HK.NCCP International Journal of Intelligent Information and Management Science
ISSN: 2307-0692, Volume 7, Issue 4, August, 2018

Simulation Analysis on 475 Diesel Engine Performances of Injection Characteristics

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Abstract: In order to study the influence of different fuel injection laws on the combustion process of 475 diesel engine. CFD software Fire was used to simulate and analyze the combustion process under the three injection Characteristics. The combustion simulation model was established and the accuracy of the model was verified. The effects of different injection laws on pressure, temperature, heat release and emission were simulated. The results show that the diesel engine had good power and economy performance under the rule of triangular injection. Because the delayed combustion period was too long, there were more mixed gases in the initial combustion, which leads to higher pressure ratio, rough work, more NOx and CO emissions, less carbon emissions in the initial combustion. The temperature and pressure in the cylinder were lower, the cumulative heat release was less, and the carbon smoke emission was more under rectangular fuel injection pattern. The diesel engine performance of trapezoidal injection was in the middle.

Keywords: Diesel engine; Injection law; Simulation analysis; Combustion

1. Introduction

The fuel injection law curve can directly show the change of fuel injection rate with crankshaft angle, which has a great influence on the performance of diesel engine[1].The effect of fuel injection on diesel performance was studied, the performance can be optimized by analyzing the fuel gas mixture and combustion process of diesel engine.

Many scholars had studied the influence of fuel injection on engine in bench test[2-5]. The combustion performance of diesel engine was studied and analyzed in different injection angles, transient flow characteristics and injection hole pressure. In view of the long cycle and heavy workload of engine bench test, some scholars had also used the method of simulation analysis to study the influence of different fuel injection laws on diesel engines. Guo C et al.[6]used CDF to simulate his experiment to study the influence of fuel injection characteristics on the free-piston diesel linear generator(FPDLG).Four injection rate curves of rectangle, wedge, trapezoid and triangle were simulated and compared.Finally, the trapezoidal injection had high engine efficiency. Wu X et al. [7] established a gas-liquid two-phase three-dimensional cavitation flow model to study the relative difference of injection rate in the orifice of the perforated diesel nozzle, which has an important impact on the combustion and emission characteristics of the diesel engine.Some scholars [8-10] also simulated and studied the influence of the related structural parameters of the nozzle on the internal flow characteristics of the nozzle. Such as spray nozzle diameter and length (hole length to diameter ratio), entrance radius, the nozzle spray and spray hole taper hole angle.

In order to optimize the combustion process of diesel engine and reduce fuel consumption and emission, the simulation model of 475 diesel engine was established use AVL FIRE. The combustion and emission characteristics of diesel engines under different fuel injection laws were studied. It can guide the optimization and upgrading of 475 diesel engine.

2. Engine Parameters and Model Establishment

2.1. Diesel engine parameters

The main technical parameters of 475 diesel engines are shown in Table 1.

Table 1. Main Technical Parameters of 475 Dieselengines

model	**475**
type	**Straight, water - cooled, four - stroke**
Combustion chamber type	Direct injection
cylinder diameter (mm)	75
stroke (mm)	85
Cylinder liner type	dry liner
piston volume (L)	1.502
Compression ratio	18
Rated power/speed (kW/r/min)	24/3200
Maximum torque (N·m)	≥85.6
Minimum fuel consumption at full load (g/kWh)	≤255
oil consumption rate at the operating condition (g/kWh)	≤2.72

2.2. Selection of computational model

2.2.1. The spray model

The FIRE software uses WAVE discrete model to describe the spray crushing process, and considering the connection between the spray droplets and the structural parameters of the injector, it is suitable for the crushing process of the jet surface.

2.2.2. Combustion model

The combustion of internal combustion engine can be regarded as turbulent combustion process, such as flame propagation, stretching and extinguishing. The commonly used combustion models were Turbulence controlled combustion model, which was proposed by Magnussen et al.

2.2.3. NOx emission model

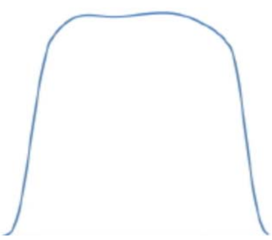
When the actual air-fuel ratio of internal combustion engine is close to the theoretical air-fuel ratio, NOx emission is applicable to the Extended Zeldovich model. NOx is produced at high temperature and oxygen-rich condition, so temperature and oxygen concentration influence NOx emission. This model calculates NOx production according to the measurement of these two parameters. The production of NOx was calculated according to these two parameters of the model.

2.2.4. The smoke model

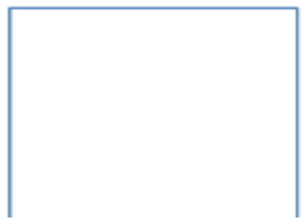
We should not only consider the NOx emissions of diesel engine, more need to consider the generation of smoke carbon (Soot).Carbon smoke was caused by incomplete combustion of fuel, which was affected by many factors, such as fuel quality and fuel atomization quality, and will form solid particles harmful to human health. Kinetic Model is usually selected for carbon smoke Model.

