喷油角度对船用低速机燃烧性能与排放的影响
A Study of Injection Directions on Improvement of Engine Performance and NOx Emission in A Low-speed Marine Engine

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摘 要：本文利用三维仿真软件 CONVERGE 建立了低速二冲程船机的计算模型，以此研究喷油角度对整机燃油消耗率和排放的影响。该研究旨在分别探究喷油角度在水平、竖直方向上变化对整机产生的影响。由计算结果可得，喷油角度在任一方向上变化时，整机油耗与 NO_x 排放都会出现“TRADE-OFF”关系。最终，8°和-16°被认为是水平和竖直方向上的最优喷射角度，并能够在以增加极少油耗为代价的前提下达到更低的 NO_x 排放。
关键字：喷油角度、CFD、低速机、NO_x

Abstract: A computational fluid dynamics (CFD) simulation model for a two-stroke low-speed marine engine has been established in CONVERGE software, to study the impact of different injection directions on fuel consumption and emissions of the engine. The goal of this research was to investigate injection angles in horizontal and vertical directions respectively. According to the simulation results, “trade-off” relationship was found in both directions between fuel consumption and NOx emission. Based on these results, 8 °and -16 °were considered as optimal injection angles in horizontal and vertical directions. With the optimized injection angles, lower NOx emission can be achieved with a little penalty on fuel consumption.
Key words: Injection angle CFD Low-speed engine NOx

0 Introduction

As the global energy crisis intensifies and the marine emission regulations become increasingly stringent [1,2], it is particularly important to reduce the fuel consumption rate and emissions of marine engines. Diesel engines are used as marine engines all the time in terms of good fuel consumption performance. However, compared with the diesel engines on land, the excess air in the cylinder and combustion temperature of low-speed marine diesel engines are much higher, which provides sufficient conditions for NOx formation [3].

In this case, many ships are equipped with after-treatment equipment to reduce NOx and other emissions from engines. However, the equipment is complex in structure and large in quality and volume, and the investment is huge [4]. Therefore, it is preferred to improve the in-cylinder combustion process to reduce emissions. Exhaust Gas Recirculation (EGR) is an effective way to reduce NOx, which can lower the combustion temperature and reduce the oxygen concentration in cylinder. At the same time, it will also cause the reduction of combustion heat efficiency [5-7].

Some studies have shown that fuel injection directions can affect the mixing process of fuel and air in cylinder, so that it plays an important role in the generation of emissions and combustion [8-11]. Many researchers have tried to optimize fuel economy and NOx emissions by using appropriate fuel injection directions. Zhou et al. used a CFD calculation model to investigate the impact of the injection angles on the low-speed diesel engine. It was found that, the fuel consumption rate decreased with the decrease of the horizontal angle between the two injectors, but it would be worse if the angle is too small, which caused sprays interfering with each other [12]. Vanegas et al. investigated the influence of the spray angle under different injection times in a common-rail DI diesel engine. The results showed that a smaller injection angle allowed for lower NOx emissions, while at the same time achieving a lower fuel consumption with appropriate injection times [13]. Lechner et al. found that narrow spray cone angle can provide an opportunity to achieve simultaneous reductions in NOx and PM, with minor penalties in fuel economy. The engine with a low flow rate, 60-degree spray cone angle injector nozzle and optimized EGR rate was realized to reduce NOx by 82% at the expense of a modest increase (4.5%) in fuel consumption [14].

Due to the high experimental cost and complicated test process of the two-stroke low-speed diesel marine engine, a calculation model was established based on the marine test engine parameters. And in order to investigate the effect of injection directions in multiple dimensions, not only horizontal direction, but also vertical direction was explored. Then the influence on fuel consumption and emissions of the engine was found to achieve optimization.

1 Calculation Model

A one-cylinder calculation model is established in CONVERGE 2.3 software [15], based on a 6-cylinder, two-stroke low-speed marine test engine. The specific structural parameters of it are shown in Table 1. In addition, the rail pressure is 738 bar and SOI timing is 360.2 CAD. Two injectors are arranged symmetrically on the cylinder head. The geometric structure of the three-dimensional model is shown in Figure 1, which consists of three parts: scavenge box, cylinder and exhaust port.

Table 1 - Test engine specifications.

