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Influence of diesel injector arrangement on the ability to ignite methanol in CS21DF-M methanol-fuel

Dual Fuel / Gas / Diesel

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ABSTRACT

Methanol is a green, low-carbon fuel that reduces greenhouse gas emissions and alleviates global energy shortages. Methanol has high latent heat of vaporisation (LHV) and low cetane number (LCN) physicochemical properties, so it needs diesel fuel to ignite when used as an engine fuel. In order to study the influence of the arrangement of diesel injector on the ignition capacity of methanol, this paper investigates the process of diesel ignition of methanol in a 210mm bore methanol-fuelled medium-speed engine by using three-dimensional simulation software AVL-FIRE. The results show that the diesel fuel injector can effectively ignite methanol when it is tilted sideways. The tilt angle is too large, which will lead to the heat load of the cylinder liner, which is not conducive to the stable operation of the engine. The tilt angle is too small, which will make the diesel fuel consumption rise, and reduce the maximum replacement rate that the engine can achieve. When the distance between the diesel injector and the methanol injector nozzle is too small, it will make the interference between diesel and methanol increase, resulting in higher temperatures near the nozzle, and is not good for nitrogen oxides emissions; the distance is too large, the diesel flame and the methanol spray interference with the oil beam becomes less, so there is an optimal value of the two positional relationships.

1 INTRODUCTION

Maritime transportation plays a crucial role in the development of the global economy, with ships accounting for 90% of worldwide goods transportation. However, the significant amount of greenhouse gases emitted by ships is exacerbating environmental pollution, highlighting the urgent need for suitable green and clean alternative fuels. In recent years, methanol and natural gas have emerged as key alternative fuels being researched and promoted for high-power marine internal combustion engines. Among these, methanol stands out as one of the most promising options due to its wide availability, efficient combustion performance, and established production technology, which allows it to be produced on a large scale.

SMDERI initiated a methanol fuel retrofit design project based on the 6CS21 diesel engine and successfully built the 6CS21M methanol engine. The engine adopts two independent injection systems, with methanol as the main fuel and its injector centrally arranged in the center of the cylinder head, and diesel fuel using in-cylinder direct injection to ignite the methanol, with an inclined arrangement of the injector, which can flexibly control the injection volumes and injection timing of both methanol and diesel fuel, and thus achieve a higher methanol substitution rate in a wider range of operating conditions. In the process of engine design, the process of diesel ignition of methanol is studied by simulation. The influence of two parameters, the angle of the methanol nozzle and the angle of the diesel nozzle, on the ability of diesel ignition of methanol, is studied in depth. The above will be introduced in this paper.

2 SIMULATION MODELING AND VALIDATION

In this paper, the simulation study was carried out using FIRE software, the geometric model of the combustion chamber was constructed using PROETM, and the combustion chamber mesh was constructed by importing the combustion chamber profiles into the ESED module in the 3D Computational Fluid Dynamics software AVL-FIRE. The physicochemical properties of methanol and diesel fuel are shown in Table 1. The sub-models used in this study are shown in Table 2. The simulation calculations start from the intake valve closing moment (IVC, intake valve closing timing) to the end of the exhaust valve opening moment (EVO, exhaust valve closing timing). The main parameters of the engine are as Table 3, methanol and ignition diesel are sprayed into the cylinder using different injectors, the positional relationship of the injectors is shown in Fig. 1. The relative position of the spray of the methanol and the diesel fuel is shown in Fig. 2.

Since the mesh size will directly affect the accuracy of the calculation, a mesh sensitivity analysis is conducted before the formal study, and the total number of meshes is 865,000, 260,000, 184,000, 113,000, and 77,000 for the base mesh sizes of 2, 3, 4, 5, and 6 mm, and the length of the calculation time is 863, 2.55, 1.37, 1.04, and 0.69 hours, respectively. The results show that the differences between the cylinder pressure when the base mesh size is 5 mm and 6 mm and other base mesh sizes are more obvious, the base mesh size of 2 mm has a higher computational accuracy but a longer computational time, and considering the computational accuracy and the cost, a base mesh of 3 mm is used in this study.

