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Methanol port fuel injection technology study on CPGC M320 engine

Dual Fuel / Gas / Diesel

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ABSTRACT

Methanol is considered as a potential alternative fuel for IMO GHG reduction targets. It is a well-known fuel for internal combustion engine and widely applied in automotive. It also has advantages in storage, handling and combustion for marine application compared with other carbon-free fuels e.g., hydrogen, ammonia etc. Methanol is suitable for different combustion concepts. Methanol direct injection (DI) has advantages in high efficiency and power. Methanol port fuel injection (PFI) has a cost-efficient methanol supply and reliable injection system.

This paper focus on the methanol PFI technology. The study is based on M320 engine which is designed by CSSC Power (Group) Corporation Limited (CPGC). A six-cylinder 320mm bore test engine is retrofitted for methanol fuel to test and validate relevant technologies.

Methanol is injected into the intake port in liquid. The methanol injection position, timing and pressure are important for the spray and space distribution in order to minimize wall film. Spray test in static environment and with crosswind are studied. The methanol spray characteristic and the effect of crosswind velocity are used to calbricate the spray model setting. The flow and combustion process is simulated by CFD. The methanol injection layout and strategies are analyzed and optimized according to the simulation results.

The engine performance and combustion chamber’s thermal load between diesel and methanol are compared by the test engine. The exhaust temperature of cylinder with methanol is reduced. Meanwhile the general temperature of the cover and piston with methanol is also reduced. But the temperature distribution is different from diesel mode.

1 INTRODUCTION

Alternative fuel has continued to play a prominent role representing 50% of all tonnage new shipbuilding ordered in 2024. Methanol is considered as a potential alternative fuel for IMO GHG reduction targets. Methanol now is the second alternative fuel for vessel (118 orders and 14% shares) in 2024.[1]

Methanol is a well-known fuel for internal combustion engine and widely applied in automotive.[2]~[4] It also has advantages in storage, handling and combustion for marine application compared with other carbon-free fuels for example hydrogen and ammonia. Methanol is suitable for different combustion concepts. Methanol Direct injection (DI) has advantages in high efficiency and power.[5][6] Methanol port fuel injection (PFI) has a cost-efficient methanol supply and reliable injection system.[7][8]

CPGC M320 series engines are designed by CSSC Power (Group) Corporation Limited (CPGC) with AVL List GmbH support.[9] They are developed for marine propulsion and genset. Now these series engines include diesel engine, sole gas engine and natural gas dual fuel engine. M320 methanol dual fuel engine is the new developing engine based on M320 series engine design. The main technical specification of M320 series engine is shown in table 1.

Table 1. M320 main technical specification

	M320F	M320G	M320DF	M320DM
Type	Diesel	Gas	Gas dual fuel	Methanol dual fuel
Cylinder No.	6-9			
Bore/mm	320			
Speed/rpm	750			
Power/kW per cylinder	500	405	405	500
BMEP/MPa	2.37	1.92	1.92	2.37

The methanol direct injection system development is relatively more challenging and the cylinder head is difficult to arrange both methanol and diesel injector for DI concept. So PFI is firstly applied for the methanol prototype engine. The concept engine design is shown in figure 1. The methanol injection system is the yellow parts in figure 1 which substitutes the natural gas injection system compared with natural gas dual fuel engine. This paper focuses on the study of the methanol injection and combustion process to support M320DM methanol PFI engine development.

Figure 1. M320DM-PFI concept design

2 COMBUSTION CONCEPT

The combustion concept of M320 methanol port fuel injection engine is similar to the natural gas dual fuel engine shown in figure 2. Methanol is injected into the intake port in the intake stroke and with the fresh air sucked into the cylinder. The methanol continues to vaporize and diffuse in the compression stroke until diesel is injected near the top dead center (TDC). Then the premixed methanol is ignited by diesel flame.

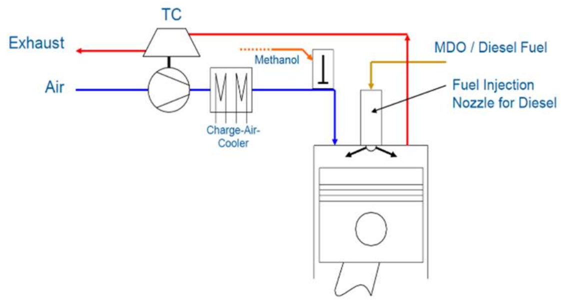


Figure 2. M320DM PFI combustion concept

The methanol injection system consists two injectors for each cylinder to get better spray quality and quicker response of the injector. The sequential injector switching strategy between one and two injectors is applied to satisfy the wide injection mass range requirement from engine low load to high load. The control hardware and software of the two injectors become more complicated. Meanwhile the injectors arrangement also become more difficult relatively.

