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The Influence of Intake Air Temperature and Varying Injection Positions on the Combustion and Emission of C.I. Engine Running on Methanol

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***Abstract*—To a deeper understanding of the influence of intake air temperature on the methanol/diesel dual-fuel mode engine, and explored the influence of different methanol injection positions on intake air temperature, in this study, experiments carried out on Yunnei D30 common rail intercooler inline 4-cylinder engine. At the Pre-intercooler, post-intercooler, and intake manifold, methanol was injected into the engine by compound injection. The experimental works were constant at 200N.m load and a constant engine speed of 1600rpm. Experiments showed that with increased methanol substitution rate (MSR) because the high latent heat of vaporization of methanol caused lower intake air temperature. Compare to other injection positions, the pre-intercooler position made higher inlet temperature due to the high temperature of turbocharge system, make air charge lower, reduce the indicated thermal efficiency, and higher exhaust gas temperature. When added methanol into the diesel engine, changed the intake air temperature, prolonged ignition delay time, shorten subsequent combustion phase and lower peak cylinder pressure and higher peak of heat release rate, reduce NOx emission, while increased carbon monoxide (CO) and hydrocarbons (HC) slightly. However, from the results found when methanol injected under different positions, the effects would be different, because changed intake air temperature when methanol injected. Methanol injection at post-intercooler and intake manifold positions indicated thermal efficiency higher than pre-intercooler position.**

Keywords: Compound injection, Methanol, Diesel, Intake air temperature, Exhaust gas.

INTRODUCTION

Energy consumption, depletion of reserves, and environmental issues are related to the use of fossil fuels. Clean alternative fuels had attracted people's attention. In addition, biofuels and alcoholic fuels (such as methanol, ethanol, and propanol) are also clean alternative fuels. Because they were in a liquid state under normal conditions, high oxygen, high octane number, available from biomass fuels [1]. Methanol is one of the most promising fuels in the world that could be generated from coal, natural gas, and biomass easily. Methanol was widely used in gasoline engines because of its high octane number, low flammability limit, improved efficiency, and reduced emissions. The lack of energy, used in diesel engines has gradually attracted people's attention. Methanol had many advantages in diesel engines, reduced NOx emissions, particulates matter, and sulfide emissions. However, due to the high vaporization latent heat of methanol, low cetane number, and long ignition delay time, it was difficult to start the engine [1-3].

In the mixed process of methanol and diesel, stratification occurs, leading to the deterioration of combustion in the cylinder. The engine needed to be modified, and methanol injection devices were installed in three locations that pre-intercooler, post-intercooler, and intake manifold. Through the electronic control unit controlled the injection frequency and cycle, changed the conversion between methanol fuel and pure diesel operation, used diesel/methanol dual-fuel compound injection to increase the power output of diesel, realize advanced combustion mode [4, 5]. In addition, lots of researches had been conducted on the mixed combustion of methanol and diesel in the world. Like Yao et al[4]. analyzed the influences of Diesel/Methanol mixed combustion and emissions of diesel engine.

Experimental results showed that as the amount of methanol injection increases, nitrogen oxides decreased and carbon monoxide and hydrocarbons increased. Wei et al[6]. used a higher pre-mixed methanol fraction in a six-cylinder diesel engine. It was found that hydrocarbons and carbon monoxide increased, nitrogen oxides and particles decreased. Liu et al[7]. analyzed the influences of injection pressure on combustion and emissions of diesel-methanol dual fuel. With the increase of diesel injection pressure, CO and HC emissions decreased, emissions of carbon dioxide and nitrogen oxides increased slightly.

Methanol had higher latent heat of vaporization and lower calorific value than diesel. To obtain the same energy as diesel, more methanol needed to be injected [8,9]. The injection of methanol could effectively reduce the intake air temperature, reduce the temperature in the cylinder, and increase the charge density, prolong ignition delay time. Similarly, the decrease of intake temperature also improved the intake quality, and methanol with high oxygen content results in a larger air-fuel ratio and lean combustion [10].

The influence of the addition of methanol to diesel engines on the change of intake air temperature on combustion and emissions of internal combustion engines had attracted widespread attention. Like Adb-alla et al. [11], Kumar and Raj [12] found that higher intake air temperature increased NOx emissions, but it reduced unburned hydrocarbon and carbon monoxide emissions. Varde et al. [13] found that a certain methanol mass fraction reduced the intake temperature and the peak pressure of the cylinder and increased the ignition delay time. Su et al.[14] found that the changed intake air temperature had a great influence on the spray and atomization of diesel. The increase of intake air temperature improved the activity of diesel oil, accelerated the evaporation of diesel, and changed the penetration of the nozzle. Under certain methanol energy fraction, reduced the intake air temperature to reduce NOx emissions[14].