As shown in Fig. 3, the comparison between the test and simulation values under 100% working conditions with a 75% methanol substitution rate, from the results, the simulated in-cylinder pressure and exothermic rate are in good agreement with the test results, which indicates that the model has good accuracy and credibility. The NOx amount calculated from the simulation is slightly lower than the test data, but the overall trend is consistent with the test, and the error is within the acceptable range.

Table 1. Properties of methanol and diesel fuel

Physical and Chemical Properties	Methanol	Diesel
Density (g/cm)	0.79	0.82-0.86
Flash Point (℃)	11	52
Autoignition Temperature (℃)	470	300-340
Viscosity (mPa-s)	0.59	3.35
Cetane Number	3-5	55
Low Calorific Value (MJ/kg)	19.7	42.5
Latent Heat of Vaporization (MJ/kg)	1.11	0.27
Carbon Content (wt%)	37.5	86
Hydrogen Content (wt%)	12.5	14
Oxygen Content (wt%)	50	0

Table 2. Submodels

Items	Submodels
Turbulence model	RNG κ-ε model
Droplet fragmentation model	KH-RT model
Spray-wall action model	Rebound/slide model
Droplet collision model	NTC collision model

Nitrogen oxide mechanism	Sage model
Turbulence model	Extended Zeldovich NOx

Table 3. Main engine parameters

Items	parameters
Engine Type	inline six-cylinder engine
Rated Power	1320kW@1000r/min

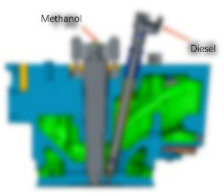

Figure 1. Methanol/diesel injector arrangement

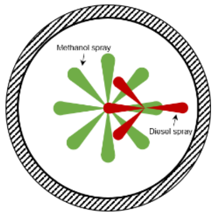

Figure 2. Methanol/diesel spray effect

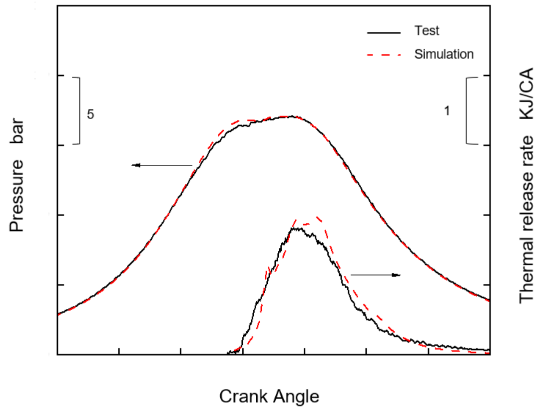

Figure 3. Comparison of in-cylinder pressure and heat release rate between test and simulation