2.3. Fuel injection regulation setting

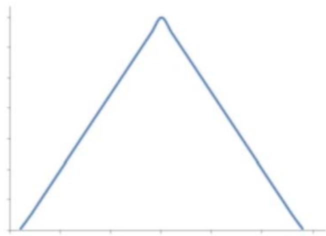
In this paper, the effects of three fuel injection regular curves (trapezoid, rectangle and triangle) on the performance of 475 diesel engines were studied. The curves of the three oil injection patterns are shown in figure 2.For convenience, the trapezoidal oil injection rule is denoted as a, the rectangular oil injection rule is denoted as b, and the triangular oil injection rule is denoted as c. Injection time is from 712 ° CA to 732 ° CA. Total fuel injection quantity is 3.23 mg.



(a) trapezoidal



(b) rectangular



(c) triangle

Figure 1. Three types of fuel injection regular curve

2.4. Model building

The related parameters of the injector were set in Sketcher. Injector fuel injection hole number is 5, spray hole diameter is 0.2 mm, spray hole diameter is 0, the outer taper Angle of nozzle hole is 8 °, the cone Angle is 0, the spray Angle is 152 °.As shown in figure 2.

The model mainly simulates the spray and combustion process, so the calculation is carried out in the interval between the inlet valve closing and the exhaust valve opening. FAME and FAME Engine, the grid division tools of the FIRE, are used to build and divide the grid. After gridding, the two-dimensional dynamic grid is exported, as shown in Figure 3.

3. Validation of Engine Model

In this paper, the condition was simulated, that engine speed is 3200r /min and 75% load. Every 0.2 ° crank Angle as the calculating step length in the process of calculating. The temperature at the piston is set to 583K.The temperature at the cylinder wall is 413K.The temperature at the top of combustion chamber is 553K.Other parameters were set as follows: pressure was 1 atmosphere, temperature was 363K, turbulence kinetic energy was $30.8m^2/s^2$, turbulence length was 0.0045m, and turbulence diffusion rate was $6241.59m^2/s^3$.

In order to ensure the accuracy of the established calculation model, the calculated cylinder pressure curve was compared with the actual bench pressure curve, as shown in figure 4.It can be seen from the figure that the pressure curve of the simulated calculation is basically consistent with the measured curve, which can effectively guarantee the accuracy of the simulated calculation.

