION CHARACTERISTICS OF DIESEL ENGINE WITH DIMETHYL ETHER INJECTED INTO FUEL PIPELINE

by

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This article presents a new on-line dimethyl ether/diesel mixing method, researches its blend characteristics, and also validates combustion and emission effects on a light-duty direct injection engine. This new blend concept is that dimethyl ether is injected into the fuel pipeline to mix with local diesel as the injector stops injection, and this mixing method has some advantages, such as utilization of the original fuel system to mix dimethyl ether with diesel intensively, flexibility on adjustable mixing ratio varying with the engine operating condition, and so on. A device was designed to separate dimethyl ether from the blends, and its mixing ratios and injection quantity per cycle were also measured on a fuel pump bench. The results show that compared with the injected diesel, the percentages of dimethyl ether injected into fuel pipeline are 13.04, 9.74, 8.55, and 7.82% by mass as the fuel pump speeds increase, while dimethyl ether injected into fuel pipeline are 45.46, 35.53, 31.45, and 28.29% of wasting dimethyl ether. The power outputs of engine fueled with the blends are slight higher than those of neat diesel at low speeds, while at high speeds, its power outputs are a little lower. Smoke emissions of the blends are lower about 30% than that of neat diesel fuel at medium and high loads with hardly any penalty on smoke and NO_x emissions at light loads. The NO_x and HC emissions of the blends are slight lower than that of neat diesel fuel at all loads.

Key words: *Diesel engine, dimethyl ether, fuel pipeline, emission characteristics, mixing*

Introduction

Diesel engines are extensively used as high efficiency power sources. However, due to diesel fuel properties, *e. g.* high viscosity, it is difficult to vaporize, and its molecular structure contains many C–C bonds and almost no oxygen content. These factors lead to high emission levels of Diesel engines. This problem has been studied for many years at great expense and endeavor [1, 2]. Moreover, the gradual depletion of fossil energy is also an important issue. Candidate fuels, like dimethyl ether (DME), biodiesel, ethanol and methanol, *etc.*, have caught wide attention [3-6]. Among these fuels, DME has the advantage of a satisfied substitutive fuel for application in a variety of prototype engines with occasional slight

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modifications and almost smoke-free combustion. Many researches have been carried out on DME to determine its candidate suitability [7-9]. This is due to its low auto-ignition temperature, almost immediate vaporization as sprayed into the cylinder, rich oxygen content (around 35% by mass) and no C–C bonds in the molecular configuration. As an alternative liquid fuel, DME can be refined not only from natural gas, residual oil, coal and crude oil, but also from waste products and on-farm-grown biomass [10-12]. However, as an alternative fuel for replacing diesel fuel in compression ignition (CI) engines, DME has some deficiencies, such as low combustion enthalpy, low viscosity, and low modulus of elasticity [13]. Especially, DME fueled CI engines need a high performance fuel injection system for pressurizing DME into liquid in fuel tank, diminishing cavitations in the fuel injection system, preventing leakage, improving low lubricating property, shortening long injection period, and ensuring good sealing [14, 15].

There are different ways to deliver DME into the cylinders of a CI engine. The DME can be injected into the cylinder directly [16-20], and this fuel delivery method is widely used in those reported studies. The DME can also be mixed with diesel fuel in a fuel tank, and then the DME/diesel mixture is fed to the cylinders [21-23]. The third way is that DME is injected into engine port or cylinder while other fuel (maybe diesel, natural gas, *etc.*) is simultaneously introduced to the cylinder by another fuel system, and this method is called the dual fuel combustion mode or compound charge compression ignition combustion [24-27].

In the DME/diesel blend method, the mixture ratio between the fuels is set up as required in a sealed fuel tank pressurized to more than 0.5 MPa thus to maintain DME in liquid phase. Its advantages are to exploit diesel fuel viscosity to reduce the wear of moving parts in the fuel system, and promote diesel fuel combustion due to the flash boiling spray of mixing fuels, oxygen content improvement and less C–C bonds [21, 22]. However, blending DME/diesel is a complicated process, and its mixing ratio is fixed and could not be changed flexibly in accordance with the engine operating condition. Furthermore, DME in mixing fuels has a corrosive effect on plastic seal components of original diesel fuel system. In the other two methods, an independent fuel system is necessary for DME, which needs lubricity-enhancing additives and anticorrosive sealing materials to ensure leakage-free operation [17, 24, 25]. Obviously in these two methods, DME and diesel are fed into the cylinders *via* separated routes, hence the low boiling point DME has no chance to make contribution towards diesel atomization.