3 ANALYSIS OF THE DIESEL IGNITION PROCESS OF METHANOL

Figure 4 shows the distribution of in-cylinder temperature and NOx under high load. 0°CA ATDC when the diesel fuel has been compression ignition, its flame temperature has reached 1700K~1900K, at this time the methanol fuel has not yet been injected, and the development of diesel fuel spray and combustion process is the same as conventional diesel engine, the distribution of NOx is the same as high-temperature area. At 4 ° CA ATDC can be clearly seen methanol and diesel oil beam in the center of the combustion chamber area of direct interference, the right side of the combustion chamber of the diesel oil beam has not yet been affected by the methanol spray, and the diesel flame temperature of about 1900K, the center of the combustion chamber area of the diesel flame temperature is reduced to 700K or so, the methanol fuel to make a significant drop in the local flame temperature, this is due to the higher latent heat of vaporization of methanol This is due to the higher latent heat of vaporization of methanol. From the NOx distribution, it can be seen that the NOx content in the center region of the combustion chamber decreases significantly at 4°CA ATDC, which is due to the fact that NOx production is strongly dependent on the temperature, and a decrease in temperature will lead to a decrease in the amount of production. Methanol and diesel interference not only affects the NOx generation rate, but also prolongs the stagnation period of diesel in the center region of the combustion chamber, which is driven by the rear injection of diesel spray at 8°CA ATDC, resulting in the front end of diesel to reach the inner wall of the piston pit will be to the sides of the movement, at this time, the diesel on the right side of the combustion chamber has begun to burn violently, and the flame temperature is already as high as 2,800 K. In the center region of the combustion chamber, diesel is driven by methanol vaporization and heat absorption, which leads to a decrease in NOx generation. Diesel fuel in the center of the combustion chamber by methanol vaporization heat absorption has not yet begun to burn vigorously, the temperature is about 1700K, and the distribution of NOx in the cylinder is mainly concentrated in the right side of the combustion chamber in the high-temperature diesel fuel flame area. Figure 5 for 8 ° CA ATDC, 10 ° CA ATDC, 12 ° CA ATDC, 18 ° CA ATDC cylinder methanol concentration distribution, from the figure can be obtained in the left side of the combustion chamber and the right side of the distribution is not symmetrical, the left side of the combustion chamber of the methanol spray through the distance is long, the propagation speed is fast, the rate of consumption is fast, and the right side of the spray through the distance is short, the propagation of the methanol, the rate of consumption is slower and more close to the top of the piston, so that more methanol accumulates at the bottom of the pit on the right side of the piston, this is because of the interference of the diesel oil beam, the development of the right side of the methanol oil beam is hindered, Figure 6 shows the distribution of fuel equivalence ratios at 18 ° CA ATDC, the right side of the combustion chamber of the methanol oil beam and diesel oil interference occurs many times and leads to the fuel equivalence ratio is greater than 4, the left side of the fuel equivalence ratio of the methanol is closer to 1, so the left side of the combustion chamber of methanol is more preceded by the ignition. Therefore, the