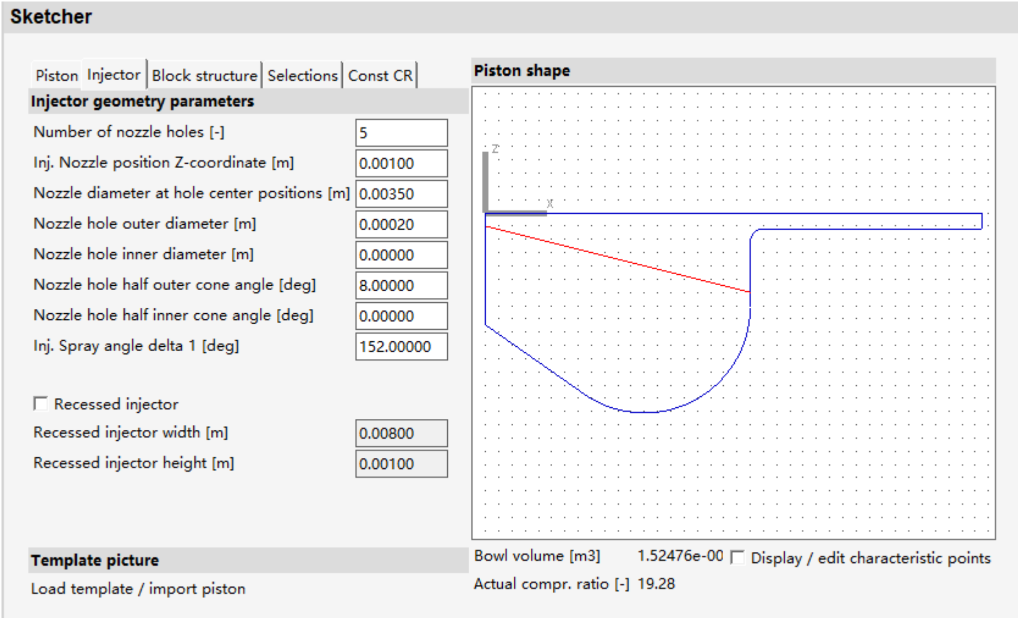


Figure 2. Basic structure parameter setting of fuel injector

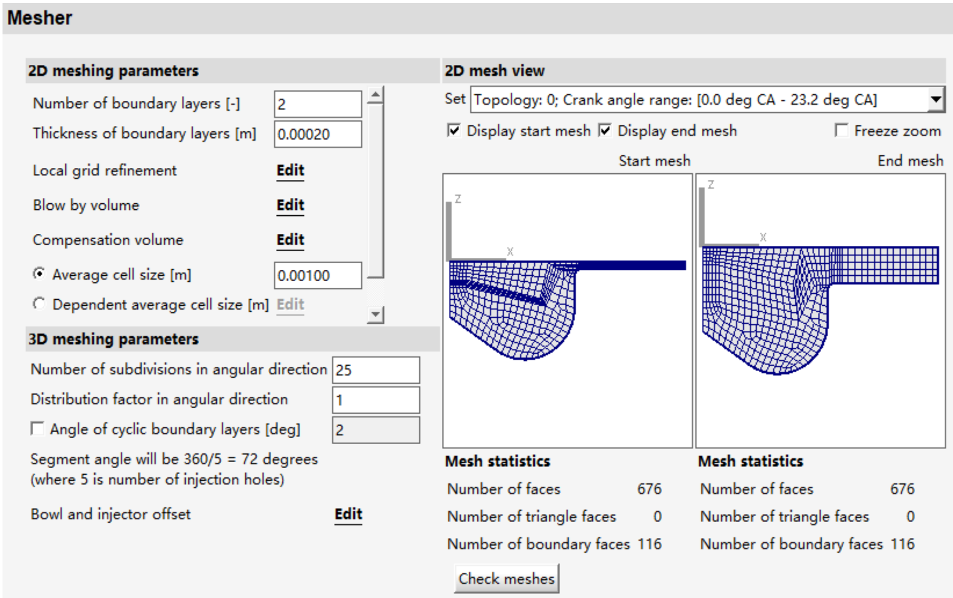


Figure 3. Two-dimensional grid

4. Comparison and Analysis of Simulation Results

4.1. Comparison of pressure in the cylinder under three injection laws

As can be seen from FIG. 5, the average pressure curve of the diesel cylinder under the three fuel injection laws is roughly the same, and there is a trend of first increasing and then decreasing. The maximum explosion pressure is the highest when the oil is sprayed according to the triangle spray law, which is 7.66MPa.The maximum explosion pressure of trapezoidal injection law is next, and the maximum explosion pressure is lowest in cylinder when the oil is sprayed according to the rectangular injection law, which is 7.01MPa.In addition, the maximum pressure outburst points are slightly different, the time of rectangular oil injection regular is earlier, and the time of triangular oil injection regular is later. In general, the highest pressure point roughly located at top dead center (720 ° CA) after 8 ° CA - 10 ° CA. The ignition delay period of rectangular fuel injection is the shortest and the triangle is the longest.

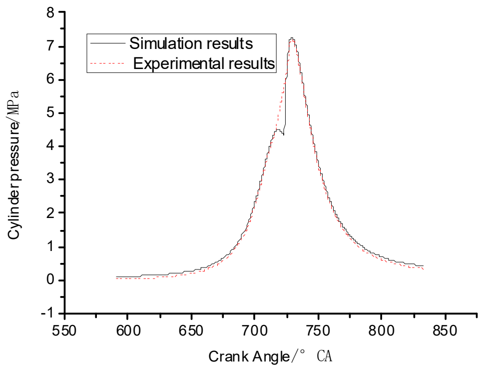


Figure 4. Comparison between simulated pressure and measured pressure

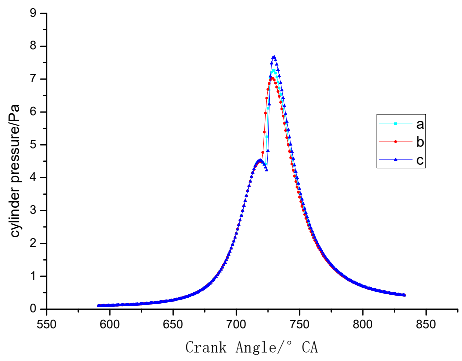


Figure 5. The change of pressure in cylinder with crankshaft turning angle

Why is there a big difference in cylinder pressure? First of all, compared with rectangle and trapezoid fuel injection law, triangle fuel injection law cases injection rate is lower, the early stage of the jet fuel movement speed slower, time of arrival in the cylinder wall is shorter. There is more opportunity to use the air flow in the cylinder to form a more uniform mixture. The amount of mixed gas in the cylinder is more in the later combustion, so there will be more pressure in the combustion chamber. If the fuel injection rate in the early stage is too fast, there are more fuel entering the cylinder, and the mixed gas in the cylinder is too thick to exceed the concentrated combustion limit, and the mixed gas cannot be burned. Moreover, when the mixture accumulates too much in the cylinder during subsequent combustion and burns together, the pressure increase rate will be too high, the maximum combustion pressure and temperature are high, and the work will be rough. The relationship between the pressure in rectangular and trapezoid cylinder is also analyzed for the same reason, which is opposite to that of the early injection rate. The relationship of fuel injection rate in the early stage is as follows: rectangular>trapezoidal>triangle, the relationship between the pressure inside the cylinder is as follows: triangle>trapezoidal>rectangular.