In previous studies, at specific injection positions changed certain intake air temperature had a significant impact on the combustion and emission characteristics of diesel-methanol dual-fuel engines. However, the coupling effect of changing the methanol mass fraction at different injection positions on intake air temperature had not been extensively studied. Therefore, this article analyzed and compared the effects of injection at different positions on engine performance and emissions. The methanol injection position was set to the pre-intercooler injection, post-intercooler injection, and intake manifold injection. In the experiment, experiments at different injection positions of methanol would affect intake air temperature and have different effects on emissions and engine performance. To better study the influence of the methanol substitution rate and injection position on the intake air temperature, an experimental study was carried out. This effect was more obvious at the post-intercooler and intake manifold. Because of high exhaust temperature of the engine, increasing the temperature of methanol injected at pre-intercooler would tend to reduce the production of CO & HC, increase emission of NOx slightly.

EXPERIMENTAL SETUP

Used Yunnei D30 turbo in-line intercooler turbocharged common rail 4-cylinder diesel engine for testing. Table 1 showed the engine parameters. Figure 1 was a schematic diagram of an engine test bench.

TABLE I

ENGINE DESCRIPTION

ENGINE TYPE	D30 4 CYLINDER IN-LINE
AIR INTAKE FORM	TURBOCHARGED INTER-
CYLINDER NO.	4
FUEL	DIESEL
DISPLACEMENT	2.977L
MAXIMUM POWER OUTPUT	115 KW
SPEED	3200RPM
MAX HP	156 HP
MAX TORQUE	350N.M
MAX TORQUE SPEED	1500-2700RPM
MIN FUEL CONSUMPTION FOR	< 208G/KW·H
BORE X STROKE	95MM X 105MM
VALVE TRAIN	4

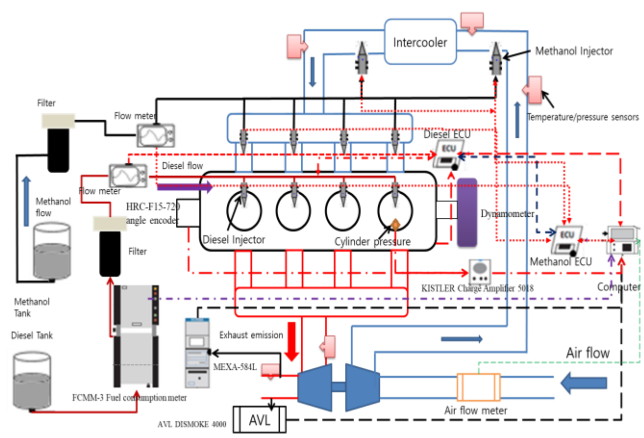


Figure 1 Layout of experimental equipment

The three injection positions showed in Figure 1 were the post-intercooler, the intake manifold, and the pre-intercooler. Methanol injection was controlled by a separate methanol ECU. The ECU communicates with the original ECU via the CAN bus, synchronizes crankshaft and camshaft signals, and was connected to the computer via the ETAS592 to control the methanol injection cycle and pulse width to adjust the injection volume through the INCA system. It was necessary to install a set of K-type thermocouple meters before and after each methanol injection position to measure the changes in intake air temperature.

The exhaust emissions were measured by the HORIBA MEXA-584L analyzer. The cylinder pressure data in the experiment was the average value of 100 consecutive data cycles. The cylinder pressure signal collected by the KISTLER 6056A pressure sensor, amplified by KISTLER Charge Amplifier5018 and collected by the HR-CA-B1 combustion analyzer.

FUEL PROPERTIES

The diesel used in the test was commercial No. 0# diesel. The sulfur content of diesel was less than 10ppm. The methanol used was chemical methanol with a purity of 99.99%. Table 2 showed the properties of methanol and diesel.