Diesel fuel has been used widely for more than 100 years and likely will remain as one of the major fuels to use for many years in the future. How to use DME in improving diesel atomization and combustion, thus improving the engine's performances, is an interesting question and also one of research focuses. This paper presents a novel on-line DME/diesel mixing method, and reports some results from the feasibility study on developing a new DME/diesel mixing technology potentially by which the fuel mixing ratio is able to be adjusted in accordance with the engine operating condition automatically.

Principle of DME/diesel on-line mixing

In order to enable real-time adjustment of the fuel mixing ratio, a novel DME/diesel mixing method is proposed based on the principle of fuel design [2]. The method is that DME is introduced into fuel pipeline when the injector is not in operation (*i. e.* the fuel pressure in fuel pipeline as residual pressure is low) so that adjustable quantity DME is mixed with diesel within the fuel pipeline and injector.

This DME/diesel mixing method can be explained using the fuel pressure time trace shown in fig. 1. In a pump-tube-injector fuel system, the fuel pressure in fuel pipeline changes with the cam angle of fuel pump or corresponding time. According to fuel pressure magnitude and its attenuation, an injection cycle is divided into three stages, injection stage, pressure fluctuation stage, and pressure stablized stage. In the injection stage, the fuel pressure is surged high, and this provides the energy for fuel injection. In the pressure fluctuation stage, the fuel pressure fluctuates, and fades gradually. In the pressure stablized stage, the fuel pressure is settled down to a residual pressure of about 4 MPa, with insignificant pressure fluctuations. Briefly speaking, the proposed mixing method is that DME is injected into fuel pipeline to mix with local diesel fuel in the pressure stablized stage. The required amount of injected DME can be determined according to the engine operation conditions.

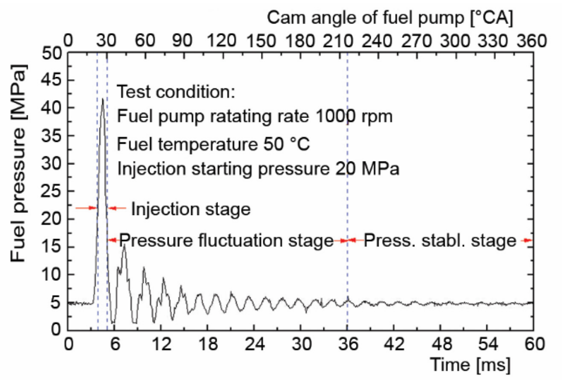

Figure 1. Fuel pressure in pipeline near injector

The schematic diagram of DME/diesel mixing system is illustrated in fig. 2. In this pump-tube-injector fuel system, the total capacity is about 10 cm^3, including the capacities of fuel pipeline, injector and fuel delivery valve. If the diesel injection mass through the mixing injector is about 40 mg per cycle and DME/diesel fuel mixing ratio is 10%, the injected DME mass is only 4 mg (about 6 mm^3), which volume is less than 1/1600 of the filling diesel volume of fuel system. Therefore, DME can be fed into fuel line and mix with local diesel fuel under a proper injection pressure.

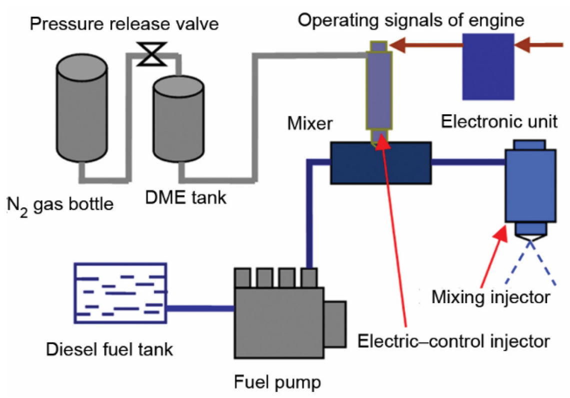

Figure 2. The DME/Diesel mixing system

In this new mixing method, diesel fuel is supplied by a conventional pump-tube-injector system, and by an electric-control injector, DME is fed into the fuel pipeline when the fuel injection to the cylinder is on hold. The electric-control injector is the key component to determine the DME/diesel mixing ratio, and its core part is a high speed electromagnetic valve used to control fuel injection.

Compared with the predetermined DME/diesel blend method, this novel method has following advantages.