methanol on the left side of the combustion chamber fires first. From the temperature and NOx variation plots, it can be seen that the methanol at the periphery of the spray is ignited by the diesel fuel at the early stage of the methanol spray development, but up to 10°CA ATDC the inside of the methanol spray is still at 900K and has not yet started to burn. At 10°CA ATDC, the methanol oil beam penetrated the diesel oil beam sprayed to the center of the combustion chamber and collided with the diesel oil beam on the right side of the combustion chamber, and the methanol accumulating at the bottom of the crater lowered the temperature of the diesel flame on the right side of the combustion chamber, which led to a decrease in the NOx concentration at the bottom of the piston crater, and the NOx distribution area was mainly concentrated on the edges of the piston crater, with a very low concentration of NOx in the region traversed by the methanol spray. At 12 ° CA ATDC, the center of the combustion chamber temperature rises rapidly, the diesel fuel in the middle region of the combustion chamber compared with the diesel fuel on the right side of the combustion chamber, the beginning of the moment of intense exothermic delayed 4 ° CA, the center of the regional flame temperature can reach a maximum of 2,700 K, the combustion lasts nearly 10 ° CA, resulting in a large number of NOx generated in the center region of the combustion chamber, by Figure 5 cylinder methanol fuel concentration distribution map It can be seen that there is no methanol fuel in the center of the combustion chamber, so it can be determined that the NOx is generated by diesel combustion. From the temperature distribution diagram at the moment of 20°CA ATDC, it can be seen that the methanol on the left side of the combustion chamber starts to burn before the methanol on the right side, and the methanol flame temperature on the left side of the combustion chamber can reach up to 2500K, and the flame temperature on the left side of the fire bank reaches 2700K due to the relatively large amount of methanol accumulated in the left side of the fire bank, and the methanol and diesel fuel mixture on the right side of the combustion chamber in the bottom of the piston crater simultaneously starts to exothermic, with the temperature up to 2700K, and with the development of combustion, the high temperature region gradually expanding, NOx distribution area is also getting bigger and bigger, from the NOx distribution diagram can be obtained, methanol in the left side of the combustion chamber to produce NOx is very little, in the left side of the fire bank has a small amount of NOx generation, this is because the methanol flame propagation is fast, high-temperature flames in the left side of the combustion chamber of the residual time is short, the fire bank of the higher temperatures and the residual time is a little bit longer, combustion chamber The NOx generated at the bottom of the piston pit on the right side of the combustion chamber is significantly less than that at the fire bank on the right side of the combustion chamber, which indicates that the combustion of methanol and diesel fuel blends generates less NOx than that of pure diesel fuel combustion. During the whole in-cylinder combustion process, the highest combustion temperature of methanol on the right side of the combustion chamber only reached 1900 K. The low-temperature combustion of this part of methanol made the NOx distribution in the right side of the combustion chamber in the whole combustion process to be at a low level.