Bore(mm)	340
Stroke(mm)	1550
connecting rod length(mm)	1550
cylinder number	6
Injector number	2
nozzle number	2*4
compression ratio	21
Speed(r/min)	142.5
Power(kW)	3672

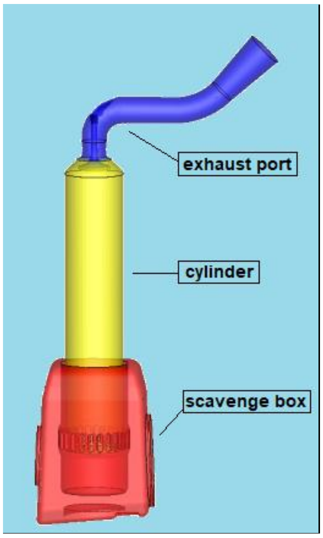

Figure.1 - The three-dimensional geometric structure of the model.

The initial inlet temperature and initial pressure of the model are set to 310.6K and 424600Pa. The temperature of the cylinder wall, cylinder head surface and scavenge box surface are set to 498K, 823K and 310.6K respectively. Besides, the exhaust zone boundary temperature and pressure are set to 616K and 404600Pa.

The base grid size of the computational model is set to 20mm, and Automatic Mesh Refinement (AMR) is used in CONVERGE software. In order to ensure the calculation accuracy, spray area is set to be intensive at level 2 and combustion area is set to level 1.

Table 2 - Sub-models used in calculation.

Turbulence	RANS k-ε
Spray breakup	KH-RT model
Collision	NTC model
Drop drag	O'Rourke model
Combustion	CTC/SHELL
NOx	Extended Zeldovich mechanism

The sub-models used in the study are listed in Table 2. Among these, the RANS k-ε sub-model [16] was used as turbulence model in this project. The Kelvin-Helmholtz and Rayleigh-Taylor sub-model [17] was chosen to calculate spray droplet breakup, and NTC model [18] was employed to simulate the collision of droplets. The initial spray temperature is set to 295 K, besides the fuel injection duration and injection timing are set to 17 CAD and 360.2 CAD. In order to predict the combustion and ignition of the diesel engine better, CTC/SHELL sub-model [19] was used in the project. In the existing research, $C_{14}H_{30}$ has been proven to be an alternative fuel for diesel in low-speed marine engines [20], so that the model used n-tetradecane as fuel. In this work, the simulated working speed is 142.5 r/min, and the circulating fuel injection amount is 12.86 g, which is equivalent to 75% load working condition at this speed.

1.1 Model Validation

In order to verify the reliability of the calculation model, figure 2 compares the calculated in-cylinder relative pressure curve with the experimental results under the 75% load which is the common working condition for low-speed engines. Among them, the experimental data was obtained from cooperation company. Figure 3 shows the error rate between the calculation results and experimental results, in terms of power (P), maximum compression pressure (Max Com.p), indicated specific fuel consumption (ISFC), maximum burst pressure (Max Cyl.p) and NOx emission. The error rates are calculated by the equation:

$$\frac{|\text{Simulation}-\text{Experiment}|}{\text{Experiment}} * 100\% \tag{1}$$

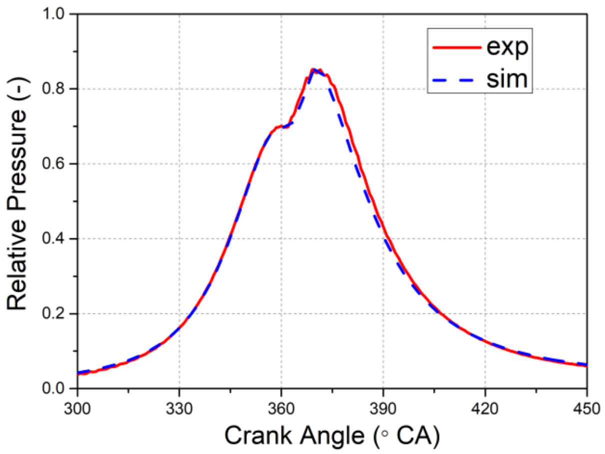

Figure.2 - The comparison of experimental and simulated in-cylinder pressure data.

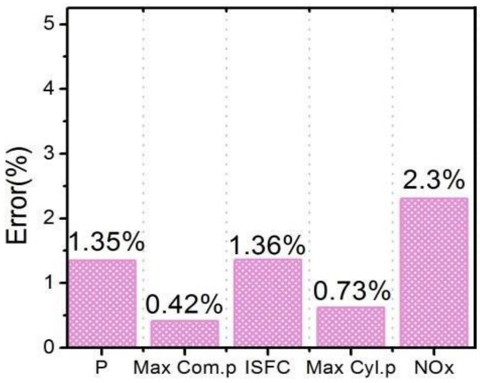

Figure.3 - The error rate between experimental and simulated results.