The diesel injection system is pump-line-nozzle (PLN) which is the same as M320 diesel engine. It is proven a reliable and cost solution for combustion heavy fuel oil if methanol is not available or in emergency condition. The compression ratio is also the same as diesel engine to keep high efficiency and power in the diesel mode.

On the other hand, we have to balance the performance in methanol mode. The methanol share is limited to combustion stability in low load and knock risk in high load. The poor performance of PLN system in small injection amount leads methanol ignition unstable. High compression ratio increases methanol knock risk.

Excepts for these factors, the methanol spray, mix, evaporation and final concentration distribution are also very important for the engine performance and emission.

3 PFI INJECTION SPRAY

M320DM methanol injection mass for one cylinder is up to 10g/shot. Limited to injection pressure (about 10bar) and intake port space, Sauter mean diameter (SMD) of the spray is 100-200 μm. The methanol is injected into the port when the intake valves are open. Most methanol droplets can't evaporate in such a short time. The methanol is still carried into the cylinder in liquid droplets with intake fresh air.

So the methanol spray characteristic is very important for reduction residual methanol in the intake port and understanding the methanol distribution in the cylinder.[10]

A spray test is used to figure out the injector spray characteristic and validate the injector design. The spray characteristic includes spray tip penetration, spray angle, droplet diameter distribution etc. The spray test setting is shown in table 2. These test settings are trying to simulate actual application environment. The cases are designed to get the gradient for injection pressure, environment pressure and temperature.

Table 2. Spray test setting for static environment

Case	Injection pressure/bar	Environment pressure/bar	Environment temperature/℃
1	9	3	25
2	9	3	38
3	9	3	50
4	8	2	25
5	7	1	25
6	9	6	25
7	9	1	25
8	9	2	25

The test injector nozzle has 180 holes which consist of 4 concentric circles. The individual nozzle diameter is 0.3mm. The spray tests result of case 1 in table 2 is shown in figure 3.

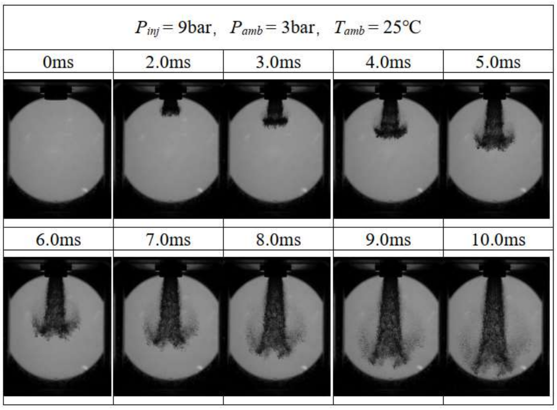


Figure 3. Methanol spray shape

Spray developing characteristic of case 1 is shown in figure 4. The spray tip penetrations are out of the window range (about 125mm) and its gradients are from 8.2 to 22.4 mm/ms in the above eight cases. The spray angles in static environment are from 10.5 to 26.4 degree in the cases.

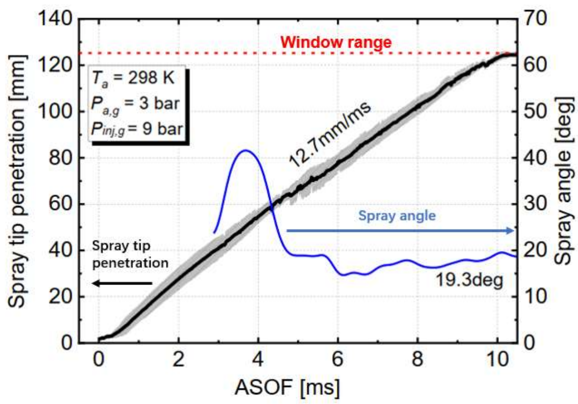


Figure 4. Spray developing characteristic

When methanol is injected, the air in the intake port is not static and the velocity variation up to 50-60m/s. The fresh air flow also has great effect on the spray. The methanol spray with crosswind test is compared to figure out the effect of air flow velocity. Limited to the air flow rate of the testbed, the maximum velocity is 27m/s. The spray shapes with crosswind velocities 10m/s, 20m/s and 27m/s are shown in figure 5. The other parameters are the same as case 1.