– The DME is injected into fuel pipeline of the original engine by a separate fuel system, and the original fuel system only needs to have minor modifications. In the predetermined DME/diesel blend mode, DME/diesel mixing vessel need to be pressurized to above 0.5 MPa for liquidizing DME, thus its fuel system requires significant modification, *e. g.* using anti-corrosive sealing materials.

– A 4 MPa residual fuel pressure is enough to keep injected DME in liquid [9], and the fuel pressure fluctuation is beneficial for DME to mix with diesel within the pipeline and injector.
– The DME/diesel mixing ratio could be adjusted flexibly in accordance with the engine operating condition by modulating the injection pulse width of electric-control injector, which determines the volume of the DME injection.

Measurement of the mixing ratio and mass of the fuels

Principle of measuring mixing ratio and mass

An apparatus was designed for metering the mixing ratios and injection quantity per cycle, illustrated as fig. 3. The boiling points of DME and diesel, are –25 °C and 180~370 °C at atmospheric pressure, respectively. The DME exists as a gas while diesel a liquid at an ambient temperature and pressure. Therefore, DME/diesel mixture can be easily separated after injection, and their mixing ratios could also be computed once the masses of the fuels are weighed. The average fuel injection quantities per cycle can be obtained by its total injected mass and total injection time.

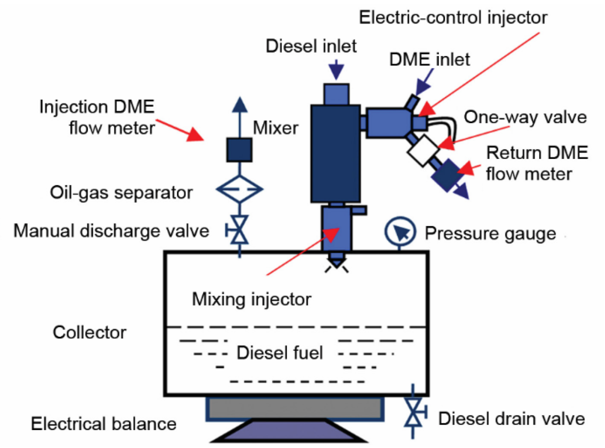

Figure 3. Schematic diagram of separating DME from diesel

Firstly, the apparatus mass, m_0, is recorded by an electrical balance. The DME is injected into the mixer by an electric-control injector, which is regarded as one part of fuel pipeline leading to the mixing injector, shown as fig. 3. The DME/diesel blend fuels are injected into a collector, which has a manual discharge valve upside for exhausting gaseous DME and a diesel drain valve on the other side for gathering the liquid diesel. The manual discharge valve connects with a self-made oil-gas separator. After counting a given injection times, N, the total mass, m_1, including the apparatus and the blend fuels, is weighed. As the injection is over, the manual discharge valve is switched on to emit the gaseous DME, and the mass, m_2, including the apparatus and injected diesel, is weighed. So, the mixing ratio x_1 of DME is derived:

$$x_1 = \frac{m_1 - m_2}{m_1 - m_0} \tag{1}$$

Then, the mass of diesel fuel in the collector is calculated as $m_2 - m_0$, and the mixing ratio x_2 of diesel fuel is deduced as eq. (2):

$$x_2 = 1 - x_1 \tag{2}$$

The mixing fuel quantity per cycle q is shown as eq. (3):

$$q = \frac{m_1 - m_0}{N} \tag{3}$$

The injected DME quantity per cycle q_1 is inferred as eq. (4), and the injected diesel quantity per cycle q_2 as eq. (5):

$$q_1 = \frac{m_1 - m_2}{N} \tag{4}$$

$$q_2 = \frac{m_2 - m_0}{N} \tag{5}$$

The DME return port of electric-control injector is limited by a 5 bar one-way valve so that the return DME is kept as a liquid before exhausting. A gas flow meter links with the one-way valve to gauge the return DME flow rate Q_3. Meanwhile, another gas flow meter is joined with the oil-gas separator to measure the injected DME flow rate Q_1. The return DME quantity per cycle q_3 is:

$$q_3 = q_1 \frac{Q_3}{Q_1} \tag{6}$$

Test equipment

The DME/diesel mixing system was set-up on a fuel pump bench, which provided the power for fuel pump. The type of fuel pump bench is LBD-D, produced by Shandong Rabotti Experiment Equipment Co., Ltd., Torino, Italy. The matched fuel pump is a BH4QT85R9 fuel pump made by Shandong Kangda Group Co., Ltd., Shandong, China.