It can be seen that, the simulated in-cylinder pressure curve is highly consistent with the experimental results, and the error rates of the maximum compression pressure (Max Com.p) and the maximum burst pressure (Max Cyl.p) are only 0.42% and 0.73%. In terms of overall engine performance, the error rates of engine power (P) and indicator specific fuel consumption (ISFC) are 1.35% and 1.36%, both within the error tolerance. In emissions performance, the NOx emission error rate is 2.3%, which is acceptable [21]. So that the model is reliable for the calculation of NOx emission.

The above results show that, the calculation model can predict the combustion and emissions performance of the marine test engine well, and it can be used to further improve the performance of the two-stroke low-speed marine engine. In this research, when the injection angles θ_1 and θ_2 in horizontal and vertical directions change, the influence of the low-speed diesel engine at 75% load is investigated. The direction of the eddy current is considered as the positive direction of θ_1, which changes from -13 ° to 18 °, and the direction perpendicular to the cylinder head upward is set as the positive direction of θ_2, which changes from -31 °to 8 °, as shown in Fig. 4.

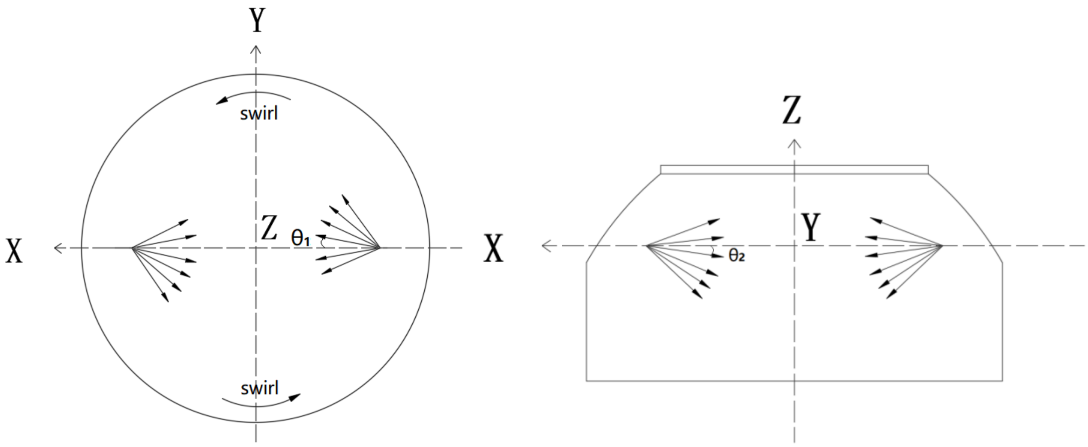

Fig. 4 - Injection angles arrangement.

2 Results and discussion

2.1 Arrangement of injection direction in horizontal direction

The two-stroke diesel engine has strong eddy current intensity during the scavenging process, so it’s important to match the fuel injection direction with the eddy direction in the cylinder. When they are matched well, the process of fuel evaporation, breakup, mixing and ignition can be promoted. In this section, the injection angle in the vertical direction is kept at -26 °, which is the parameter of the origin engine.In the case, the effects of the low-speed engine on combustion and emissions are investigated by changing the injection angle θ_1 of the double injectors in the horizontal direction.

Figure 5 shows the effects of the horizontal injection angle θ_1 on the in-cylinder pressure and heat release rate of the low-speed engine. As can be seen from the figure, when the injection angle θ_1 is 3°, the horizontal angle between the two injectors is the smallest in 6 conditions, and the peak value of the in-cylinder pressure and the heat release rate is the highest, that is, the combustion performance in the cylinder is the best. As θ_1 increases in both positive and negative directions, that is to say the horizontal angle between the two injectors increases. In that condition, the peak value of in-cylinder pressure and heat release rate continuously decrease, indicating that smaller horizontal angle between the two injectors is beneficial to in-cylinder combustion. The phenomenon may be caused by that, as the horizontal injection angle θ_1 increases in the positive direction, the fuel will contact the cylinder wall earlier. In this case, more fuel will adhere to the cylinder wall, which causes a poor mixing with air and the combustion will be worse as well.