The spray is obviously deflected when the crosswind velocity is larger than 20m/s. The crosswind helps spray spread to a wider range which makes the droplets smaller and easy to evaporate.

The test results are used to calibrate the methanol spray setting parameters in CFD simulation and to get more accurate simulation results.

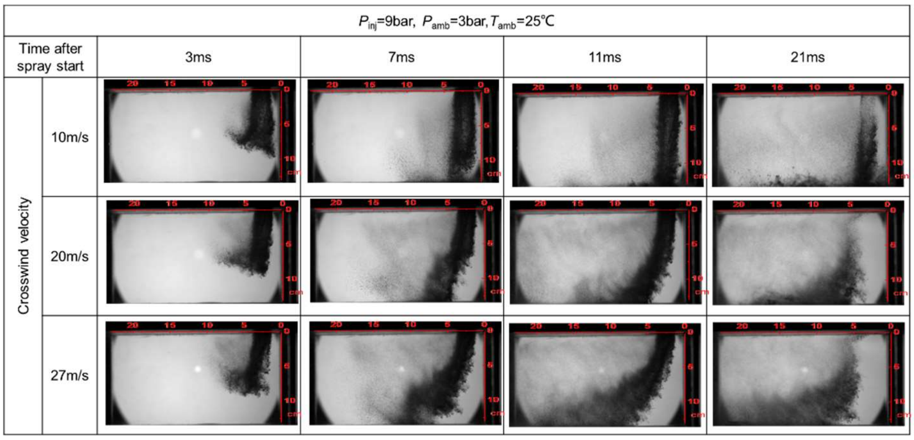


Figure 5. Methanol spray with crosswind

4 CFD SIMULATION

The aim of CFD simulation is to find optimal injection position and strategies to reduce residual methanol in the intake port and form proper methanol distribution for combustion.[8] Serval injection layouts for M320DM are designed and compared by CFD simulation.

The methanol spray direction and position are determined by the velocity relationship between the initial methanol injection and intake air flow. To simply the simulation case, the velocity of the initial methanol injection is assumed according to the fixed pressure difference between the injected methanol and intake boost air. Meanwhile the injection duration is also fixed with the specified injector nozzle. Based on natural gas port injection experience, the injection window is from exhaust valve closed timing to intake valve closed timing and considering the time which the air flow takes from the injector to the valves. Limited to the injection window, the injection start timing is almost determined at high load. The methanol spray and flow in the intake process with different injector layouts are simulated and evaluated based on the above conditions and assumptions. The simulation results from two injection layouts at 75% load are shown in figure 6 as an example.

The methanol droplets' movement is obviously deflected by the air flow. The methanol spray direct impingement on the port lower surface doesn't occur. In contrast, more methanol particles are residual on the upper surface where the direction of the air flow change greatly.

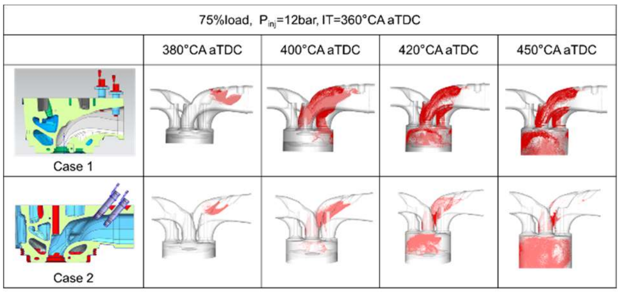


Figure 6. Methanol spray particle flow in the intake process

The methanol mass fraction distribution of the simulation results based on case 1 is shown in figure 7. In this case, most methanol droplets are sucked into the cylinder from the long-route port. The methanol is concentrated below the intake valve of the long-route port when the intake valves close. The uniformity of methanol is not significantly improved with the movement of piston in the compression process. At the moment before diesel is ignited, methanol is still stratified in the cylinder and concentrated at the long-route port side. Parts of the methanol near the combustion chamber edge is still residual after combustion. In addition, high methanol mass fraction is found at the intake port near intake valve which comes from methanol wall film evaporation on the valves' back. These lead to methanol emission in the exhaust gas increase.

