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AN IN-DEPTH COMPARISON OF DIESEL AND DIESEL METHANOL DUAL FUEL COMBUSTION MODE

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ABSTRACT

In order to understand in depth that Diesel/Methanol Dual Fuel (DMDF) could gain ultra-low emissions and high thermal efficiency, P-V map and ϕ-T map were analyzed at full load @1660 r/min. Based on the analysis of P-V map, the reasons for the increase in thermal efficiency at DMDF mode are as follows: First, the effective work of DMDF mode reduced at DMDF mode. Then, methanol evaporated in the intake manifold and cylinder will absorb large amount of heat, which will achieve waste heat recovery; Finally, the energy carried away by the exhaust gases is reduced, which is due to low exhaust temperature.

In DMDF mode, the intersection of ϕ-T map and NO generation region is obviously reduced, compared with the diesel mode. Meanwhile, ϕ-T map of DMDF mode is not covered the highest NO generation rate region. This is the reason of achieving ultra-low NOx emissions. The ϕ-T map of DMDF mode avoids soot generation regions at CA05 and CA50. This is the key to achieve ultra-low soot emissions.

Keywords: DMDF; thermal efficiency; emissions; P-V map; Φ-T map

NONMENCLATURE

Abbreviations	
DMDF	diesel methanol dual fuel
HRR	heat release rate
MSP	methanol substitution percent
EGR	exhaust gas recirculation
LTC	low temperature combustion
ECU	electronic control unit
CA	crank angle
BSFC	brake specific fuel consumption
NOx	nitrogen oxides
CO	carbon monoxide
THC	total hydrocarbons
ATDC	after top dead center
BTE	break thermal efficiency

1. INTRODUCTION

In recent years, in order to achieve ultra-low emissions and higher engine efficiency, most research in diesel engines is focused on Low Temperature Combustion (LTC)[1], and dual fuel combustion mode was one of efficient methods to achieve LTC. Diesel Methanol Dual Fuel (DMDF) is a kind of LTC combustion mode. and DMDF mode could simultaneously achieve high efficient combustion and low emissions. However, the research of DMDF is mostly concentrated on parameter research. The research of in-depth comparison of diesel and DMDF combustion mode is rarely reported. Thus, it is difficult to clearly explain the reason of why DMDF could achieve ultra-low emissions and high thermal efficiency[2].

Therefore, it is necessary to carry out relevant research to explain the reason of why DMDF could achieve ultra-low emissions and high thermal efficiency. In this manuscript, P-V map will be used to explain the reason of why DMDF could achieve high thermal efficiency. ϕ-T map will be used to explain the reason of why DMDF could achieve ultra-low emissions.

2. EXPERIMENTAL APPARATUS, METHOD AND COMPUTATIONAL MODEL

2.1 *Engine and experimental facilities*

The original diesel engine was a four cylinder electronically controlled unit pump engine. The engine specifications are shown in Table 1. There were four methanol injectors in the engine manifold, which was used to achieve DMDF combustion mode. Figure 1 shows the schematic of the engine layout.

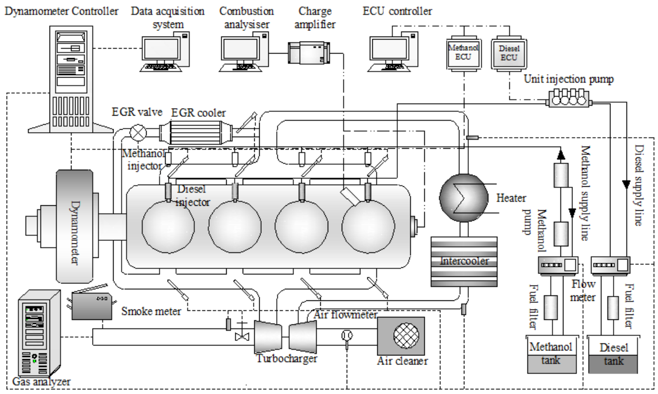


Figure 1 Schematic of the experimental setup

The consumption mass of diesel and methanol are measured by fuel consumption meter (FCM-05; BoHao test Co., Ltd). The EGR rate was regulated by adjusting the EGR valve and the exhaust backpressure. In this work, the EGR rate is defined as the ratio of CO2 concentrations in the intake and exhaust gases. The gaseous emissions including CO, HC and NOx were measured by using a gas analyzer system (MEXA-7100 DEGR; Horiba. Meanwhile, a smoke meter (415SE; AVL) was used for soot emissions measurements. A piezoelectric pressure transducer (6125CU20; Kistler) was used to measure the cylinder pressure. The combustion timing mainly includes Crank Angle(CA) 05, CA50, and CA90. The mass fraction burnt was calculated by integrating the HRR. During the test, 500 consecutive cycles of cylinder pressure data were recorded and were ensemble averaged, then the average data was a representative cylinder pressure trace[3].