TABLE II
CHARACTERISTICS OF DIESEL AND METHANOL

PROPERTIES	METHANOL	DIESEL
DENSTY G/ML	0.7866	0.829
BOILING POINT ℃	65	187-343
OCTANE NUMBER	136	15-25
CETANE NUMBER	3.8	46
ENERGY DENSITY MJ/L	16	46
LHV MJ/KG	20.1	42.8
LATENT HEAT OF EVAPORATION MJ/KG	1.2	0.23-0.60
MELTING POINT℃	-97	-40--34
COOLING POINT ℃	12	74
AUTO-IGNITION TEMPERATURE ℃	463	235
VISCOSITY PA·S	0.5445*10	-

EXPERIMENTAL METHOD

At each injection position, the engine parameters would be recorded at constant torque (200N.m) and constant speed of 1600rpm. The five methanol substitution rates at each test point were 0%, 10%, 20%, 30%, and 40%. After each experimental point operated stable for 3 minutes, and the data of each experimental point would be recorded 3 times. According to the mass consumption rate of diesel and methanol in the engine, the methanol substitution rate (MSR) could be calculated. The formula is:

$$\mathrm{MSR} = \frac{M_{Deat} - M_{Ddual}}{M_{Deat}} * 100\% \qquad (1)$$

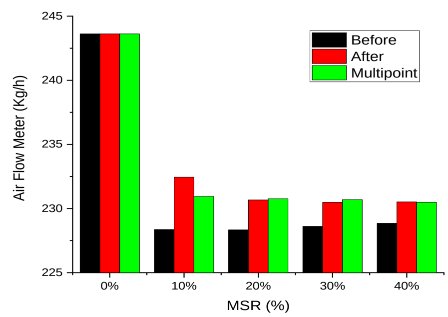
In the formula, M_{Dneat} represents the diesel fuel consumption [Kg/h] when the pure diesel engine was running, and M_{Ddual} represents the diesel fuel consumption [Kg/h] after methanol injected. Both of these data were the average consumption measured by the AVL735 fuel flow meter.

RESULTS AND DISCUSSION

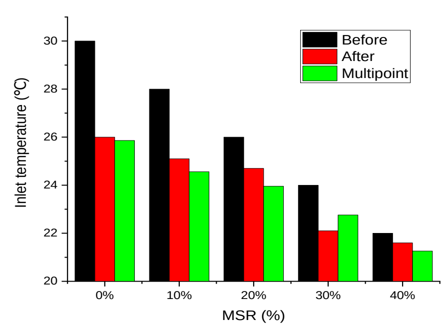
The experimental results showed that the change of the methanol injection quantity at different injection positions causes the intake air temperature variation. The intake air temperature was one of the important parameters of the compound injection engine operation, which changed the operation of the engine, changed the charge quality, fuel consumption, ignition delay, combustion phase, exhaust gas temperature, and exhaust composition.

INTAKE AIR QUALITY AND INTAKE AIR TEMPERATURE

Figure 2 showed the amount of methanol injected under various injection positions, resulting in different effects on intake air temperature in Figure 2(a) and intake air quality in Figure 2(b). At three methanol injection locations, the increase of methanol substitution rate caused lower intake temperature out, and the intake quality would slightly increase. However, turbocharge system nearby to the pre-intercooler injection position made the temperature higher, caused the intake air quality tends to decrease. The main reason for the reduction was that when the charging temperature was higher than the boiling point of methanol, the evaporated methanol replaced the same quality of air, resulted in a lower intake air amount. So under the condition of a certain methanol substitution rate, with the increased intake temperature, the intake quality would decrease. The same results carriedout by Chen,C. et al. [8] & Yao et al.[4].



(a) Influence of different injection positions on intake air quality

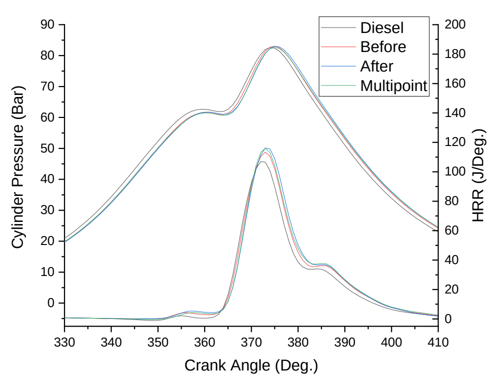


(b) Influence of different injection positions on intake air temperature

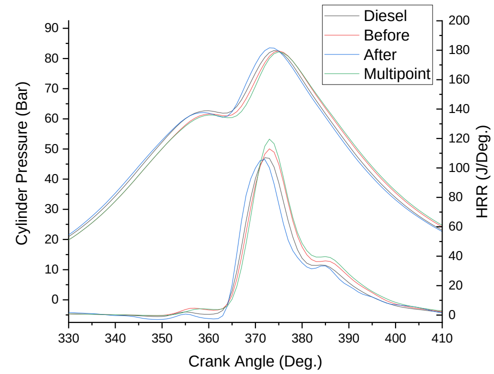
Figure 2. Influence of different injection positions on intake air quality((a)) and intake air temperature((b))