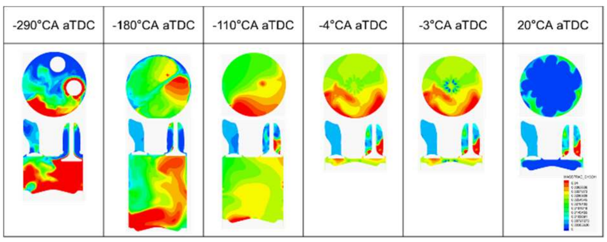


Figure 7. Methanol mass fraction distribution in case 1

The corresponding cylinder temperature distribution is shown in figure 8. When the methanol share ratio is moderate, diesel diffused combustion is dominated. The flames spread to the edge of the combustion chamber. But when the methanol share ratio is high, the diesel ignition delay time increases and diesel flames don’t spread to the whole combustion chamber. The combustion concentrates in the middle of the combustion chamber.

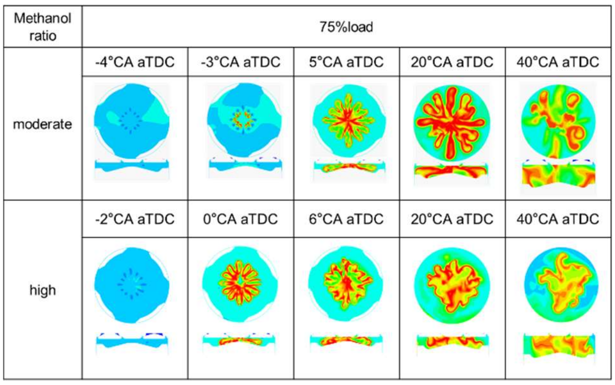


Figure 8. In-cylinder temperature distribution in case 1

5 ENGINE PERFORMANCE

5.1 Test engine

The methanol PFI technologies are tested in the modified test engine with the methanol fuel supply system and fuel valve train. The main technical specification of the test engine is shown in table 3.

Table 3 Test engine main technical specifications

Item	Unit	Value
Type	/	4-stroke, L
Cylinder number	/	6
Bore	mm	320
Stroke	mm	420
Rated power	kW	3000
Rated speed	r/min	750
BMEP	MPa	2.37
Diesel injection		Pump-line-nozzle

5.2 Methanol operation range

The methanol share limitation in the whole engine operation range are explored. The results of the engine propulsion curve are shown in figure 9. The maximum methanol share in energy is 56% at 75% load. In the lower load, the thermal condition is worse and hard to combust stably. In the higher load, the restriction is maximum cylinder pressure.

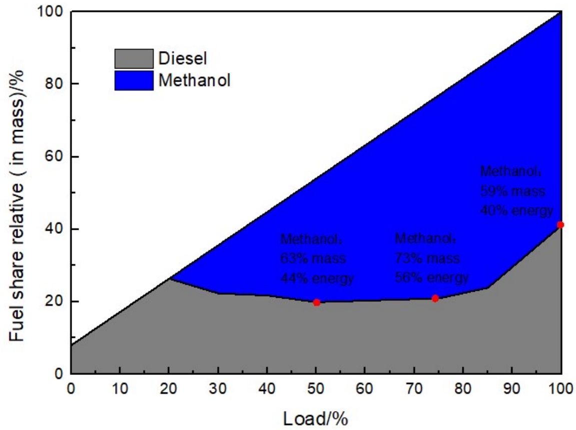


Figure 9. Methanol share in engine propulsion curve

Figure 10 shows the cylinder pressure and heat release rate with 33% and 52% methanol share in energy at 75% load (BMEP 21.7bar). The increased methanol reduces the compression pressure at TDC and delays the diesel ignition. The premixed methanol isn’t ignited well by the diesel flame and knock occurs when the methanol share is high.