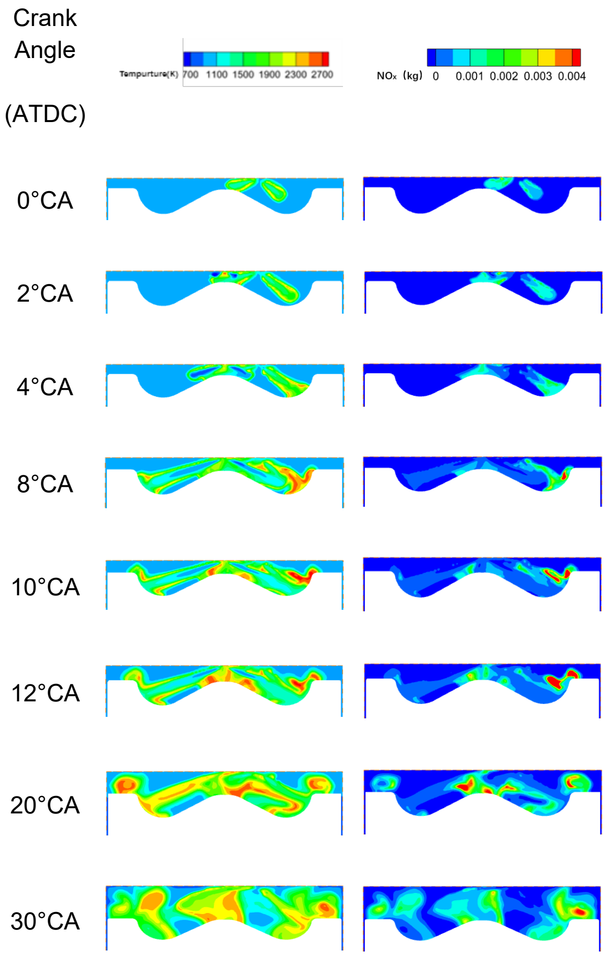

Figure 4. Cylinder temperature and NOx distribution

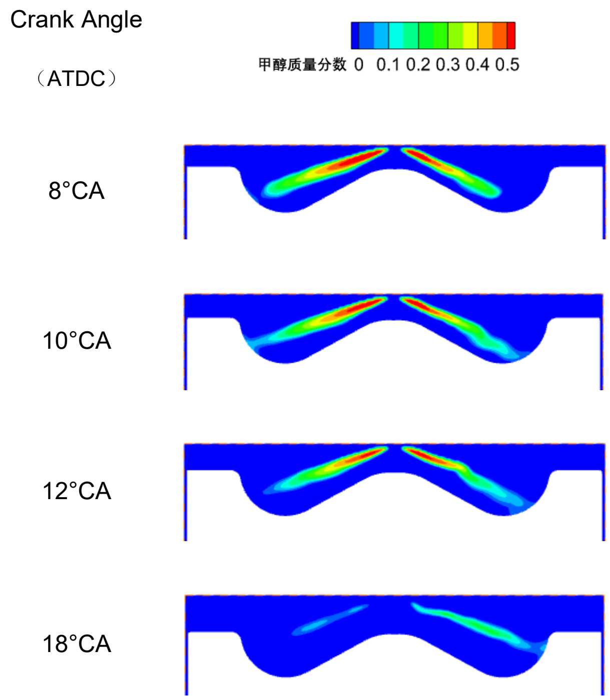

Figure 5. Distribution of methanol mass fraction

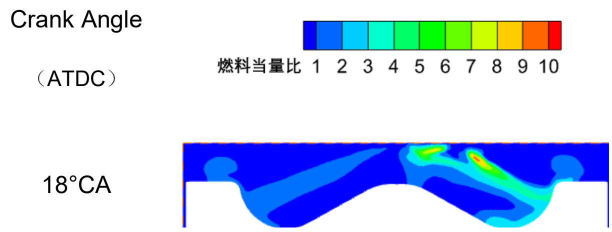

Figure 6. In-cylinder fuel-equivalent ratio distribution

4 INFLUENCE OF NOZZLE ANGLE

4.1 Effect of methanol nozzle angle

Figure 7 shows the temperature distribution at different methanol spray entrapment angles. From the figure, it can be seen that at 3°CA ATDC, when the methanol spray nozzle pinch angle is smaller for 130°-142°, the front end of the methanol spray is not ignited, and when the methanol spray nozzle pinch angle is 146°, at the early stage of the development of the methanol spray, the periphery of the methanol oil beam has been ignited by diesel fuel. The size of the methanol spray nozzle angle directly determines the spatial distribution of the methanol oil beam, and the larger the methanol spray nozzle angle, the stronger the interference with the diesel oil beam, it can be clearly seen in the 9 ° CA ATDC, when the methanol spray nozzle angle is smaller, the methanol oil beam is closer to the bottom of the piston pit, and the right side of the single ignition of the diesel oil beam of the interference effect of the smaller, when the methanol spray nozzle angle is larger, the methanol oil beam and the bottom of the pit diesel oil When the angle of the methanol injection hole is larger, the interference between the methanol oil beam and the diesel oil at the bottom of the pit is obvious, and the temperature of the diesel oil high-temperature combustion zone decreases with the increase of the angle of the methanol injection hole, and the area of the high-temperature combustion zone decreases, which suggests that this part of the diesel oil is reduced by the influence of the high latent heat of vaporization of methanol. This was particularly evident at 18° CA ATDC, where the methanol oil bundle formed a narrow space with the top surface of the piston, which increased with the increase of the methanol nozzle. At 20° CA ATDC, it was found that the larger the methanol spray angle, the more fuel was distributed at the edge of the piston pit and at the fire bank, and the stronger the flame recoil, which adversely affected the cylinder liner heat load.