In order to precisely control DME injection time and injection duration, the pick-up and release process of electromagnetic valve in electric-control injector should be regulated precisely. Therefore, the electric control system needs an effective and reliable driver circuit in which drive current is achieved by a pulse-width modulation (PWM) drive method. The experimental electric-control injector, F3-07-11-27s, was made by Wuxi Fuel Injection Equipment Research Institute, Jiangsu, China [28]. The power supply, driver circuit and controller are shown in fig. 4. The mixing injector is a mechanical injector produced by Longkou Hongchang Mechanical Manufacture Co., Ltd. Its injection starting pressure was adjusted from 28 MPa to 18 MPa so as to lower the residual pressure in fuel pipeline for admitting more DME injected by the electric-control injector. These two injectors fit together as illustrated in fig. 5.

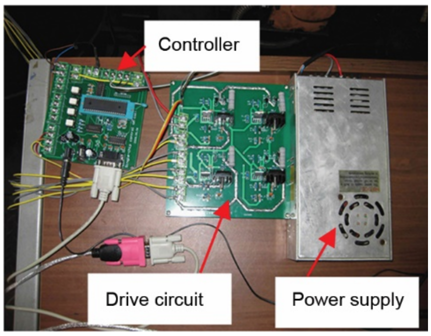

Figure 4. Power supply, driver circuit and controller of electric-control injector

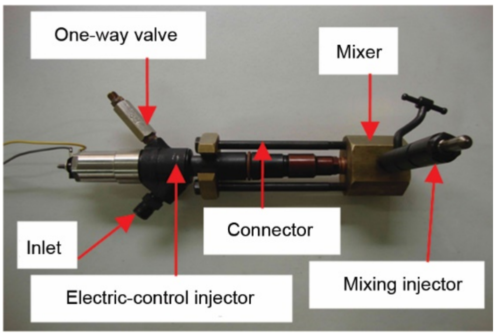

Figure 5. Electric-control injector and mixing injector

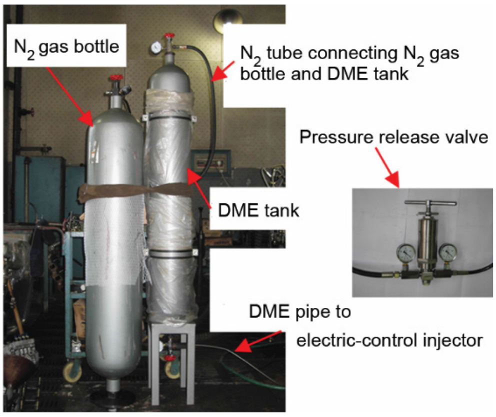

Figure 6. The N_2 gas bottle, DME tank and pressure release valve

The specification of N_2 gas bottle is 63 L and 400 MPa maximum pressure, while the DME tank is 32 L and the same maximum pressures. This two vessels are linked by a pressure release valve, all customized from Fenghua Chaori Hydraulic Co., Ltd., Ningbo, China, shown as fig. 6.

During the test, the charged pressure in the N_2 gas bottle is 28 MPa, then reduced to 21 MPa for the DME tank by the pressure release valve. The gas flow meters were manufactured by Fuyang Huayi Instrument Technology Co., Ltd., their models are LZB-10 and LZB-4, and their accuracy is 2% FSN. The LT10KA-1 electronical scale was fabricated by Changshu Tianliang Instrument Co., Ltd., Changshu, China, which weighing scope is up to 10 kg, and its accuracy is 0.1 g. A Ferro magnet was fastened on the rotating disc of fuel pump bench, combined with a Hall sensor to provide an accurate injection time for the electric-control injector operation.

Measuring results and discussion

The DME/diesel mixing fuels injected into the collector include the injected diesel and wasting DME, and the wasting DME consists of DME injected into fuel pipeline and return DME from the electric-control injector. The injected diesel mass and wasting DME mass per cycle are presented against different fuel pump speeds in fig. 7. A 5 ms injection pulse width was used for the test. Their mass comparison is also revealed at the same operation conditions in fig. 8.