4.2. Comparative analysis of temperature in cylinder

Through the analysis of the temperature curve in Figure 6, it can be concluded that the average temperature in the cylinder under the three injection laws is approximately the same at all times, and the trend of the temperature curve is also the same. The temperature increases firstly and then decreases with the turning Angle of the crankshaft. Secondly, we can find that the average temperature in the cylinder under the rule of triangular oil injection is larger than the other two cases. The temperature under the trapezoidal injection law is in the middle, while the temperature under the rectangular injection law is the smallest. The difference between the highest and lowest temperatures is 134K. Finally, we can also find that the crankshaft rotation Angle corresponding to the peak of the average temperature in the cylinder is approximately the same in three cases.

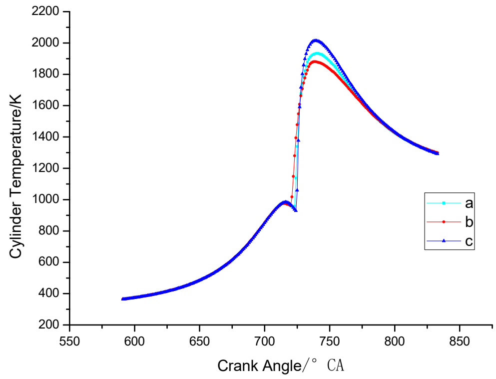
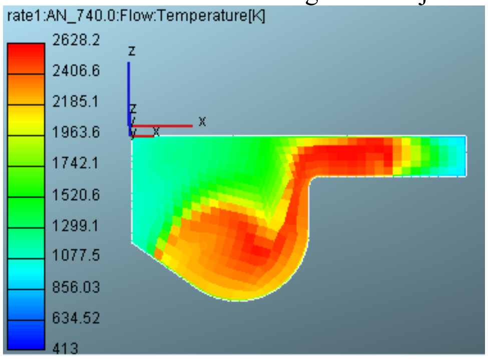


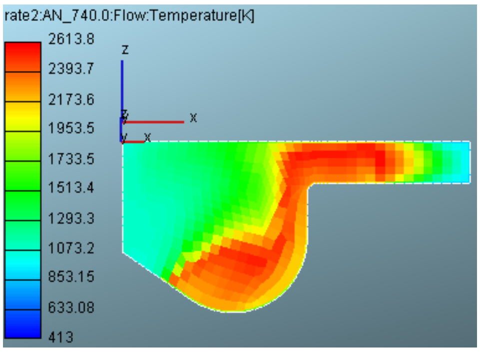
Figure 6. Curve of temperature in cylinder changing with crankshaft turning angle

In the triangular oil spraying rule, the highest oil spraying rate appears in the middle of the oil spraying. The mixed gas burned per unit time is the most, the quantity of heat released from the working material to the combustion chamber is more, and the temperature in the cylinder is naturally the highest. The temperature of trapezoidal injection is middle, while that of rectangular injection is lowest.

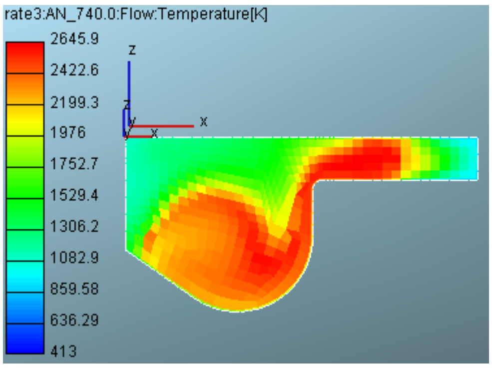
When the temperature reached the highest in cylinder (740 ° CA),it can be seen that there is no significant difference in temperature distribution in the cylinder under the three conditions, as shown in figure 7. Because of the high injection rate in the medium term, the combustion temperature of mixed gas is higher in triangle and trapezoid injection than in rectangular injection law. The high-temperature area at the bottom of the combustion chamber is the smallest under the rectangular oil injection rule.



(a)Temperature distribution under trapezoidal oil injection law



(b)Temperature distribution under rectangular oil injection law



(c)Temperature distribution under triangular oil injection law

Figure 7. Temperature distribution in cylinder at the 740° CAunder the three spray patterns

4.3. Comparative analysis of exothermic rate

According to the simulation results of heat release rate in Figure 8, we found that the peak heat release rate of rectangular oil injection law was the smallest, about 10J/deg. The maximum heat release rate of trapezoidal injection is higher than 15J/deg. The maximum heat release rate of triangular oil injection pattern is about 23J/deg. The crankshaft rotation Angle corresponding to the peak exothermic rate is compared.