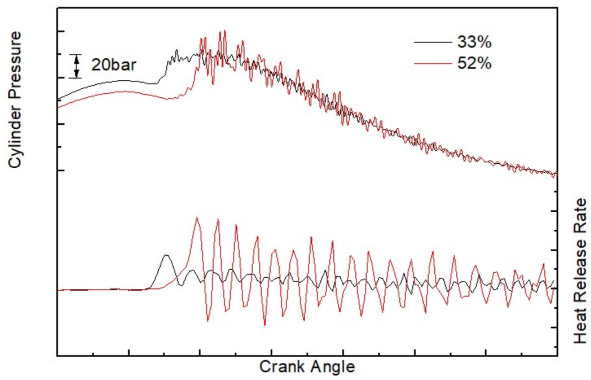


Figure 10. The cylinder pressure and heat release rate of 33% and 52% methanol share in energy

The relatively cycle-to-cycle variation of maximum pressure and IMEP are shown in figure 11. The variations of maximum pressure are relatively lower than the variations for natural gas engine. But the variations of IMEP is closed to that for natural gas engine. The variation of maximum pressure and IMEP are both used to evaluate the combustion stability in the calibration. The maximum pressure is relatively more stable and easier to identify.

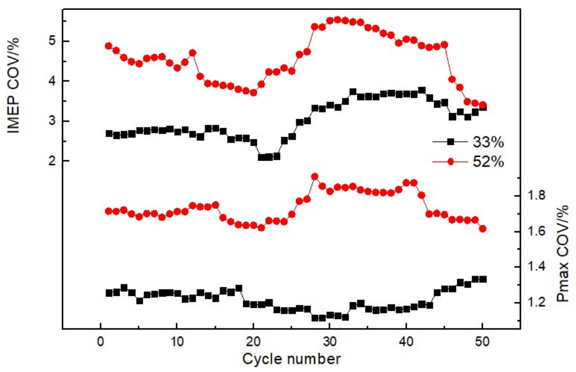


Figure 11. IMEP and maximum pressure cycle-to-cycle variation.

5.3 Methanol injection strategy

When the engine operation speed and load are changed, the air pressure and flow velocity in the intake port will change at the same time. So the methanol injection strategies should change according to the engine speed and load. The injection pressure and injection start timing are two main injection parameters to study in the test.[11]~[13]

The injection pressure affects not only the spray characteristic but also injection duration with given methanol mass. It is important to ensure injection duration is in the suitable window period. To improve the spray droplet diameter and reduce the injection duration in high load, higher injection pressure is applied and get better performance. In low load, the injection mass is low and so the injection duration is short. Lower injection pressure can improve the small injection mass stability of the injector and methanol distribution uniformity. So the injection pressure is optimized according to the engine speed and load.

The injection start timing is also important to make the injection process in the suitable window period. Early injection makes methanol directly escape to exhaust pipe in the scavenge process. Late injection when the air flow velocity is low conducts the methanol droplets are not timely sucked into the cylinder before intake valves close. The injection start timing is scanned in the test and optimal timing is selected according to the thermal efficiency and methanol slip.

5.4 Intake and exhaust

Methanol has higher latent heat of vaporization and extra oxygen content compared to diesel. It conducts the exhaust energy and turbocharging balance point change in the methanol mode.

The boost pressure and exhaust temperature before the turbine between methanol and diesel modes are shown in figure 12. The boost pressure of methanol mode is slightly lower than that of diesel mode at 25%, 50% and 75% load, but it is 0.19bar higher than that of diesel mode at 100% load.

In terms of exhaust temperature before the turbine, the methanol mode is lower than the diesel mode. The maximum difference is 27℃ at 75% load. The minimum difference is 6℃ at 100% load. The exhaust temperature before the turbine indirectly reflects the average heat load in the cylinder, indicating that the thermal load in the cylinder is generally reduced in methanol mode.

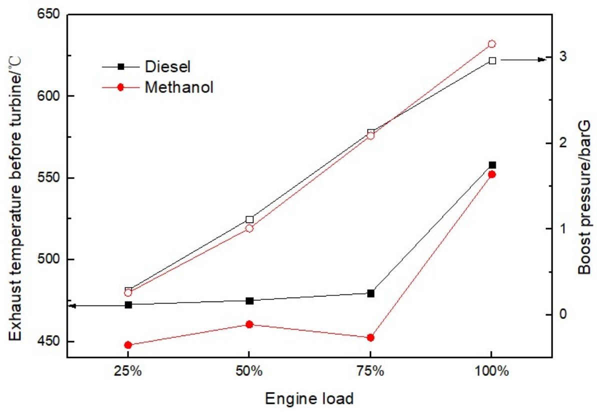


Figure 12. Boost pressure and exhaust temperature

6 COMBUSTION PARTS TEST

The temperatures of the cylinder head and liner are measured by thermocouples to figure out the thermal load of the combustion parts between methanol and diesel mode.