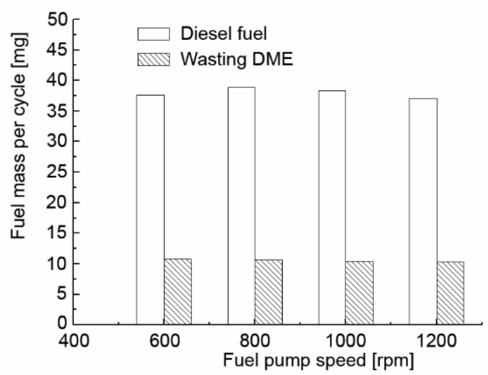

Figure 7. Mass of injected diesel and wasting DME per cycle at different speeds

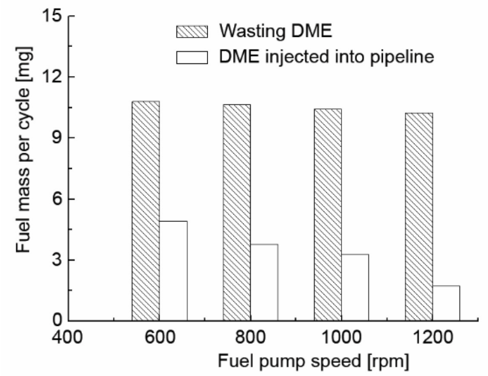

Figure 8. Mass of wasting DME and DME injected into fuel pipeline mass per cycle at different speeds

In fig. 7, the injected diesel mass per cycle is kept almost constant as the fuel pump speed is increased, while the wasting DME mass per cycle decreases slightly. The reason is that as the injection pulse width maintaining constant, the residual fuel pressure in fuel pipeline increases as the fuel pump speed is increased, and DME injection pressure is far greater than the residual fuel pressure in fuel pipeline, so the wasting DME mass remains almost constant. The DME injected into fuel pipeline lowers as the fuel pump speed increasing in fig. 8. The reason is that the residual fuel pressure in fuel pipeline increases as the fuel pump speed is increased, which raises the backpressure as DME is injected into the mixer. Due to maintaining the injection pulse width constant, the mass of DME injected into the fuel pipeline decreases. Compared with the injected diesel, the percentages of DME injected into fuel pipeline per cycle are 13.04, 9.74, 8.55, and 7.82% by mass as the fuel pump speeds are 600, 800, 1000, and 1200 rpm, respectively. The DME injected into fuel pipeline per cycle are 45.46, 35.53, 31.45, and 28.29% of wasting DME at different fuel pump speeds.

Figure 9 clarifies the changes of wasting DME and DME injected into fuel pipeline with its injection pulse width increasing as defining the fuel pump speed as 1000 rpm. With the fuel pump speed going up, both the wasting DME and DME injected into fuel pipeline have the linear increases. The cause is that the injection quantity, including wasting DME and DME injected into fuel pipeline, is proportional to the DME injection pulse width. As the DME injection pulse width increasing from 2-8 ms, the wasting DME mass per cycle rises up from 4.11-16.69 mg, while DME mass injected into fuel pipeline per cycle from 1.3-5.27 mg.

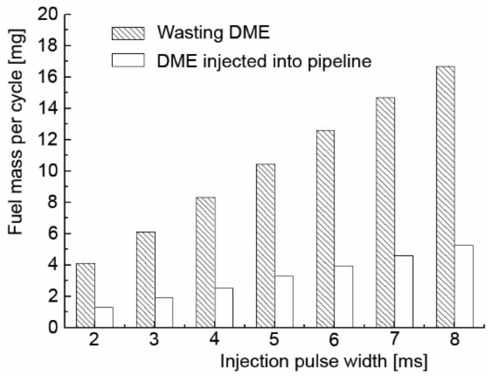

Figure 9. Mass of wasting DME and DME injected into pipeline per cycle at different injection pulse width

Engine experiments

Experimental equipment and test procedure

A light-duty direct injection engine, Model 498, manufactured by Zhejiang Xinchang Diesel Engine Co., Ltd., Zhejiang, China, was used for testing in this study. This engine is a four-cylinder, 4-stroke, naturally-aspirated Diesel engine. Its specifications are illustrated in tab. 1.

Table 1. Technical parameters of engine

Item	Parameter	Item	Parameter
Engine type	498	Rated speed	2400 rpm
Bore × stroke	98 × 105 mm	Idling speed	750 ± 30 rpm
Displacement	3.168 L	Intake type	Naturally-aspirated
Compression ratio	18.5	Lubricating method	Pressurized and splashing lubrication
Cylinder alignment	In-line	Cooling type	Water cooled
Rated power	45 kW	Fuel delivery advance angle	10 bTDC*

* bTDC – before top dead center

No more modifications were made on the engine except adding the DME delivery system and four electric-control injectors. The pressure value of N_2 gas bottle is 28 MPa, and