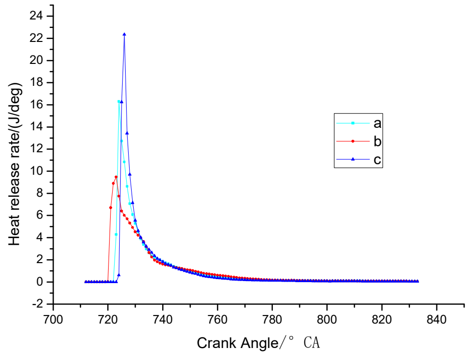


Figure 8. Change curve of exothermic rate with crankshaft turning angle

We find that the peak time relationship of the exothermic rate of the three oil injection patterns is as follows: rectangular exothermic time is the earliest, triangle exothermic time is the latest, the trapezoidal exothermic moment is centered. The essence of heat release in diesel cylinder is the combustion of working medium. Therefore, the starting time of exothermic rate can reflect the combustion time of diesel and air mixture from the side. It can also reflect the retardation period of each case. Through the observation we found working medium under the rectangular fuel injection law first combustion, ignition delay period is the shortest, roughly 8°CA.Mixture began burning time at the latest under the triangle fuel injection law, ignition delay period is the longest, roughly 12°CA.

4.4. Comparative analysis of cumulative heat release

In the physical sense, the cumulative heat release can be the sum of the heat release from the beginning of combustion of the mixture, that is, from the beginning of heat release to the turning Angle of the crankshaft at any position. It can be seen from figure 9 that the total amount of heat released from the beginning of combustion to the end of combustion is basically the same under the three fuel injection laws. This is because the amount of circulating oil is the same in all three cases.

The hysteretic burning period determines the starting point of exothermic heating, so it can be seen from the above analysis that the exothermic starting point of rectangle is earlier than trapezoid and trapezoid is earlier than triangle. The triangular fuel injection rule does not start burning until the piston reaches the upper stop point. At this point, the fuel quantity in the cylinder is more than that in the other two cases. The mixed gas burns together when the combustion condition is reached, the cumulative heat release rate is higher.

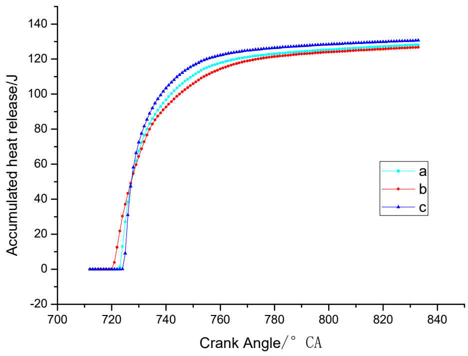


Figure 9. Cumulative heat release curve with crankshaft turning angle

The triangular oil spraying rule has the higher oil spraying rate in the middle of oil spraying, which accelerates spreading combustion and prevents the decrease of thermal efficiency. The mixing gas in the cylinder is sufficient and the combustion is complete in this period. At the later stage, the cumulative heat release rate will be flat due to the decrease of oil injection rate. The injection rate has not started to decrease before the end of the injection in the case of rectangle and trapezoid. At this point, the oxygen in the cylinder is not sufficient because the mixture is burned before, and the exhaust gas from the mixture is stored in the cylinder all the time. The fuel injected into the cylinder cannot be fully burnt. The rate of fuel injection in the middle and later stages of oil injection has started to decrease under the rule of triangular oil injection, which reduces the incomplete combustion of the above mixture gas, so its cumulative heat release is the highest. The trapezoidal injection pattern also reduces the incomplete combustion of mixed gas due to the decrease of the later injection rate. So we get the relationship between the cumulative heat release under the three fuel injection laws as follows: triangle > trapezoid > rectangle.

4.5. Comparative analysis of NOx emission

Through simulation calculation, the relationship between the mass fraction produced by nitrogen oxides and the turning Angle of crankshaft is obtained, as shown in figure 10.

As can be seen from figure 10, NOx is the first to be generated under the rectangular oil spraying rule, but the total NOx emission is the least. NOx is produced at the latest in triangular oil injection pattern, but the total NOx emissions are the highest. We already know the relationship between the size of the retardation period of the three fuel injection patterns, rectangle < trapezoid > triangle.