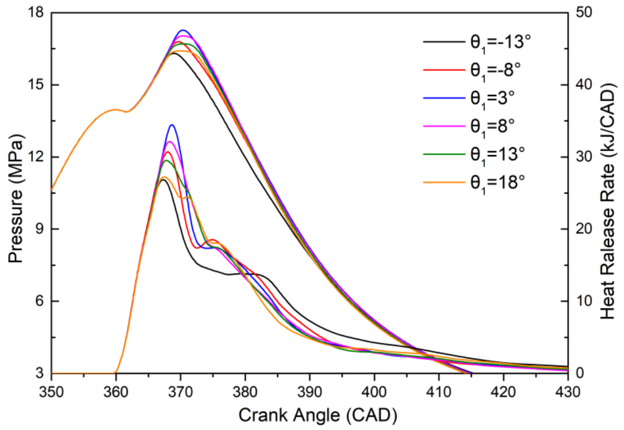

Figure.5 - Effects of injection angle θ_1 on in-cylinder pressure and heat release.

It can be observed that, the positive and negative angles which have same absolute value (such as 8°and -8°, 13°and -13°) don't have equal peak values of in-cylinder pressure and heat release rate, and the peak value of positive direction angle is larger than the negative angle's. This shows that although the installation positions of the two injectors are symmetrical in the structure, due to the influence of the eddy in the cylinder, the fuel injection along the direction of the eddy is more favorable for the combustion, and the performance is better than the case which has opposite injection direction.

The distribution of equivalence ratio in the cylinder at different horizontal injection angles are shown in figure 6. As can be seen from the figure, the eddy current plays an extremely important role for the distribution of the gas mixture in the cylinder. When the injection angle is negative, the fuel spray changes direction under the influence of the eddy current and moves in the direction of the eddy current. It can be seen from the distribution at 366 CAD that, the case (θ_1 = -13°) has larger angle in the negative direction, which is more different from the eddy current direction, resulting in the spacing between the two fuel sprays more narrow than case (θ_1 = -8°) under this condition. At 370 CAD, it can be seen that the larger the positive direction angle is, the more the gas mixture is in contact with the cylinder wall earlier. At 374 CAD, due to the conflict between the injection velocity of the negative direction and the eddy current velocity, the distribution of the gas mixture in the cylinder is not homogeneous, mainly concentrated in the center. In comparison, the positive angle injection can make the gas mixture distribution more homogeneous.

Figures 7 and 8 show the distribution of temperature and NOx emission in the cylinder at different horizontal injection angles. In the negative injection direction, the heterogeneous distribution of the gas mixture caused by the increase of injection angle limits the increase of the combustion temperature in cylinder, thereby suppressing the generation of NOx. In the positive injection direction, it can be seen that at 374 CAD, as the angle increases, the area of the red region decreases, that is, the NOx emission in the cylinder decreases. From the comparison of the above figures, it can be found that NOx emission is mainly produced in the region where the temperature is high and the gas mixture is evenly distributed.

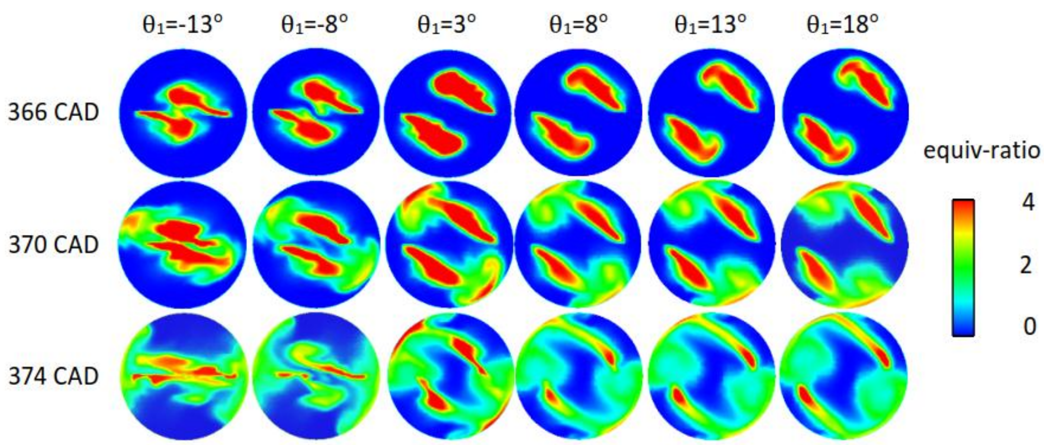

Figure.6 - The distribution of equivalence ratio in the cylinder at different θ_1.