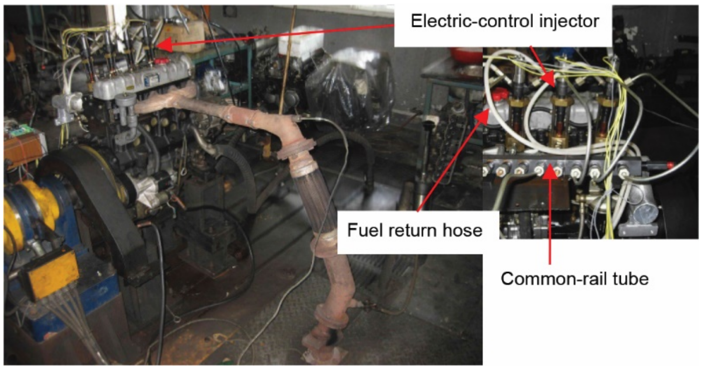

Figure 10. Engine test bench

reduced to 21 MPa for the DME tank through a pressure release valve. Meanwhile, the DME injection pulse width was defined as 5 ms. In addition, due to the mass of return DME through the electrical-control injector is larger than that of the DME injected into the pipeline, it is not led into the engine to burn out. This is also for consideration on detecting the effect of this new mixing method on the combustion and emission characteristics of engine. The engine test bench is shown in fig. 10.

An engine test system EIM0300II was used in experiments, which was made by Hangzhou Keyi Automation Meter Co., Ltd., Hangzhou, China. The relative standard deviation of torque, speed and fuel consumption rate is 0.4, 0.1, and 0.4% of the full scale ranges, respectively. Gaseous emissions were recorded by AVL exhaust gas analyzer AVLDiGas 4000. The CO, HC, and NO_x emissions are average values of the acquired data at each steady-state operating condition. All the tests were repeated. The resolution of NO_x, CO, and HC concentration is $1 \cdot 10^{-6}$, 0.01%, and $1 \cdot 10^{-6}$, respectively. The opacity of smoke was analyzed by a part-flow smoke opacimeter (AVL FTY-100), and its resolution rate is 0.1%.

The engine was warmed up until the cooling water and lubricating oil reached approximately 85 °C, and then loaded to the test points. The emissions were determined to gauge after exhaust temperatures reached equilibrium. During the test period, the engine speed and torque were maintained constant. The characteristics of mixing fuel engine under different speeds were experimentally investigated, and its exhaust emissions were tested and analyzed. Furthermore, these results were compared with those of original engine, to commentate the combustion and emission characteristics of the mixing fuel engine. Specifically, since the testing engine is 4-stroke engine, its speed is two times of fuel pump speed. 1200, 1600, 2000, and 2400 rpm of engine speeds correspond to 600, 800, 1000, and 1200 rpm of fuel pump speeds.

Engine test results and discussions

Fuel consumption and power output characteristics

Since the DME tank is very heavy, no high accurate electrical balance is suitable for measuring the DME consumption in this study. Furthermore, one end of DME tank joins with the N_2 gas bottle through the pressure relief valve and another end connecting with the common rail tube by a metal fuel pipeline, and it is very difficult to meter the fuel flow rate in the DME tank dynamically and independently. In experiments, the diesel fuel consumptions were recorded, and the DME mass injected into the pipeline is evaluated according the results of fuel pump test. However, due to the high backpressure in combustion chamber, the DME mass injected into the pipeline during the engine test is less than that in the fuel pump test. This approach can provide a reference to the real DME consumption in engine experiments.

Figure 11 demonstrates the diesel fuel consumptions of original engine and mixing fuel engine at speed characteristics of full load, and also lines the reference DME consumption. In comparison with those of neat diesel operation, the diesel fuel consumption of the blend operation is lower and the difference is similar at various speeds. Nevertheless, according to the reference DME consumption tendency, the DME consumption in real state might be lower with the engine speed increasing. More experiments need to explore the real DME consumption.