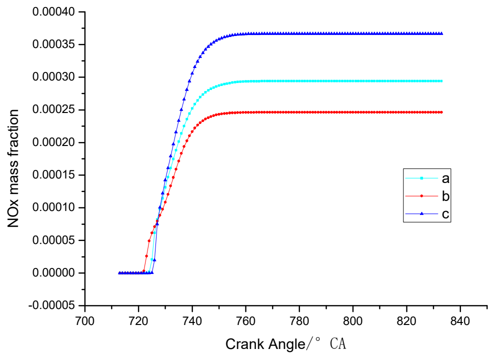


Figure 10. Curve of mean mass fraction of NOx with crankshaft turning angle

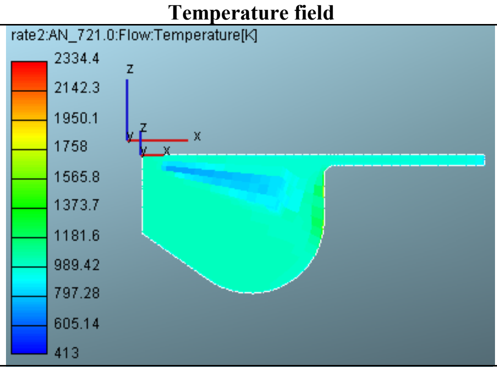
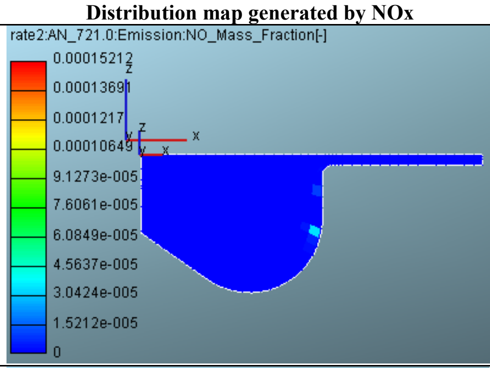
In the case of rectangular oil injection rule, the mixture in the cylinder is the first to burn, and the temperature in the cylinder is the first to rise, so NOx is the first to be generated. Because of the large accumulation and combustion of mixed gas in the process of oil injection under the rule of triangular oil injection, the average temperature peak in the cylinder is the highest, and more NOx is generated than other two cases. Similarly, in the case of rectangle, the average temperature in the cylinder is lower, and the NOx generated is not as much as triangle and trapezoid.

The formation mechanism of NOx requires high temperature, sufficient oxygen and sufficient reaction time. The distribution of temperature and NOx in the cylinder at different times is analyzed with rectangular oil injection rule as an example, as shown in the Table 2. Firstly, NOx is formed in the local high temperature region. As time and temperature increased, NOx production gradually increased.

4.6. Comparative analysis of soot emission

It is not hard to see from Figure 11 that the total amount of carbon smoke in the cylinder keeps increasing first, then decreasing, and finally tends to be stable under the three oil injection regular curves. In terms of emissions, the triangular fuel injection pattern produced the lowest carbon emissions, followed by trapezoids, and rectangular emit the most carbon smoke. The maximum carbon smoke emission in the cylinder corresponds to the same time under the three curves. The triangular oil spraying rule has a high fuel injection rate, high fuel pressure and good atomization in the middle period of oil spraying. Therefore, the better mixture can be formed under the rule of triangular oil injection and the combustion is more complete, the carbon smoke generated is naturally less than the rectangle and trapezoid. The rectangular fuel injection rate is not as good as the other two. The mixture is formed poorly, the combustion is not sufficient, and the carbon smoke is the most. The distribution of carbon smoke under the three oil spraying laws is shown in Fig- ure12.

Table 2. Temperature distribution and NOx generation distribution in the cylinder at each time under rectangular oil injection rule