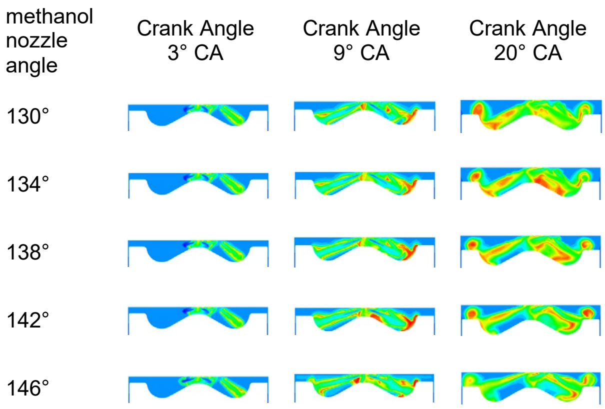

Figure 7. Temperature distribution at different methanol nozzle angles

Figure 8 is the change of equivalent fuel consumption rate with the spray nozzle clamp angle, from the curve it can be clearly seen that with the increase of spray nozzle clamp angle, the equivalent fuel consumption rate gradually decreases. Through the above analysis of the combustion process can be obtained, the larger the methanol spray angle, the wider the spatial distribution of methanol fuel, and the more oxygen can be utilized by the fuel, which makes the combustion more compositional, leading to a reduction in the equivalent fuel consumption rate. However, it is worth noting that the increase in the methanol spray nozzle angle will make the cylinder combustion temperature, Figure 9 intuitively reflect this phenomenon, when the spray angle of 146 °, the cylinder combustion temperature is much higher than the smaller spray nozzle angle of the cylinder combustion temperature, at the same time in the large methanol spray nozzle angle, the edge of the piston pit and the fire bank at the distribution of the more fuel, greatly elevating the cylinder liner heat load, so you can not just raise the Therefore, it is not possible to increase the methanol nozzle angle to reduce the equivalent fuel consumption rate, and it is more appropriate to take 138°-142°.

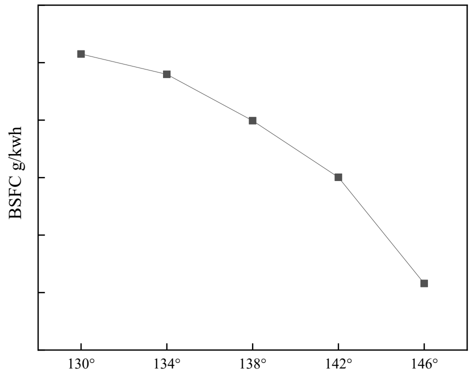

Figure 8. Fuel consumption at different methanol nozzle angles

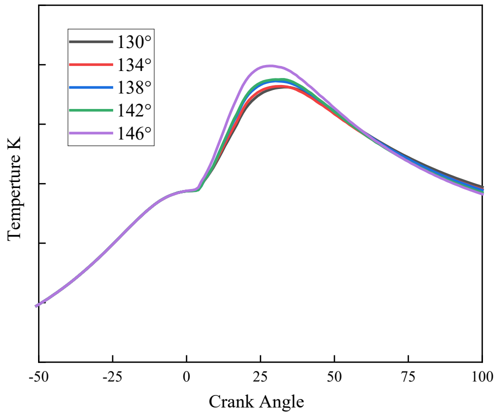

Figure 9. In-cylinder temperatures at different methanol nozzle angles

Figure 10 shows the NOx generation at different methanol spray angles, and from this figure, it can be obtained that the NOx generation increases with the increase of the spray hole angle. In order to further understand the causes and trends of NOx generation, the distribution map of NOx is analyzed in detail, as shown in Fig. 11. From the NOx distribution map, it can be visualized that NOx is mainly distributed at the bottom of the right pit, and with the increase of the methanol spray nozzle angle, the generation of NOx in this region decreases, which indicates that the NOx is mainly generated by the high-temperature combustion of diesel fuel. From the distribution diagram corresponding to 15°CA ATDC, it can be seen that the NOx distribution under 130° and 134° methanol spray angle exhibits the characteristics of less in the center and more at the edge of the pit, while the opposite is true under 142° and 146° spray angle, where the narrow space formed by the methanol spray and the upper top surface of the piston increases with the increase of the spray angle, and this area provides sufficient oxygen for diesel combustion. NOx generation exhibits the characteristics of more center and less crater edge. Due to the larger volume of the space in the narrow region, the NOx is much more than that generated by a single diesel oil bundle on the right side, so the overall pattern of the larger spray angle of methanol spray, the more NOx generation is shown.