2.2 Engine operating method and test conditions

Experiments were conducted at 1660 r/min and full load condition. This is because that it is difficult to increase break thermal efficiency (BTE) at full load case. Meanwhile, it is difficult to simultaneously reduce NOx and soot emissions for DMDF combustion mode at full load case. At this test case, diesel injection timing was 0° CA ATDC, and intake air temperature after intercooler was 35°C. The maximum EGR rate of this case was 17%, and the maximum EGR rate was used to control combustion phase and reduce NOx emissions.

2.3 Computational model

In the present research, to figure out the combustion process of the DMDF mode, commercially available CFD software CONVERGE is used[4]. There were seven nozzle holes in the engine diesel injector, and a 51.4° mesh was used in this study. The computational mesh is shown in Figure 2. Comparison of experimental and simulated results at full mode was shown in Figure 3.

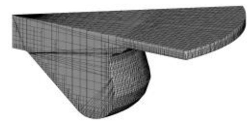


Figure 2 Computational mesh of engine simulations

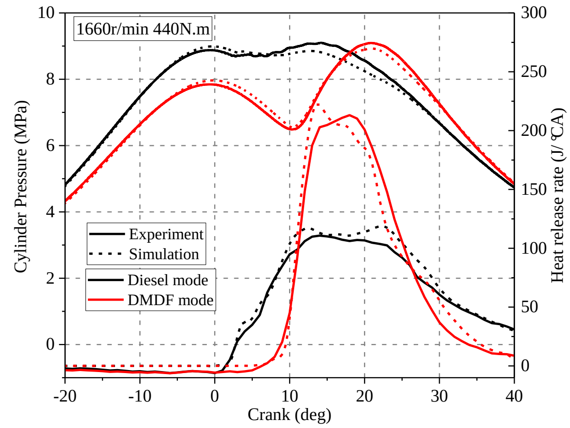


Figure 3 Model verification and simulation results of diesel and DMDF mode at full load

2.4 Results

Figure 4 shows the comparison of P-V map between diesel mode and DMDF mode at full load. For DMDF mode, the cylinder pressure in compression stroke is obviously lower than diesel mode, which is beneficial to reduce compression work. When the piston moves to the compression TDC, cylinder pressure of diesel mode is obviously higher than DMDF mode. The combustion timing of diesel mode is near to TDC, and combustion exothermic reactions cause the cylinder pressure increasing. However, according to the law of piston motion, the volume change rate is small when the piston is near to TDC, the higher pressure is not converted into the effective output work. When the piston is moving down during the expansion process, the cylinder pressure of DMDF mode significantly reduces, which is due to that combustion occur after 10 °CA ATDC for DMDF mode. Once the combustion occur, the cylinder pressure rises rapidly. The maximum of DMDF mode is near to diesel mode. At this time, the volume change rate is large, and the higher pressure is converted into the effective output work.

When the piston is moving to -40 °CA ATDC, cylinder pressure of DMDF mode is lower than diesel mode. This is because that the combustion duration of DMDF mode is shorter than diesel mode, and there is little late combustion phase. Longer late combustion phase will increase the heat loss and increase the energy carried away by the exhaust gases. The exhaust temperature after turbine of diesel mode is 665 °C, which is 577 °C for diesel mode. During power stroke, the output work of diesel mode is 2513.79J, and the output work of DMDF mode is 2446.91J.