<table>
<tr><th></th><th>Temperature field</th><th>Distribution map generated by NOx</th></tr>
<tr><td>721°CA</td><td>
</td><td>
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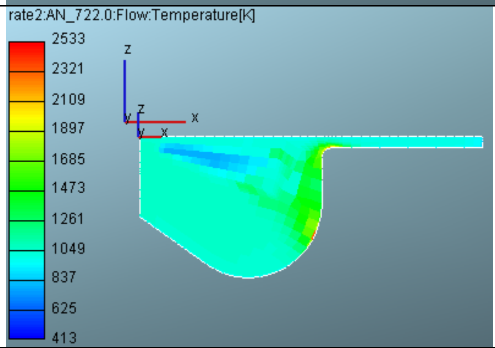
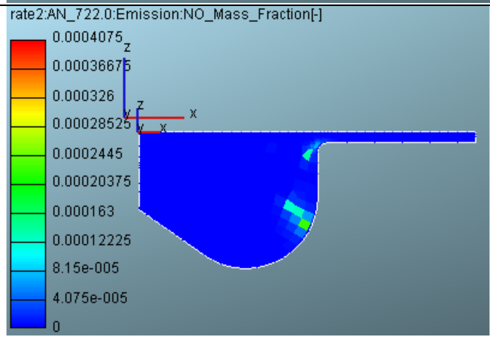
<tr><td>722°CA</td><td>
</td><td>
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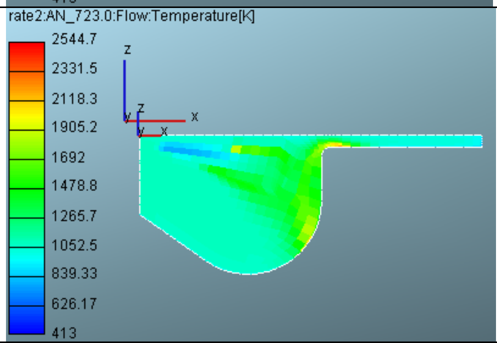
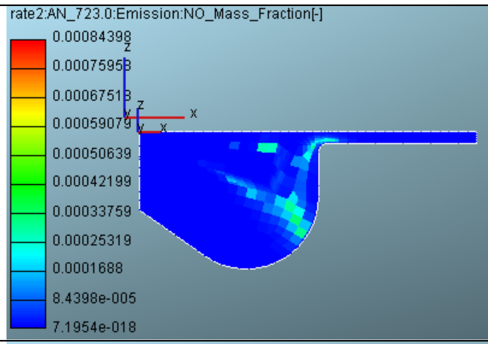
<tr><td>723°CA</td><td>
</td><td>
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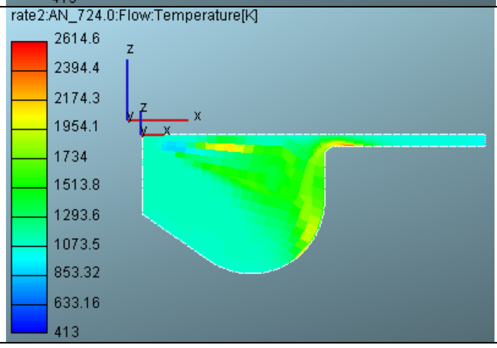
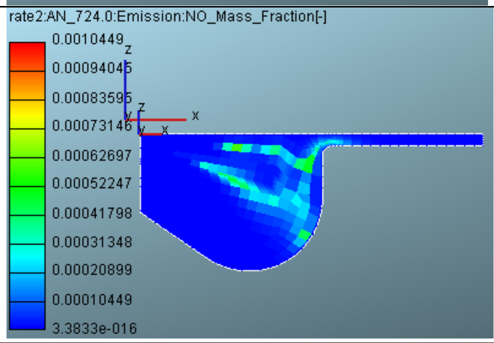
<tr><td>724°CA</td><td>
</td><td>
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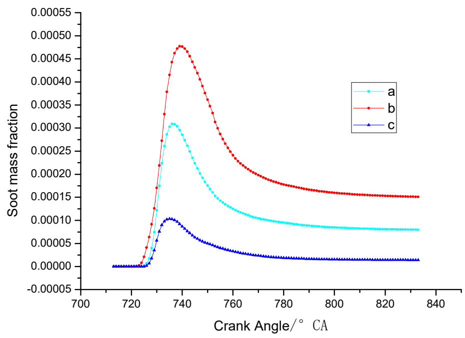
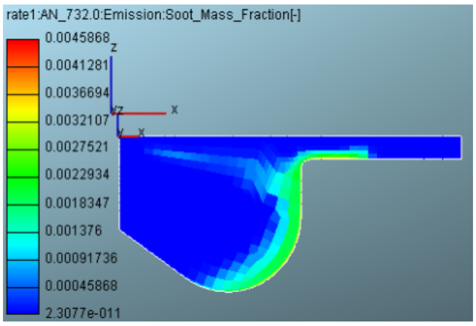
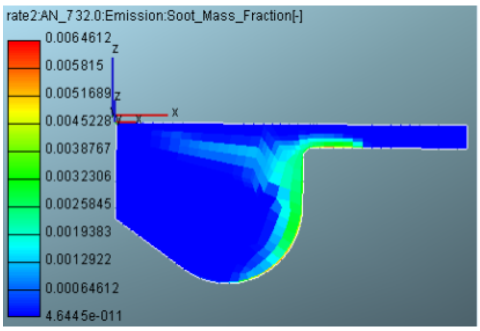


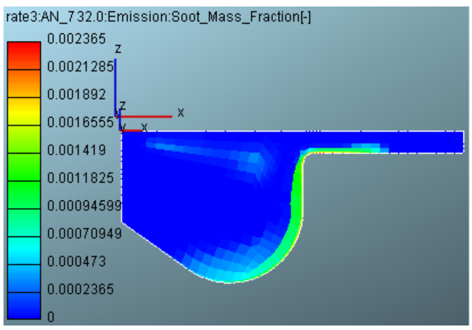
Figure 11. Curves of average soot mass fraction with the crank shaft angle



(a) trapezoidal



(b) rectangular



(c) triangle

Figure 12. Carbon smoke distribution in 732°CA under three kinds of fuel injection law

There is a contradiction between carbon smoke and NOx emission in diesel engine. Since the elimination of carbon smoke requires complete combustion, the temperature in the cylinder will increase, and the emission of nitrogen oxides will increase. The measure to reduce NOx emission is to reduce oxygen or temperature, which will increase the emission of carbon smoke. This is the famous "trade-off" relationship of diesel emissions[1]. Therefore, for the triangle oil spraying rule, the NOx emission is high, which means the carbon emission is low. Most of the carbon smoke will be burned in the subsequent process of combustion, so the curve of the carbon smoke mass fraction will first increase, then decrease, and finally flatten out.

4.7. Comparative analysis of CO emission

As can be seen from Figure 13, the final amount of CO emissions is roughly the same in the three cases, and the generation of CO in the cylinder also presents the trend of first increasing and then decreasing. Only the rectangular spray pattern is a bit different, during which there are two peaks. The production time of CO is roughly the same as that of NOx. The production time of rectangular oil injection is earlier than triangle oil injection, trapezoid oil injection is in the middle.