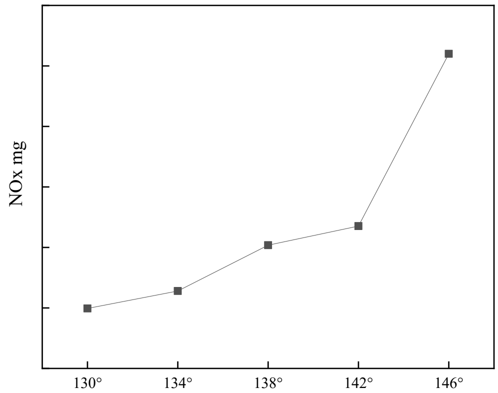

Figure 10. NOx emission at different methanol nozzle angles

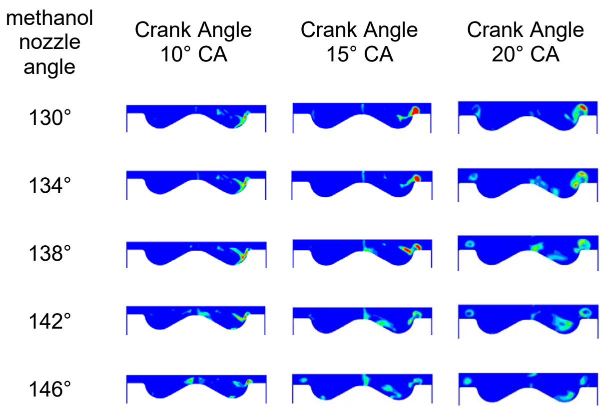

Figure 11. NOx distribution at different methanol nozzle angles

4.2 Effect of diesel nozzle angle

Figures 12 and 13 show the NOx and equivalent fuel consumption rates for different priming diesel spray clamp angles. As the diesel spray angle increases, the generation of NOx increases gradually, and the generation of NOx increases by 11% when the spray angle increases from 116° to 128°. The equivalent fuel consumption rate decreases with the increase of the ignition diesel spray angle, and the fuel consumption rate decreases by 1.3g/kWh when the angle is increased from 116° to 122°, and the fuel consumption level is comparable between the spray angle of 128° and that of 122°. The methanol spray at the spray angle of 116° is far away from the combustion flame, which is not conducive to the complete combustion of the fuel.

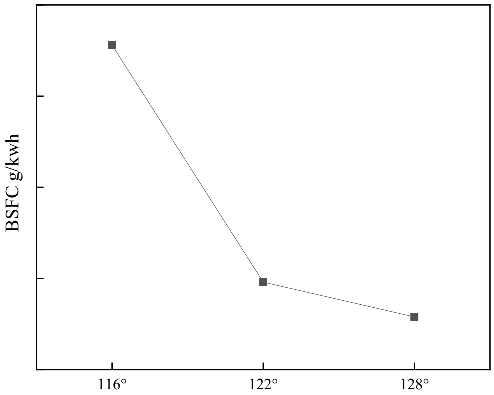

Figure 12. Fuel consumption at different diesel nozzle angles

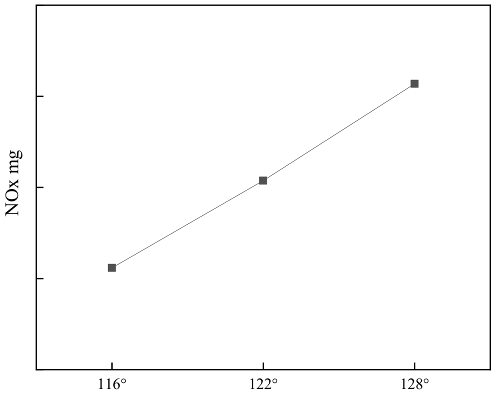

Figure 13. NOx distribution at different diesel nozzle angles

Figure 14 and Figure 15 show the temperature and NOx plots at different spray angles of the ignited diesel fuel. From the temperature at 2°CA ATDC, it can be seen that the spray angle of the ignited diesel fuel affects the effect of the initial diesel flame ignition of methanol, the spray angle of 116° when the diesel flame in the center of the combustion chamber can not be completely wrapped around the methanol oil beam when the angle is expanded to 128° when the ignition effect is better. The larger the ignition diesel spray angle, the smaller the degree of interference between the single diesel beam and the methanol oil beam on the right side, the high-temperature region of the diesel flame at the edge of the pit on the right side of the 10 ° CA ATDC increases as the degree of interference decreases, resulting in the production of more NOx in this region. Due to the fixed spray angle of methanol, the size of the slit space formed by the methanol spray and the piston top did not change, and the change in the angle of the diesel spray did not lead to a change in the NOx distribution in the slit area. The increase in the angle of diesel spray mainly leads to more NOx distribution at the right pit edge and fire bank, and the NOx generation increases with the increase in the angle of diesel spray for ignition.