6.1 Cylinder head

The measured points layout of the cylinder head is shown in figure 13. The temperature measured points of the cylinder head are selected in the cylinder head flame surface, cooling gallery and valve seat.

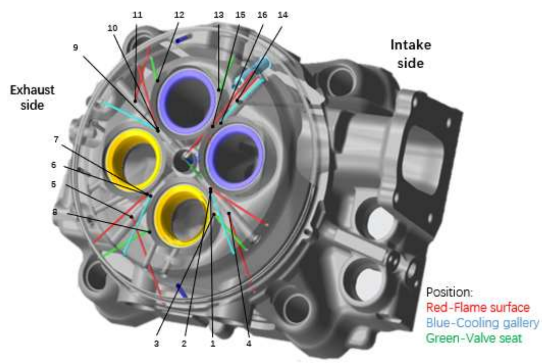


Figure 13. Cylinder head measured points layout

In diesel mode, the temperature of the cylinder head is generally increased with the increase of load. The temperature on the flame surface of the cylinder head in diesel mode are shown in figure 14.

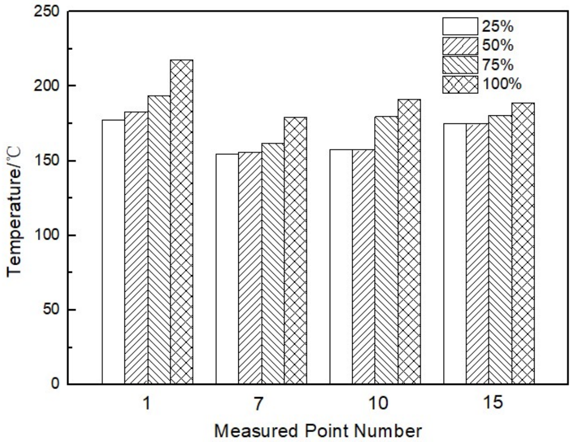
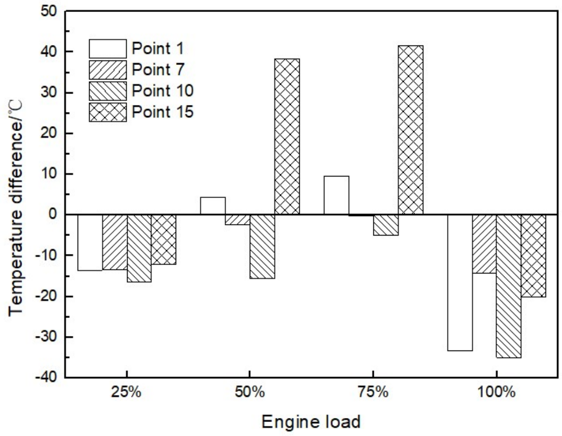
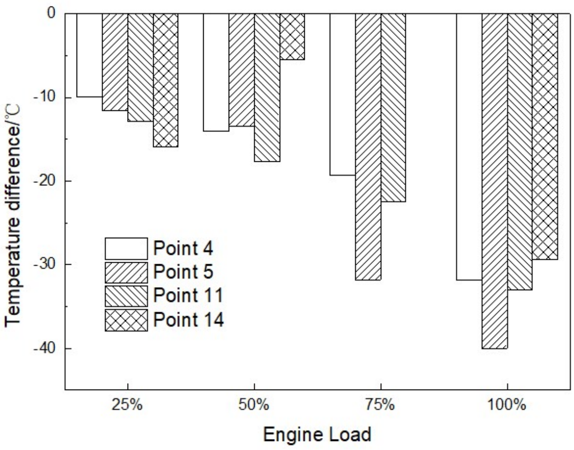


Figure 14. Cylinder head flame surface temperature in diesel mode

The regularity of cylinder head flame surface in methanol mode is less significant than that in diesel mode. The temperature difference between methanol and diesel mode is shown in figure 15. In general, the flame surface temperature of methanol mode is significantly lower than that of diesel mode. The difference between the two modes increases with the increase of engine load, up to 40℃. The measured points near the edge of the cylinder head have stronger regularity. The points between the valves have the same law at 25% and 100% load, but at 50% and 75% load they have higher temperature in methanol mode. The temperature in the middle of the two intake valves (point 15) increases most, which increases by 42℃. The temperature between the intake valve and the exhaust valve (point 1) also increases slightly. The distribution of methanol concentration in the cylinder is uneven, which causes the heat release concentrate on the intake side and corresponding temperature rises.