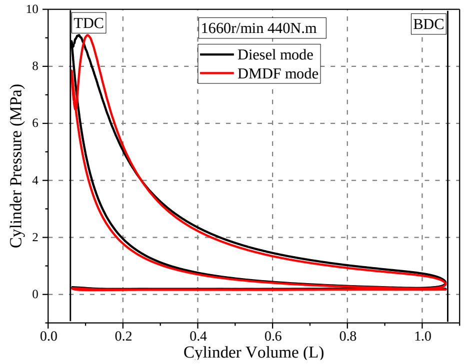


Figure 4 Comparison of P-V map between diesel mode and DMDF mode at full load

Table 1 shows the comparison of key parameter between diesel mode and DMDF mode at full load. The analysis of these parameters will be helpful to explain the results presented in P-V map. As mentioned earlier, the compression work of DMDF mode is lower than diesel mode. The decrease of compression work is mainly due to decreasing of intake air temperature and pressure. There is little difference in the total mass entering the cylinder between the two modes. Methanol high latent heat of vaporization is the key reason for the decrease of intake air temperature.

The BTE of DMDF mode is 42.65%, which is increased by 14.9% compared with diesel mode. The reasons for the increase in thermal efficiency are as follows: First, the effective work of DMDF mode is higher than diesel mode. Then, methanol evaporated in the intake manifold and cylinder will absorb large amount of heat, which will achieve waste heat recovery; Finally, the energy carried away by the exhaust gases is reduced, which is due to low exhaust temperature. Together these factors act to make the BTE of DMDF mode is obviously higher than diesel mode.

Table 1 Comparison of key parameter between diesel mode and DMDF mode at full load

Project	Unit	Diesel mode	DMDF mode
Diesel consumption rate	kg/h	17.32	3.58
Methanol consumption rate	kg/h	0	24.5
BSFC	g/kW.h	226.57	197.17
BTE	%	37.12	42.65
MSP	%	0	79.30
Intake air mass	kg/h	319.5	294.4
Intake pressure	MPa	0.185	0.175
Intake manifold temperature	℃	43	23
Exhaust temperature	℃	665	577
NOx emission	g/kW.h	1.18	0.81
Soot emission	g/kW.h	0.95	0.006
CO emission	g/kW.h	8.4	6.5
HC emission	g/kW.h	0.04	3.05
Compression work	J	-1042.88	-949.29
Output work	J	2513.79	2446.91
Effective work	J	1470.92	1497.63
Cumulative heat release	J	3087.7	2941.6

As can be seen from Table 1, compared with diesel mode, NOx emission of DMDF mode is reduced by 31.35%, and soot emissions is reduced by 99.37%. This result can be reasonably explained by the analysis of the ϕ-T map. It can be seen from Figure 5 that the ϕ-T map of DMDF mode avoids soot generation regions at CA05 and CA50. This is the key to achieve ultra-low soot emissions. High premixed ratio of methanol can significantly reduce diesel mass. At the same time, the inhibition effect of methanol on diesel low temperature reaction will increase ignition delay, and this is the key to reduce the equivalent ratio of direct injection diesel fuel. In DMDF mode, the intersection of ϕ-T map and NO generation region is obviously reduced, which is compared with diesel mode. Meanwhile, ϕ-T map of DMDF mode is not covered the highest NO generation rate region. This is because that the maximum cylinder temperature is significantly reduced in DMDF mode. When the temperature exceeds the generation condition of NO, the rate of NO generation will be exponentially increased with cylinder temperature increasing. Thus, NO emissions will be reduced by decreasing cylinder temperature.