COMBUSTION CHARACTERISTICS

Figure 3(a) and (b) showed the effect of intake air temperature on combustion characteristics at 20% and 40% methanol substitution rates, respectively. Because of the low cetane number and high latent heat of vaporization of methanol, methanol would prolong ignition delay. A higher charge temperature would advance the ignition delay, promoted combustion phasing. At a lower intake temperature, the pressure in the cylinder could easily reach its peak during the expansion process. Therefore, the pressure peak in the cylinder decreased as the methanol substitution rate increased. With the increase of methanol, substitution rate led to the air intake charge temperature decreases, and the heat release rate and the appearance of pressure peaks would also be delayed in the cylinder. The heat release in the second combustion stage increased as the substitution rate increased could be found in results from Figure 3 (a) and (b), the heat release of premixed combustion increased with the increase of methanol substitution rate. But methanol injected at the post-intercooler position, lowest heat release rate and highest cylinder pressure be found from Figure 3 (b), because methanol had more oxygen atoms, increased intake air charge, promoted combustion, caused cylinder pressure high, decreased ignition delay time then caused lower heat release rate. In previous studies, the long ignition delay caused by the addition of methanol and the appearance of a higher heat release rate had also been confirmed [5-7, 15]. And injecting methanol at different injection positions caused changes in the temperature of the intake charge, thereby changing the spray, atomization, and evaporation effects[14]. The injection position of the pre-intercooler caused charge temperature increase accelerates the low-temperature reaction of the diesel-methanol-air mixture and could shorten the ignition delay [16, 17], reduced the heat release rate.



(a) The influence of intake air temperature on combustion characteristics at a methanol substitution rate of 20%



(b)The influence of intake air temperature on combustion characteristics at a methanol substitution rate of 40%

Figure 3 The influence of intake air temperature on combustion characteristics at 20% and 40% methanol substitution rates

INDICATE THERMAL EFFICIENCY

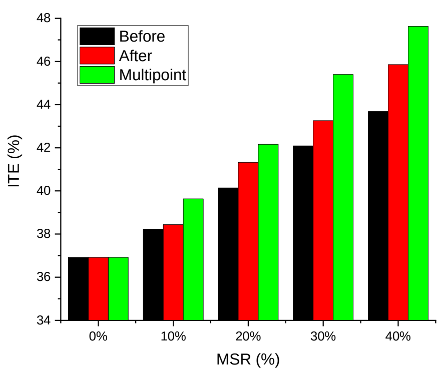
Figure 4(a) showed the relationship between indicated thermal efficiency at different methanol substitution rates. In the dual fuel injection mode, as the methanol substitution rate increased, the inlet temperature decreased, resulted prolong ignition delay and short combustion duration and the heat transfer loss was shortened. This caused the indicated thermal efficiency of most data points to increased. Under the same methanol substitution rate, compared to three injection positions, the thermal efficiency of the methanol injected at the manifold position was very high. When methanol was injected, the methanol content increased and the intake air temperature decreased, prolonged the ignition delay time. This meant that the burning time was shortened and, the heat was intensively released, resulted in a high heat release rate. The same results were carried out by Yao et al.[5]. Figure 4(a) showed that the inlet temperature decreases as the methanol substitution rate increases, and the indicated thermal efficiency of the dual-fuel engine first increases and then decreased. At the intake manifold, the maximum thermal efficiency was close to 48%.

EXHAUST TEMPERATURE

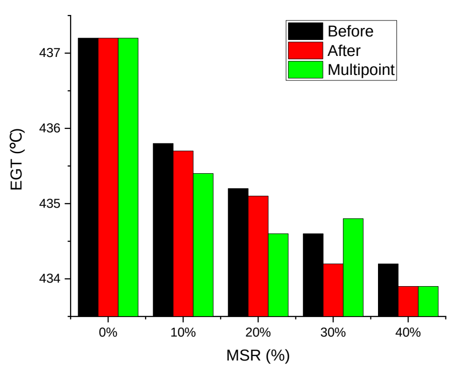
Figure 4(b) showed the influence of different methanol substitution rates on exhaust temperature. In the same injection position, when methanol substitution rates increased, the engine exhaust temperature showed a downward trend. The reason was that the increase of methanol reduced the intake air temperature, decreased the combustion temperature, reduced the exhaust temperature. Especially, at the intake manifold, certain methanol substitution rate, the exhaust gas temperature showed the highest temperature at the position of pre-intercooler. This was because the total exhaust gas temperature would affect the intake temperature and caused the exhaust gas temperature to increase.