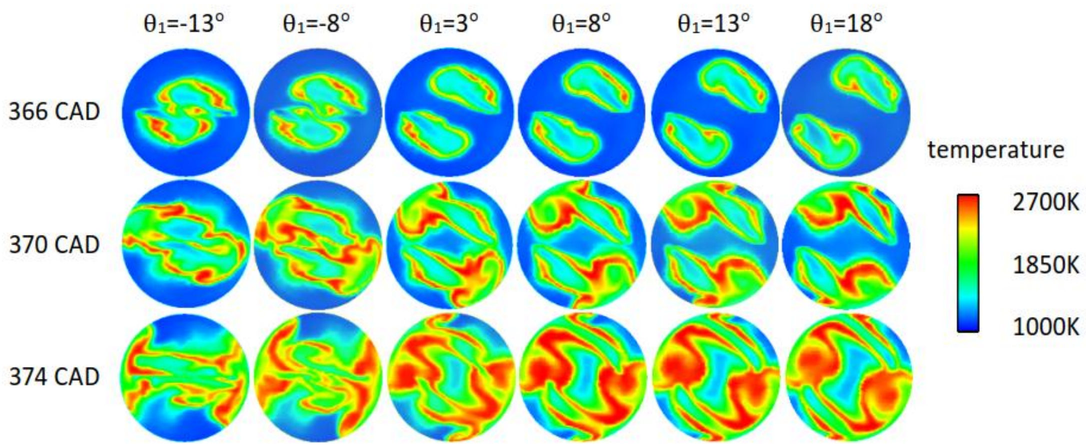

Figure.7 - The distribution of temperature in the cylinder at different θ_1.

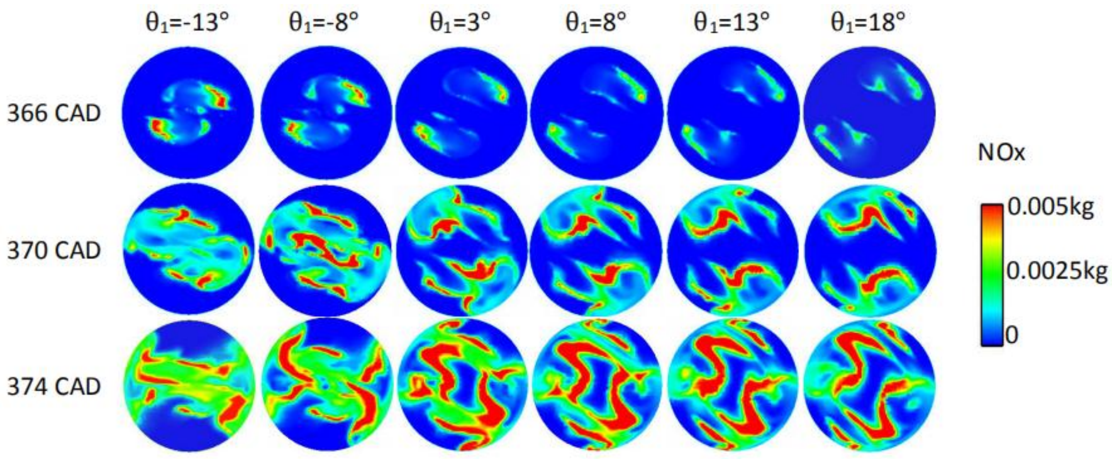

Figure.8 - The distribution of NOx emission in the cylinder at different θ_1.

Figure 9 illustrates the performance of the indicated specific fuel consumption (ISFC) and NOx emission with different horizontal injection angles θ_1. It can be seen that, the NOx emission increases as the absolute value of the horizontal injection angle decreases. And it indicates that the closer the two injectors are in the horizontal direction, the more favorable the in-cylinder combustion is. This is in accordance with the previous analysis of the in-cylinder pressure and the heat release rate. When the angle between the two injectors is large, it is easy to cause the fuel injection to hit the wall, deteriorating the fuel atomization and breakup condition, which is not conducive to sufficient combustion, and thus the fuel consumption increases. In this case, the in-cylinder combustion temperature is lowered, and the NOx emission is lowered, showing a "trade-off" relationship with the fuel consumption.