(a) points closed to cylinder center (between valves)



(b) points closed to the cylinder edge

Figure 15. Cylinder head flame surface temperature difference between methanol and diesel mode

The points on the cooling gallery of the cylinder head are arranged directly above the points which is on the flame surface closed to the center of the cylinder (between the valves). The temperature difference of the cooling gallery between the two modes is shown in figure 16. The temperature difference of the cooling gallery has the same trend as the flame surface. The overall temperature of the methanol mode is decreased, but at 50% and 75% load the temperatures between intake valves are increased. Compared with the flame surface, the temperature difference on the cooling gallery is obviously reduced.

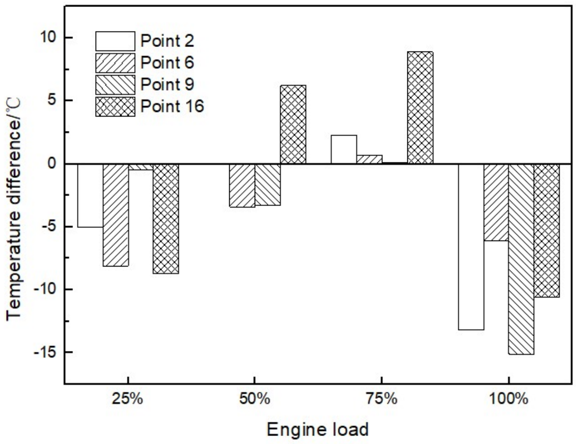


Figure 16. Cylinder head cooling gallery temperature difference between methanol and diesel mode

The temperature difference of valve seat between the two modes is shown in figure 17. The temperature of the valve seat in methanol mode is generally lower. The temperature differences between the two modes are different. Point 12 which is on the intake valve seat decreases largest. The temperature reduction is 61℃. Meanwhile point 13 on the other side of the same intake valve seat also decreases by 26℃. The temperature drop of the intake valve seat is mainly caused by the heat absorption of methanol which is on the back of intake valve. The exhaust valve seat is not affected by methanol wall film and the variation trend of temperature difference is consistent with that of flame surface.

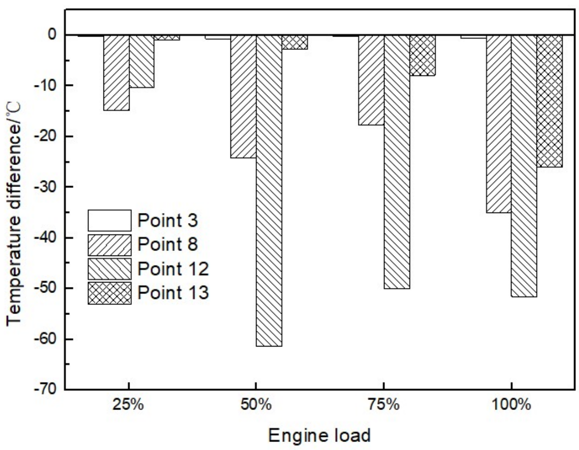


Figure 17. Valve seat temperature difference between methanol and diesel mode

The overall temperature of the cylinder head decreases in methanol mode. But the temperatures at some positions increase due to the concentration of methanol combustion. The temperature of intake valve seat further decreases because the methanol wall film at the back of the intake valve.

6.2 Cylinder liner

The temperature measured points of the cylinder liner are mainly selected from the high temperature part which is the upper part of the liner. The points are arranged at the middle of the wear ring, the first piston ring and the cooling water inlet. 8, 8 and 4 measured points are set along the circumference of the cylinder liner. The measured points layout is shown in figure 18.

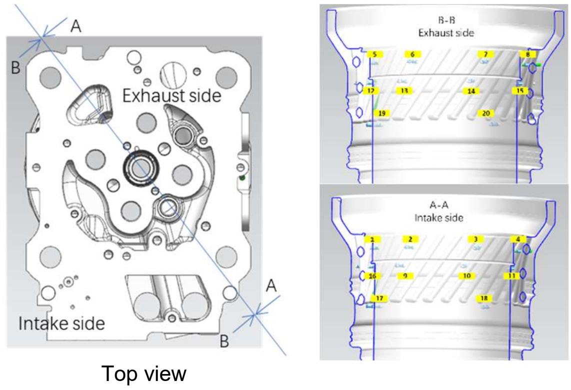


Figure 18 Cylinder liner measured points layout

The average temperature difference between methanol and diesel at three heights are compared and the results are shown in figure 19. The average temperature of cylinder liner in methanol mode is lower than that in diesel mode. The temperature difference increases with the increase of load and decreases when measured position moves down. The average temperature difference of the wearing ring between the two modes at 100% load is 37℃ which is the largest difference.