When the methanol substitution rate reached a certain value, the temperature of exhaust gas tended to increase. And the flame propagation speed was fast in the subsequent methanol combustion process, the combustion accelerates and the exhaust gas temperature increased.

Under pure diesel conditions, the change of the diesel combustion phase was one of the main factors affecting the exhaust temperature. In the compound injection engine, as methanol substitution rates increased, helped to lower the exhaust gas temperature. Liu et al. [6] and Masimalai et al. [18]. the same corroborating experiment was also done on this, got the same result. When methanol injecting, the combustion temperature of methanol was low, the latent heat of vaporization and heat of evaporation were high, and the exhaust gas temperature could be reduced. On the other hand, methanol burned fast, fast propagation speed, a high volumetric combustion ratio of methanol, and a low heat exchange rate helped to reduce the energy consumption of exhaust gases and reduce emissions.



(a) Indicated thermal efficiency at different methanol substitution rates



(b) Different methanol substitution rate on exhaust temperature

Figure 4 Different methanol substitution rates on the indicated thermal efficiency and exhaust gas temperature

NO_x EMISSIONS

Figure 5 showed the influence of different methanol substitution rates on NOx emissions. Generally, at a certain methanol substitution rate, the conversion rate of methanol was higher, the difference in the injection positions could lead to different NOx emissions. In comparison, injected methanol at pre-intercooler produced more NOx. At the post-intercooler and the intake manifold, injected methanol, NOx emissions would gradually decrease. In the same injection position, with a high methanol substitution rate, the phenomenon of NOx reduction was more obvious. It was found that at lower intake air temperature, the intake manifold was most obvious, NOx decreased with the increase of methanol substitution rate.

The formation and emission of NOx depended on the temperature of the combustion chamber, the ratio of local air to fuel, and the time available for NOx dynamics[19, 20]. When injecting methanol, there were many reasons for the change of NOx emissions. First of all, methanol had a higher heat of vaporization and a lower adiabatic flame temperature, which helped to reduce the temperature of the gas in the cylinder and reduce NOx emissions. Secondly, methanol injection could prolong the ignition delay time of diesel, and post-combustion phasing helped to reduce NOx. Thirdly, with the increase of methanol mass ratio, more air provided, mixed combustion became thinner. Abd-Alla et al.[11] showed through experiments that in dual-fuel diesel engines, NOx emission increased with the increase of inlet air temperature. With the increased intake air temperature, the combustion temperature of the mixture increased, the production rate of NOx increased. Furthermore, the intake air quality decreased with the increase of intake air temperature, So that the equivalence ratio increased with the increase of methanol substitution rate, reduced the intake air temperature and NOx emissions. Many researchers like Yao et al.[4]，Chueng et al.[21]， Liu et al.[5]， Wei et al.[6] and Masimalai et al.[18] obtained similar results.

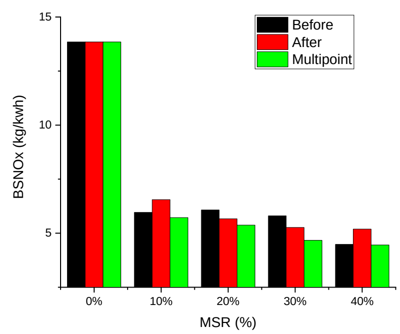


Figure 5 the effect of intake air temperature on BSNOx under different replacement rates

HC EMISSIONS

Figure 6 showed the effect of intake air charge temperature on HC emissions under different methanol substitution rates. With the addition of methanol, HC emission was much higher than that of pure diesel running. For a given injection position, with the increased methanol substitution rate, HC emission increased. There were many reasons for increasing in HC, mainly because methanol injection lowered the combustion temperature, reduced the progress of the in-cylinder reaction. In addition, the high vaporization heat of methanol fuel increased quenching, which led to an incomplete combustion reaction. Thirdly, the decreased in gas temperature caused an incomplete combustion reaction in the cylinder. Under a certain methanol substitution rate, HC emission decreased with the increase of intake air temperature. Especially when the methanol substitution rate was high, the HC emission was more. Many researchers like Yao et al.[4]，Chueng et al.[21] obtained similar results.