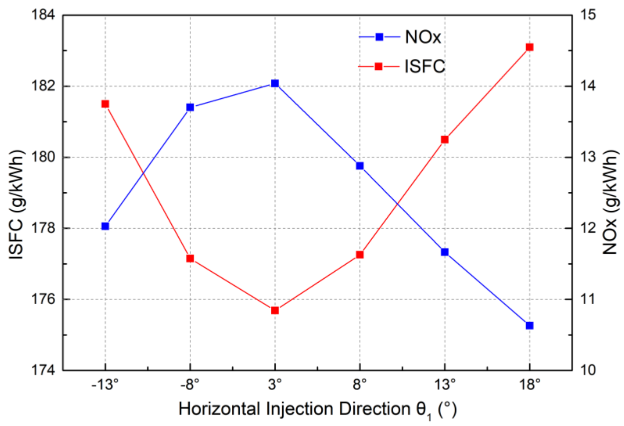

Figure.9 - ISFC and NOx emission of different injection angles θ_1.

It can be found that the engine performance of the two horizontal injection angles with the same size is different. Compared with the negative injection direction, the positive injection can reduce NOx emission without penalty of fuel consumption, and the "trade-off" relationship is improved to some extent, which also confirms the above statement. So that lower NOx emission can be attained with larger θ_1 in positive direction, but it also will cause rapid rise on fuel consumption. It's important to consider the relationship between fuel consumption and NOx emission to achieve a relative optimum.

2.2 Arrangement of injection direction in vertical direction

In the above six cases, 8°can be considered as the optimal horizontal injection angle parameter of the test marine engine, and as a control parameter in the study of the vertical injection angle θ_2 below.

Figure 10 shows the changes of in-cylinder pressure and heat release rate at different injection angles θ_2 in the vertical direction. As can be seen from the figure, when the vertical injection angle θ_2 at -31°, that is, when the angle with the cylinder axis is the smallest in the 6 cases, the peak value of in-cylinder pressure and heat release rate is the highest. This may be related to the reason that this injection angle makes the combustible gas mixture more homogeneous and therefore the combustion is more intense. At the case (θ_2 = -26°), the peak value of in-cylinder pressure and heat release rate decreases, and the after-burning phenomenon is serious. The heat release rate curve shows a "double peak" phenomenon, which may be due to the heterogeneous mixing of fuel and air, causing too much fuel to not burn quickly in the initial stage, thus forming a second heat release rate peak. At the case (θ_2 = -21°), the after-burning phenomenon is improved, and the "double peak" phenomenon disappears, but the peak phase of heat release rate is delayed. These abnormal combustion phenomena should be caused by the mismatch between the injection angle and the eddy current direction. The value of injection angle continues to decrease (θ_2 = -16°) and the combustion performance becomes normal. When the injection angle is positive, the in-cylinder pressure and heat release rate are both low. This is because the positive angle injection is easy to make the fuel contact with the cylinder head, causing poor atomization and breakup, therefore the temperature of mixture is lowered.

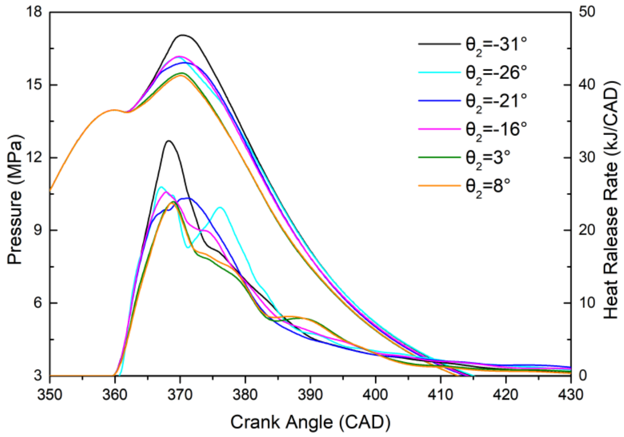

Figure.10 - Effects of injection angle θ_2 on in-cylinder pressure and heat release.