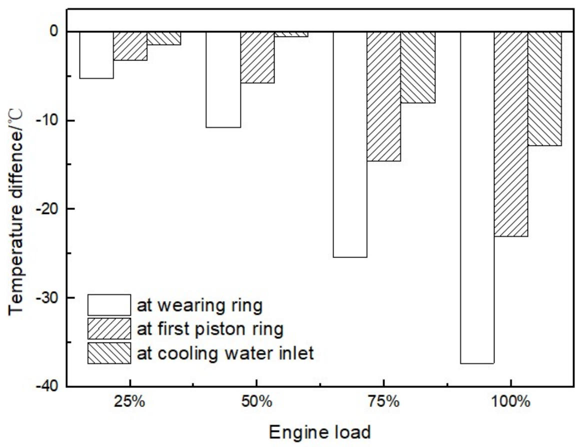


Figure 19 Average cylinder liner temperature difference between methanol and diesel

The temperature difference between methanol and diesel mode at the wear ring is shown in figure 20.

At 25% load there is no obvious temperature difference along the circumference of the cylinder liner. However, the temperature difference of point 4 and 5 is much lower than others when the load increases above 50%. These two points are located between the long-route port and exhaust port. Based on CFD simulation results, the methanol is concentrated in this area in the intake and compression process. The heat absorption by evaporation of methanol is the main reason for temperature reduction at these two points.

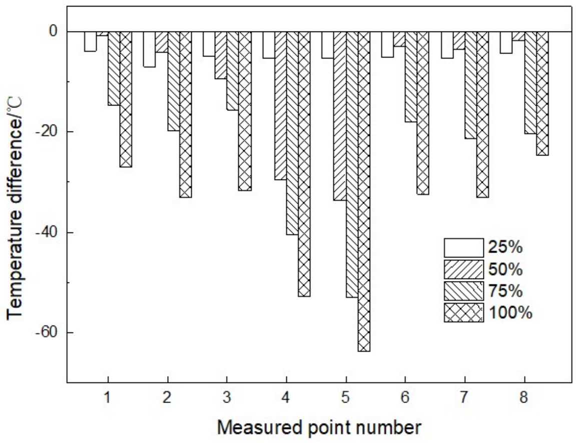


Figure 20. Cylinder liner temperature difference at wearing ring between methanol and diesel mode

7 CONCLUSIONS

The methanol PFI relevant technologies are studied based on M320 engine and guide M320 methanol dual fuel engine development.

Firstly, the methanol injection spray in static environment and with crosswind are tested. The spray tip penetrations are relatively long for the intake port. The methanol injection direction and position should be carefully designed to avoid spray directly be injected on the port wall. The crosswind in the intake port makes the spray be deflected and broken to smaller droplets. The spray characteristic from test is used to calibrate the methanol spray setting parameters in CFD simulation.

The air flow and cylinder combustion process are simulated by CFD. The simulation results for several injection layouts are compared. The methanol concentrates on the intake side of the combustion chamber. The methanol distribution in cylinder affects combustion and emission.

The M320 test engine is retrofitted to study methanol PFI performance. The maximum methanol share reaches 56% in energy at 75% load. The methanol operation range is from 20%-100%. The combustion instability and high maximum cylinder pressure are the main restrictions to further increase methanol share. The injection strategies are optimized for different load. The exhaust temperature is lower in methanol mode. The boost pressure increases at high load in methanol mode.

The temperature distributions of cylinder head and liner are compared between diesel and methanol modes. The thermal load in methanol is generally lower than in diesel mode. The temperature distribution of methanol mode is not as regular as diesel mode. The methanol nonuniform is the main reason for the temperature distribution difference.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

PFI: Port Fuel Injection

DI: Direct Injection

IMEP: Indicated Mean Effective Pressure

TDC: Top dead center

aTDC: after Top dead center (firing)

bTDC: before Top dead center (firing)

9 ACKNOWLEDGMENTS

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