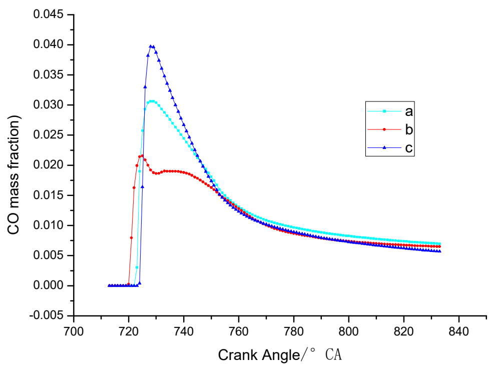


Figure 13. Change curve of CO mass fraction with crankshaft turning angle

CO was first generated because the early oil injection rate was too fast, the mixed gas in the cylinder was thicker and the combustion was incomplete in the case of rectangular oil injection rule. In the medium term, CO was further oxidized to CO_2 because of the high temperature in the cylinder, and the quality fraction of CO decreased. After the end of the injection due to poor airflow movement caused by local hypoxia.CO was generated at the bottom and wall of the combustion chamber, and CO mass fraction increases briefly. After the second peak, it was further oxidized, and the amount of CO decreased and finally remained unchanged. The pressure in the cylinder is higher because of the large amount of mixed gas, and the work is rough. The mixed gas cannot be completely burnt in a short time. At the later stage of combustion, the fuel spray rate is low, and the fuel spray pressure is low, which leads to poor atomization of fuel and incomplete combustion of mixed gas, leading to the highest amount of CO produced.

5. Conclusion

For the triangle spray pattern, because of the slow rate of fuel injection in the early stage, the pressure of fuel injection is small, the diameter of fuel particles is large, the atomization is poor, and the delayed combustion period is the longest. In addition, the maximum pressure of combustion in the cylinder is the highest, the pressure increase ratio is too high, resulting in rough work. During medium combustion, the air flow in the cylinder moves well, which makes the mixture more uniform, higher heat release rate and accumulated heat release, higher temperature in the cylinder, more NOx generation than other cases, and less carbon smoke generation. In the later stage, more CO was generated due to local hypoxia in the cylinder.

The rate of rectangular oil injection is always the same. In the medium term, the fuel injection rate is lower than the other two cases, the mixed gas is less, the pressure and temperature are lower, the cumulative heat release is lower, the NOx emission is less, the carbon smoke emission is more, and the CO emission is less.

All the parameters are in the middle position in the trapezoidal injection rule, the temperature and pressure in the cylinder are moderate, the combustion and heat release rate are good, and the comprehensive discharge performance is better than other conditions.

References

[1] ZHOU L B. Internal combustion engine[M]. Beijing: China Machine Press, 2017.

[2] Kim H J, Su H P, Chang S L. Impact of fuel spray angles and injection timing on the combustion and emission characteristics of a high-speed diesel engine[J]. Energy, 2016, 107:572-579.

[3] B. Yu, P.F., Fu, T. Zhang, H.C., Zhou. The influence of back pressure on the flow discharge coefficients of plain orifice nozzle[J]. International Journal of Heat and Fluid Flow,2013,44.

[4] Han D, Zhai J, Duan Y, et al. Nozzle Effects on the Injection Characteristics of Diesel and Gasoline Blends on a Common Rail System[J]. Energy, 2018, 153.

[5] Xue F, Luo F, Cui H, et al. Numerical analyses of transient flow characteristics within each nozzle hole of an asymmetric diesel injector[J]. International Journal of Heat & Mass Transfer, 2017, 104:18-27.

[6] Guo C, Song Y, Feng H, et al. Effect of fuel injection characteristics on the performance of a free-piston diesel engine linear generator: CFD simulation and experimental results[J]. Energy Conversion & Management, 2018, 160:302-312.

[7] Wu X, Deng J, Cui H, et al. Numerical Simulation of Injection Rate of Each Nozzle Hole of Multi-hole Diesel Injector[J]. Applied Thermal Engineering, 2016, 108:793-797.

[8] Salvador F J, Carreres M, Jaramillo D, et al. Analysis of the combined effect of hydrogrinding process and inclination angle on hydraulic performance of diesel injection nozzles[J]. Energy Conversion & Management, 2015, 105:1352-1365.

[9] Jia M, Xie M, Liu H, et al. Numerical simulation of cavitation in the conical-spray nozzle for diesel premixed charge compression ignition engines[J]. Fuel, 2011, 90(8):2652-2661.

[10] Sun Z Y, Li G X, Chen C, et al. Numerical investigation on effects of nozzle's geometric parameters on the flow and the cavitation characteristics within injector's nozzle for a high-pressure common-rail DI diesel engine[J]. Energy Conversion & Management, 2015, 89(9):843-861.