Figure 11 shows the distribution of the equivalence ratio in cylinder at different vertical injection angles. When the injection angle is positive, the yellow and green areas are mainly concentrated in the upper half of the cylinder at 372 CAD, that is, more fuel is concentrated in the upper part of the cylinder. This caused the gas mixture to remain heterogeneous. From the 390 CAD chart, it can be seen that the fuel is still mainly concentrated in the upper and middle regions of the cylinder, which is not conducive to the entire combustion process. When θ_2 = -31°, there are almost no yellow and green regions in the cylinder, which means that the gas mixture can be evenly distributed in the cylinder faster. At the case (θ_2 = -26°), there is still much gas mixture in the late stage of combustion, indicating that the after-burning condition is more serious at this condition. At the case (θ_2 = -16°), although the injection angle is downward, the in-cylinder gas mixture is mainly distributed in the upper part under the influence of the eddy current, and the gas mixture is more in contact with the cylinder wall and unevenly distributed, so that the combustion temperature in the cylinder is lowered. And in the late combustion stage, the distribution of gas mixture in the cylinder is obviously better than that in the positive direction, indicating that the in-cylinder combustion is superior.

The distribution of in-cylinder temperature and NOx emission at different vertical injection angles are shown in figures 12 and 13. It can be clearly seen in the figure that NOx is mainly generated in a high temperature region, and the high temperature region is mainly located in the stoichiometric ratio area. From the above analysis of the equivalence ratio, it can be found that when θ_2 = -16°, the in-cylinder temperature is relatively low, and NOx emission generation is also small, which is uniform. When θ_2 = -31°, the homogeneous gas mixture in cylinder makes the high temperature region larger, and more NOx emission is generated. In the later stage of combustion at the case (θ_2 = -26°), there is still a large area of high temperature in the cylinder, which confirms the analysis of that after-burning is serious. However, when the vertical injection angle is positive, the combustion temperature and NOx emission in the cylinder are significantly lower.

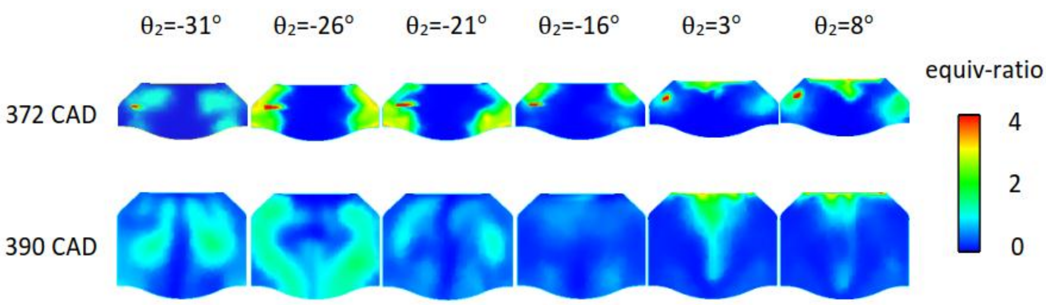

Figure.11 - The distribution of equivalence ratio in the cylinder at different θ_2.

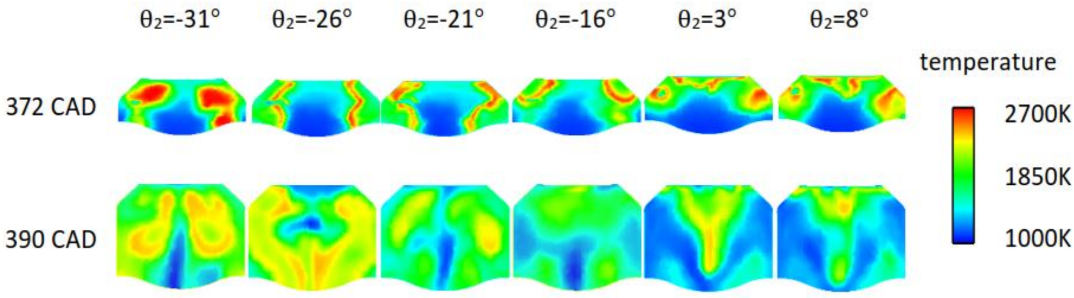

Figure.12 - The distribution of temperature in the cylinder at different θ_2.

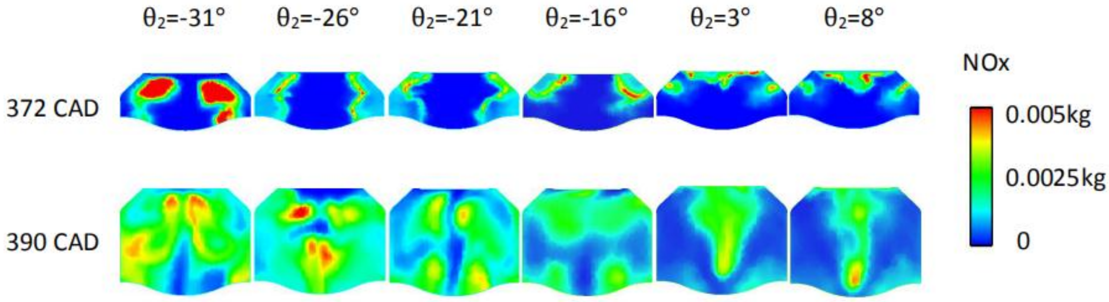

Figure.13 - The distribution of NOx emission in the cylinder at different θ_2.