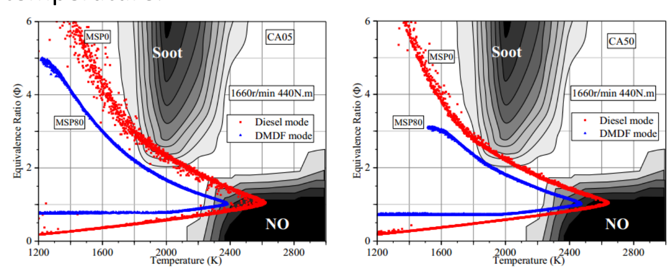


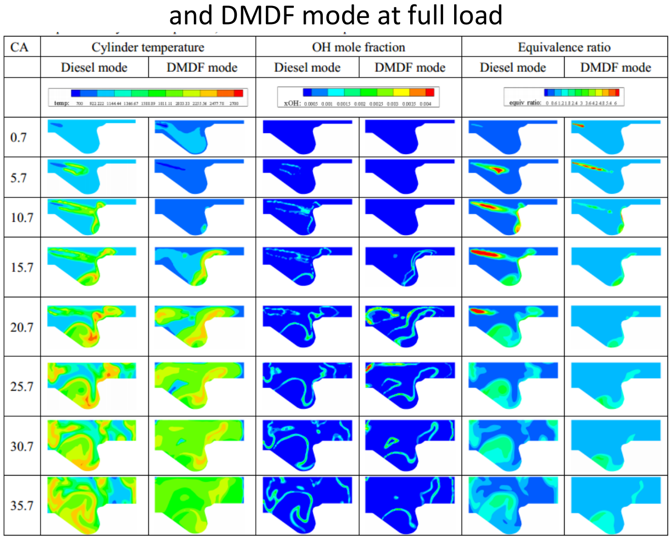
Figure 5 Comparison of ϕ-T map between diesel mode and DMDF mode at CA05 and CA50 of full engine load

In order to deeply compare the difference between diesel mode and DMDF mode, the combustion process will be discussed by analyzing the in-cylinder temperature, OH molar fraction and the equivalent ratio three-dimensional cloud map.

Table 2 shows the comparison of cylinder temperature, OH mole fraction and equivalence ratio three-dimensional cloud map between diesel mode and DMDF mode at full load. There is difference between the ignition way of diesel mode and DMDF mode. For diesel mode, when diesel is injected in the cylinder, there will form theoretical equivalent ratio fuel/air mixture charge region around diesel spray, and these regions will be ignited firstly. As can be seen from OH mole fraction map that these regions produce large amount of OH groups, which is crucial to combustion process. Meanwhile, diesel fuel keeps injecting into the cylinder, and most of diesel fuels are impinged with combustion chamber, where will form oil film over combustion chamber surface (after 10.7°CA ATDC). Due to the high temperature of combustion surface, oil film will evaporate, forming theoretical equivalent ratio fuel/air mixture charge. Then, this part of fuel will ignite. Thus, for diesel mode, combustion starts at the region around the spray and oil film over combustion chamber surface.

For DMDF mode, when diesel is injected in the cylinder, the in-cylinder temperature and equivalence ratio at this time have reached the ignition condition of the diesel. However, there is no combustion process around diesel spray (as shown in Table 2, the OH groups are difficult to detected before 15.7 °CA ATDC). This is because that methanol inhibits low temperature reaction of diesel. After diesel injected in the cylinder, diesel fuel sets off low temperature oxidation reaction, where will produce OH groups. But the OH groups around diesel spray are converted to H_2O_2 by methanol oxidation reaction, and H_2O_2 is relatively inactive group. Thus, diesel ignition delay is prolonged. Diesel and diesel low temperature oxidation product will form homogeneous charge of premixed methanol. The reactivity of premixed methanol will be increased. As the injection process continues, oil film over combustion chamber surface will be ignited firstly. Then, premixed methanol charge with evaporated diesel will be ignited.
Based on the comparison of these two combustion modes, it can find that the in-cylinder temperature distribution is more uniform for DMDF mode. The fuel rich areas are significantly reduced, and the maximum in-cylinder temperature is also greatly reduced, which is the key to achieving ultra-low NOx and soot emissions for DMDF mode.

Table 2 Comparison of cylinder temperature, OH mole fraction and equivalence ratio between diesel mode and DMDF mode at full load



2.5 Conclusions

Based on the analysis of P-V map, the reasons for the increase in thermal efficiency at DMDF mode are as follows: First, the effective work of DMDF mode is higher than diesel mode. Then, methanol evaporated in the intake manifold and cylinder will absorb large amount of heat, which will achieve waste heat recovery; Finally, the energy losses in exhaust gases is reduced due to low exhaust temperature. Together these factors to make the BTE of DMDF mode is obviously higher than that of diesel mode.

In addition, with DMDF mode, the intersection of ϕ-T map and NO generation region is obviously reduced, which is compared with diesel mode. Meanwhile, ϕ-T map of DMDF mode is not covered the highest NO generation rate region. This is because that the maximum cylinder temperature is significantly reduced in DMDF mode, and the in-cylinder temperature distribution is more uniform for DMDF mode. The ϕ-T map of DMDF mode avoids falling in soot generation regions at CA05 and CA50. This is the key to achieve ultra-low soot emissions. High premixed ratio of methanol can significantly reduce diesel mass. At the same time, the inhibition effect of methanol on diesel low temperature reaction will increase ignition delay, and this is the key to reduce the equivalent ratio of direct injection diesel fuel.

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