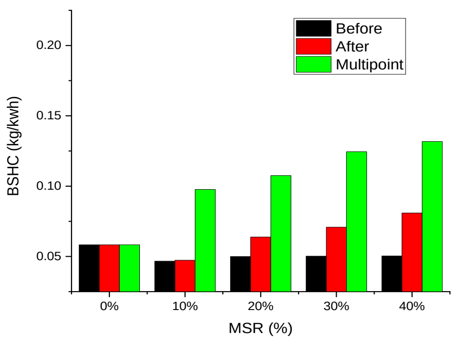


Figure 6 The effect of intake air temperature on BSHC under different replacement rates

CO EMISSIONS

Figure 7 showed the CO emissions at different injection locations and different methanol substitution rates. Methanol injected at a certain injection position, as methanol substitution rates increased, CO emission increased gradually. Under the condition of a certain methanol substitution rate, the intake charge temperature reached by different injection positions was different, with the decrease of intake air temperature, CO emission increased gradually. Because in this process, the injection of methanol could reduce the air inlet temperature and the combustion temperature, resulted in a significant increase in carbon monoxide emissions. In addition, when methanol and air are mixed into the cylinder, flame extinguishment would increase CO emissions. The CO emissions produced at the pre-intercooler position were relatively low because the higher temperature around the turbocharger was absorbed during the intake process, and the exhaust emission was reduced. Many researchers like Yao et al.[4]，Chueng et al.[21]， Liu et al.[5]， Wei et al.[6] and Masimalai et al.[18] obtained similar results.

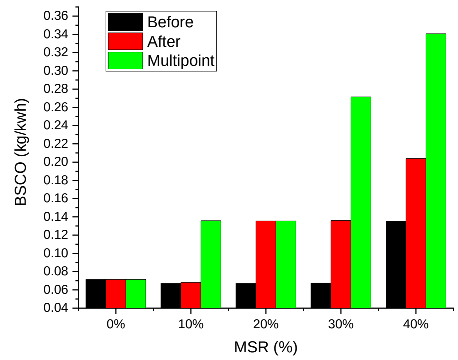


Figure 7 The effect of intake air temperature on BSCO under different substitutions

CONCLUSIONS

This paper studied that methanol could replace diesel fuel, slow down the consumption of fossil fuel, reduce cylinder knock, and improve the indicated power. The influence of intake temperature on the engine was observed when methanol was injected at different injection positions, and the choice of injection positions to improve the engine performance was beneficial to the emission reduction of the engine. The effects of methanol injection position and methanol substitution rate on the performance and emission characteristics of methanol diesel dual-fuel engine were studied. Found the following results:

The different methanol injection positions resulted in different intake air temperatures. When at MSR 20% and 40%, compared pure diesel condition, the intake air temperature will be reduced 13.3%, 4.6%, 5.4%, and 26.7%, 16.5% 18.9% at pre-intercooler, post-intercooler, and intake manifold injection position, respectively. It was found that the higher temperature at the pre-intercooler position could be attributed to the higher temperature of the turbocharger system. Make intake air quality will be reduced 6.27%, 5.31%, 5.27% and 6.06%, 5.37%, 5.38%, respectively. As a result, the intake air quality was low, cause combustion reaction incompletely in the cylinder. The high vaporization heat of methanol reduced the air temperature and increased the intake air density, reduced cylinder combustion temperature, increased hydrocarbon (HC) and carbon monoxide (CO) emissions. In addition, methanol contains 50% oxygen atoms maybe to promote combustion and higher intake air temperature could significantly reduce hydrocarbon (HC) and carbon monoxide (CO) emissions almost 20% and 6%, respectively at pre-intercooler injection position under 10% MSR.

The different injection positions of methanol resulted in lower intake temperatures, prolonged the ignition time, delayed the combustion phase, decreased the cylinder peak pressure. Increased methanol substitution rate could extend the ignition time, resulted in delaying combustion phase, increased heat release rate.

Nitrogen oxide emissions decreased with the increase of methanol substitution rate. In contrast, the NOx emission generated was higher when methanol injected at the pre-intercooler position, the NOx emission generated was the second when methanol injected at post-intercooler, then the intake manifold injected with methanol. Specifically, at intake manifold injection position, the NOx will be reduced larger than other injection positions, compared with pure diesel condition, will be reduced almost 59%, 61%, 66%, 68%, at 10%, 20%, 30%, 40%MSR, respectively.

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