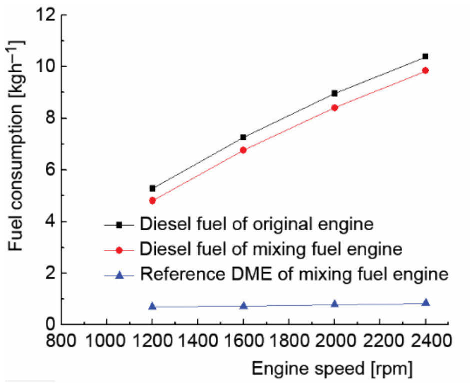

Figure 11. Comparison of fuel consumptions at full load

Figure 12 indicates the comparison of power output of the original engine and mixing fuel engine at speed characteristic of full load. It can be observed that the power outputs of engine fueled with the mixing fuel are slight higher than those of neat diesel at low speeds, regardless of that the low calorific value of blends is lower than that of neat diesel fuel. This may be attributed to a higher cetane number and an excellent auto-ignition characteristic of DME in the blends, which makes the maximum combustion pressure appearing in the appropriate position for power output. But the power of mixing fuel engine is slight lower at high speeds than that of pure diesel fuel operation, perhaps because of the lower calorific value and smaller fuel delivery energy for the mixing fuels [22]. Power output of the blends is lower about 2.4% than that of diesel operation at 2400 rpm. Slight low power output of the blends can be enhanced by increasing fuel mass injected into the cylinder per cycle.

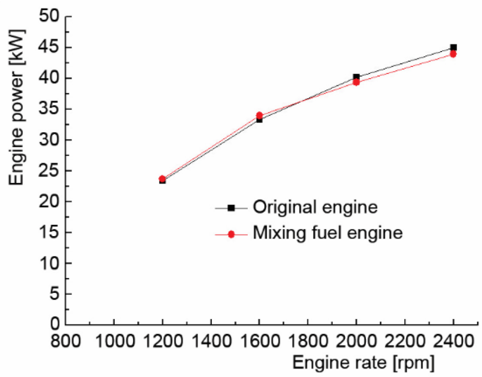

Figure 12. Comparison of power outputs at full load

Emission characteristics

Figure 13 shows the comparison of soot emissions characteristics between diesel fuel and diesel/DME blends. Smoke emissions of neat diesel fuel and the blends increase as the duty going up. Under heavier load conditions, more fuels are injected into the cylinder, and the mixture formation is inhomogeneous, which produces poor fuel combustion. It is obvious that smoke emissions of original engine and mixing fuel engine are smaller difference at light loads, while smoke emissions of the blends are lower about 30% than that of neat diesel fuel at medium and high loads. It is that an oxygenated DME is effectively introduced to the diesel fuel regions to depress soot formation in combustion chamber. More oxygen content of the blends combined with no

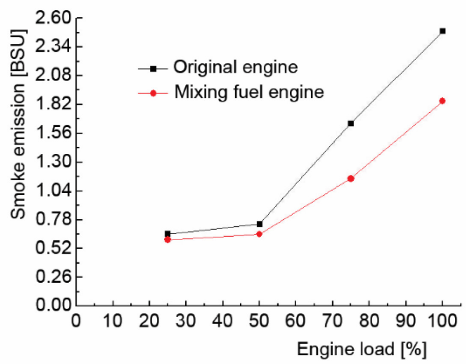

Figure 13. Comparison of smoke emissions at 2000 rpm

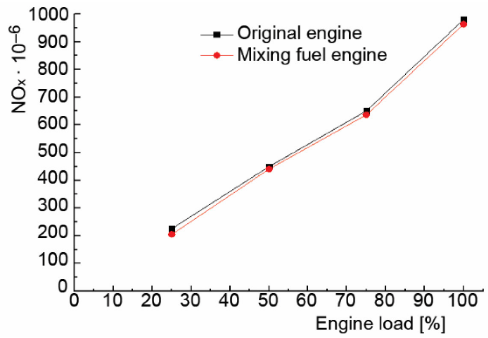

Figure 14. Comparison of NO_x emissions at 2000 rpm

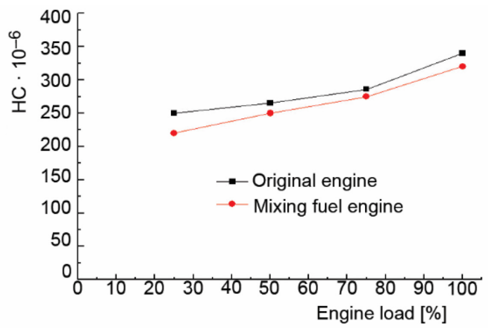

Figure 15. Comparison of HC emissions at 2000 rpm

a carbon-to-carbon bonds in DME is also supposed to dedicate the smoke reduction.