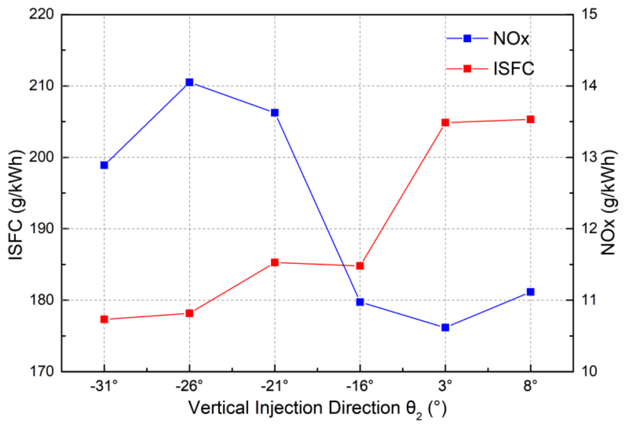

Figure.14 - ISFC and NOx emission of different injection angles θ_2.

Figure 14 illustrates the effect of different vertical injection angles θ_2 on fuel economy and NOx emission. It can be seen that, with a change from a negative angle ($\theta_2 = -31°$) to a positive angle ($\theta_2 = 8°$), the fuel consumption rate increases continuously. Especially when the angle θ_2 changes from -16° to 3°, the fuel consumption rate increases obviously, which should be caused by a positive angle of fuel injection against the cylinder head and heterogeneous gas mixture. However, the overall NOx emission showed a downward trend. When the angle θ_2 changes from -31° to -26°, the NOx emission increases because the afterburning is severe at the case ($\theta_2 = -26°$), and NOx emission continues to be generated in this process. In particular, NOx emission is significantly reduced at -21° to -16°, with a small change in fuel consumption rate. Combined with the above analysis of the heat release rate, this phenomenon is due to the reduction of the total heat release after the improvement of the after-burning (it can be seen from the heat release rate area of Fig. 10), which reduces the combustion temperature in the cylinder and effectively suppresses the generation of NOx emission. Compared with other working conditions, the case ($\theta_2 = -16°$) operating condition achieves a good result in terms of NOx emission with a little fuel economic sacrifice, so -16° is considered to be a superior vertical injection angle.

Combined with the investigation of the horizontal injection angle θ_1 and the vertical injection angle θ_2, the optimal injection angle at the calculation conditions can be obtained: ($\theta_1 = 8°$, $\theta_2 = -16°$). Especially, when compared with the condition ($\theta_1 = 8°$, $\theta_2 = -21°$), the optimal condition remains almost a same ISFC, however reduces NOx emission by 19.45%.

3 Conclusion

A simulation was studied to explore the effects of injection directions, so as to obtain optimal parameters and some guidance for engine development. Based on the study, some findings are as follows:

1. In the horizontal direction, when the angle between two injectors is relatively compact, the in-cylinder combustion can be promoted, and the peak values of in-cylinder pressure and heat release rate are high. When the injection angle is large, the temperature of the mixture is lowered due to the early impact of the fuel on the cylinder wall, and the heat release rate is lowered. Moreover, the injection at two symmetrical angles in the positive and negative directions makes different effects on combustion because of the action of eddy currents.

2. In the vertical direction, the closer the injection angle is to the cylinder axis downward, the more intense the in-cylinder combustion is. In particular, the “double peak” phenomenon of the heat release rate occurs at the case ($\theta_2 = -26°$), and the after-burning condition occurs at the case ($\theta_2 = -21°$), which are both caused by different breakup and mixing effects of different fuel injection angles in the eddy. When θ_2 is a positive angle, the peak value of in-cylinder pressure and heat release rate is lower than the conditions with negative angles.

3. According to the research results, $\theta_1 = 8°$ and $\theta_2 = -16°$ are considered as the optimized fuel injection parameters for the test marine engine. In that case, lower NOx emission can be achieved with a little influence on fuel consumption.

Arrangements

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