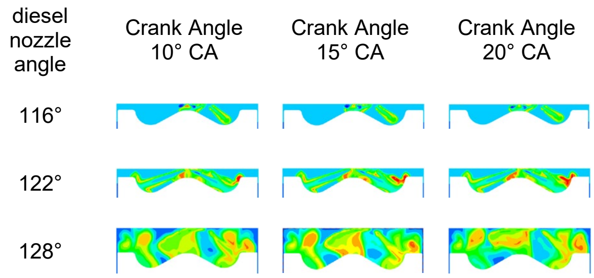

Figure 14. Temperature distribution at different methanol nozzle angles

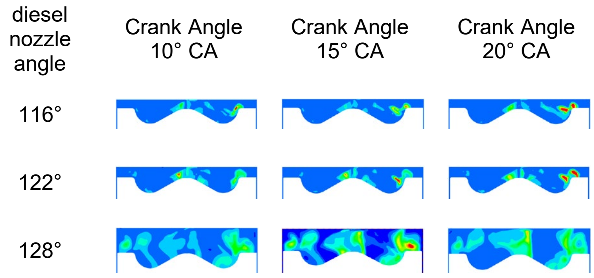

Figure 15. NOx distribution at different methanol nozzle angles

Figure 16 shows the temperatures in the cylinder under different spray angles of ignition diesel. Increase the spray angle of the ignition diesel fuel, the maximum combustion temperature in the cylinder slightly increased, 116 ° ignition diesel fuel spray angle of the highest temperature in the cylinder for 1388K, the ignition diesel fuel spray angle of 122 ° and 128 ° spray angle of the highest temperature in the cylinder is similar to that of about 1400K. The slight change in the in-cylinder temperature is mainly caused by the single ignition diesel fuel on the right side of the combustion chamber.

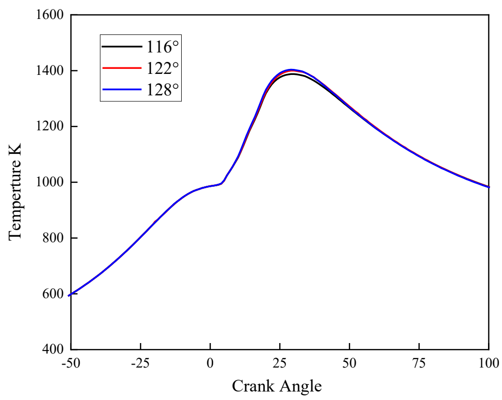

Figure 16. In-cylinder temperatures at different diesel nozzle angles

5 CONCLUSIONS

(1) The NOx generated by methanol combustion is much lower than that of diesel fuel, and the NOx generation in the engine cylinder shows obvious partitioning characteristics, with most of the NOx generated by diesel fuel in the centre of the combustion chamber near the top of the piston area.

(2) The methanol nozzle angle determines the spatial distribution of methanol fuel, increasing the methanol nozzle angle can reduce fuel consumption, but adversely affects the heat load of the cylinder liner.The increase of the methanol injection angle makes the methanol in the combustion can make full use of the oxygen in the combustion chamber, making NOx rise.

(3) The increase of diesel fuel spray hole angle mainly leads to more NOx distribution at the right pit edge and fire bank, and the generation of nitrogen oxides rises with the increase of ignition diesel fuel spray angle.The effect of diesel spray air entrainment angle on combustion is relatively small.

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