In terms of NO_x emissions exhibited in fig. 14, NO_x emissions of neat diesel fuel and the blends go up as the loads increasing. The main reason is higher in-cylinder temperature under heavier load conditions, which is helpful for NO_x growth. At all loads, NO_x emissions of original engine and mixing fuel engine are close, while NO_x emissions of the blends are slight lower than that of neat diesel fuel for several reasons. The DME has a higher cetane number and an outstanding auto-ignition performance, so the ignition delay of the blends is shorter and the premixed combustion amount is less than that of pure diesel fuel [7, 14, 16], which causes lower in-cylinder pressure and temperature, and restrains the formation of NO_x. Owing to its lower modulus of elasticity than that of pure diesel fuel, the injection timing of diesel/DME blends is lagged, this can reduce NO_x emissions [14].

The HC emissions of original engine and mixing fuel engine are listed in fig. 15. With the loads increasing, HC emissions of two engines increase. At low duty, the injected fuel mass per cycle is small and the air is relatively rich, and the temperature in the cylinder is lower which are easy to quench the flame front and produce HC [21]. At high load, high in-cylinder temperature is apt to evaporate fuel rapidly, and more homogeneous air-fuel mixtures are formed so as to lower HC emissions, but relatively scarce air makes HC concentrations higher. However, this is in accordance with general HC production pattern in CI engine. Generally, due to incomplete mixing and partial combustion as fuel being abundant, HC emissions are appeared in unburned air-fuel mixture.

It can be also shown that HC emissions of mixing fuel engine are lower than that of original engine at all loads. At the same time, HC emissions of two engines are more similar at medium duty. Compared with the original engine, the mixing engine produces less HC emissions, and this may be due to more oxygen to burn HC. As for the HC emission tendency of two engines at medium duty, this may be attributed to the results of comprehensive factors, such as fuel oxygen content, fuel injection, air motion in cylinder, mixture formation, *etc.* Further investigations on these complicated processes should be necessary.

Figure 16 reveals CO emission features. It is clear that CO emissions of mixing fuel engine are higher than that of original engine at light loads, and its CO emissions are slight higher than that of diesel at medium and high loads. High CO emissions of the blends may be instructed by the situation that the secondary injection existed from the higher residual pressure and oscillations encountered in the DME fuel system. According to the aforementioned fuel pump test, less DME is injected into the pipeline at medium and high loads, so its CO emissions are slight higher than that of original engine.

Conclusions

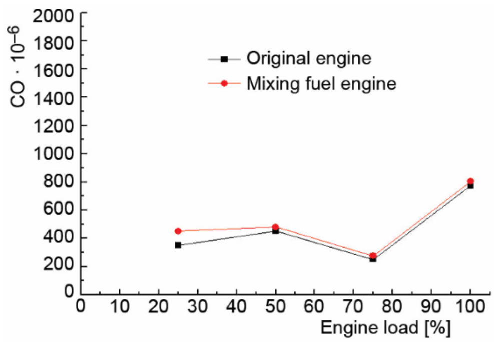

Figure 16. Comparison of CO emissions at 2000 rpm

In the enlightenment of fuel design idea, a new DME/diesel mixing method is presented. The DME is injected into the pipeline to mix with local diesel fuel in the pressure stable duration. Since DME is a gaseous while diesel is a liquid at normal pressure, a device is designed to separate DME from diesel fuel, and DME/diesel mixing ratios and injection quantity per cycle are convenient for measuring by the weighing method. The experimental results show that compared with the injected diesel, the percentages of DME injected into fuel pipeline are 13.04, 9.74, 8.55, and 7.82% by mass as the fuel pump speeds increase, while DME injected into fuel pipeline are 45.46, 35.53, 31.45, and 28.29% of wasting DME. With the fuel pump speeds going up, both wasting DME and DME injected into fuel pipeline have the linear increases at 1000 rpm fuel pump speed.

A light-duty direct injection engine 498 is tested to validate the effect of this new mixing method. The power outputs of engine fueled with the mixing fuel are slight higher than those of neat diesel at low speeds, while the power of mixing fuel engine is slight lower at high speeds than that of pure diesel fuel operation. For example, power output of the blends is lower about 2.4% than that of diesel operation at 2400 rpm. Smoke emissions of original engine and mixing fuel engine are closer at light loads, while smoke emissions of the blends are lower about 30% than that of neat diesel fuel at medium and high loads due to oxygenated DME depression effect on soot formation and less carbon-to-carbon bonds in blends. The NO_x and HC emissions of the blends are slight lower than that of neat diesel fuel at all loads, but CO emissions are slight higher than that of diesel.

However, more works should be accomplished to research this new method, such as the integration of two injectors for smaller bulk and excellent injection performance, more tests on fuel pump and engine, and some theoretical researches. For example, the engine combustion analysis is helpful for understanding the test results.

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