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Research Article

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The Impact of Fuel Injection strategies on combustion and emissions of Natural Gas Engines

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Abstract The influence of fuel injection strategy on combustion and emission of natural gas engine was explored, and the three-dimensional software FIRE was used to establish a single-cylinder simulation model of natural gas engine, and the influence of different injection strategies on the formation, combustion, and emission of mixed gas in the cylinder was analyzed. The results show that with the increase of the advance angle of fuel injection, the earlier the combustion process ends. The inflection point of the heat release curve was advanced, and the instantaneous heat release curve showed a trend of first increasing and then decreasing. The peak of the NO mass fraction is positively correlated with the injection advance angle; The duration of fuel injection increased, and the propagation range of flame areal density gradually decreased; The injection duration is short, the reaction speed is faster in the early stage, and the opposite is true when the injection duration is longer.

Keywords Diesel ignition, Natural gas engines, Injection strategy, Burn, Emission

1. Introduction

Countries around the world have taken many positive measures to face the problem of carbon emissions. China has proposed to peak carbon emissions by 2030, and the automotive industry accounts for a large share of carbon emissions[1]. Burning traditional fossil fuels as the main source of power for cars is also the main source of carbon emissions for cars. Due to the fuel characteristics of natural gas fuel, it is considered one of the best alternative energy sources for engines to solve the problem of carbon emissions. At present, the application of natural gas fuel in the engine is generally modified on the basis of the traditional gasoline engine or diesel engine, and only the optimization design of its injection system and structure can achieve low-carbon combustion of the engine, which is difficult to develop and reduces the cost. Natural gas, using direct injection in cylinders has great potential to improve thermal efficiency and reduce emissions, and many studies are currently working to improve thermal efficiency and achieve zero emissions under lean combustion conditions [2-3]. In this paper, the effects of injection strategy (injection advance angle, injection duration) on the formation, combustion and emission performance of diesel-ignited natural gas engine mixture are studied by simulation method, which provides a basis for improving the combustion and emission performance of natural gas engine.

2. Experimental setup and methods

The research in this paper is based on the test bench of Zichai Power Co., Ltd., and the dual-fuel engine used is based on the Z6170 diesel engine as the prototype, and a natural gas fuel supply system is added. Natural gas after compression in the air passage and air fully mixed into the cylinder, diesel is not the main fuel, but as a natural gas ignition source, it affects the initial combustion state of natural gas, the combustion stability of natural gas plays a very important role, the prototype used in the test is shown in Figure 1, the main technical parameters are shown in Table 1.

Figure 1: Test prototype

Table 1: Basic engine parameters

Classify	Parameters
Type	Inline 6-cylinder gas machine- Z6170
Bore × stroke（mm）	170×200
Connecting rod length（mm）	360
Compression ratio	14.5
Vortex ratio	1.2
Intake valve is closed /（°CA BTDC）	40
Exhaust valve opens /（°CA ATDC）	65

The main test equipment in the test is the P1500 model dynamometer produced by Qidong Unicom dynamometer factory, the fuel consumption rate is measured by the product HZB5000 model fuel consumption meter of Qidong wave dynamometer factory, the burst pressure test is monitored by the German Lute MSI3 burst pressure meter, the soot test is completed with FQD-102A smoke meter, and other components in diesel engine emissions, such as CO, HC, NO and CO2 are tested by HORIBA The gas analyzer collects the main equipment information shown in Table 2.

Table 2: Main instruments

Device name	Model	Manufacturer
Dynamometer	P1500	Qidong Unicom Dynamometer Co., Ltd
Fuel consumption meter	HZB5000	Qidong wave peak dynamometer factory
Burst pressure gauge	MSI3	German Lute
Smoke meter	FQD-102A	State-owned Wenzhou Instrumentation Factory

3. Simulation models and validation

Engine geometry

Since this article does not address the effect of gas flow in the cylinder on combustion, the content of this article does not include the intake and exhaust strokes, and the calculation range is 580 °CA to 835 °CA for the crankshaft angle included in the period from the time the intake valve closes to the opening of the exhaust valve, and in summary, the modeling software SolidWorks is used to draw a three-dimensional model according to the geometry of the Z6170 diesel engine combustion chamber, as shown in Figure 2, and complete the meshing.

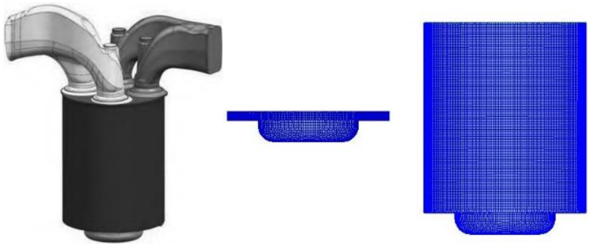


Figure 2: Combustion chamber geometry (left); grid at top dead center (medium); Grid at bottom dead center (right)

Model Selection

Table 3: Model settings

Type	Model settings
Turbulence model	Coherent Flame model
Broken models	K-ξ-f model
Evaporation model	KH-RT model
Wall-bumping model	Multi-component model
Combustion model	Walljet1 model
NO_X and CO model	Extended Zeldovich model

Boundaries, initial condition setting

The boundary conditions involved in the simulation mainly include temperature and speed, and the temperature of the piston top, cylinder head and cylinder wall is set to 575.15K, 550.15K, and 475.15K respectively according to experience, and the piston head is a moving wall, and the cylinder head and cylinder wall are fixed walls.

The setting of the initial conditions mainly includes two parts, the first is the setting of pressure, temperature, turbulent kinetic energy and other related parameters, and secondly, natural gas adopts the inlet pre-mixed intake method, and this article does not involve the inlet part, so it is assumed that natural gas as a component of air has been evenly mixed in the combustion chamber. In this paper, the initial pressure is set at 0.2 MPa, the temperature is 370.15K, the turbulent kinetic energy TKE=37.5m^2/s^2, the turbulent length scale TLS=0.00631m, and the engine cycle fuel injection is set to 0.331g.

Model Validity Validation

In this paper, the test of the engine at 100% load, the speed control at 1500 r/min, and the natural gas substitution rate of 75% is compared with the simulated cylinder pressure curve, as shown in Figure 3. By comparing the cylinder pressure curve obtained by the simulation and the bench test, it can be found that the trend change and value size of the curve are similar, and there is a certain error in the peak pressure, but the error is less than 5%, and the calculation result has greater reference value, so the simulation model can be applied to this paper.

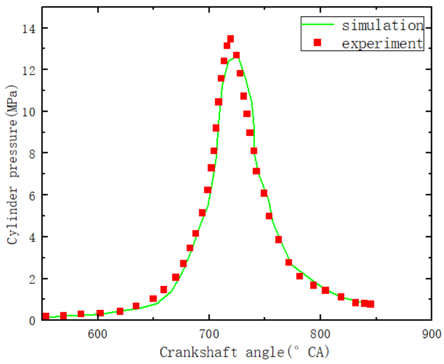


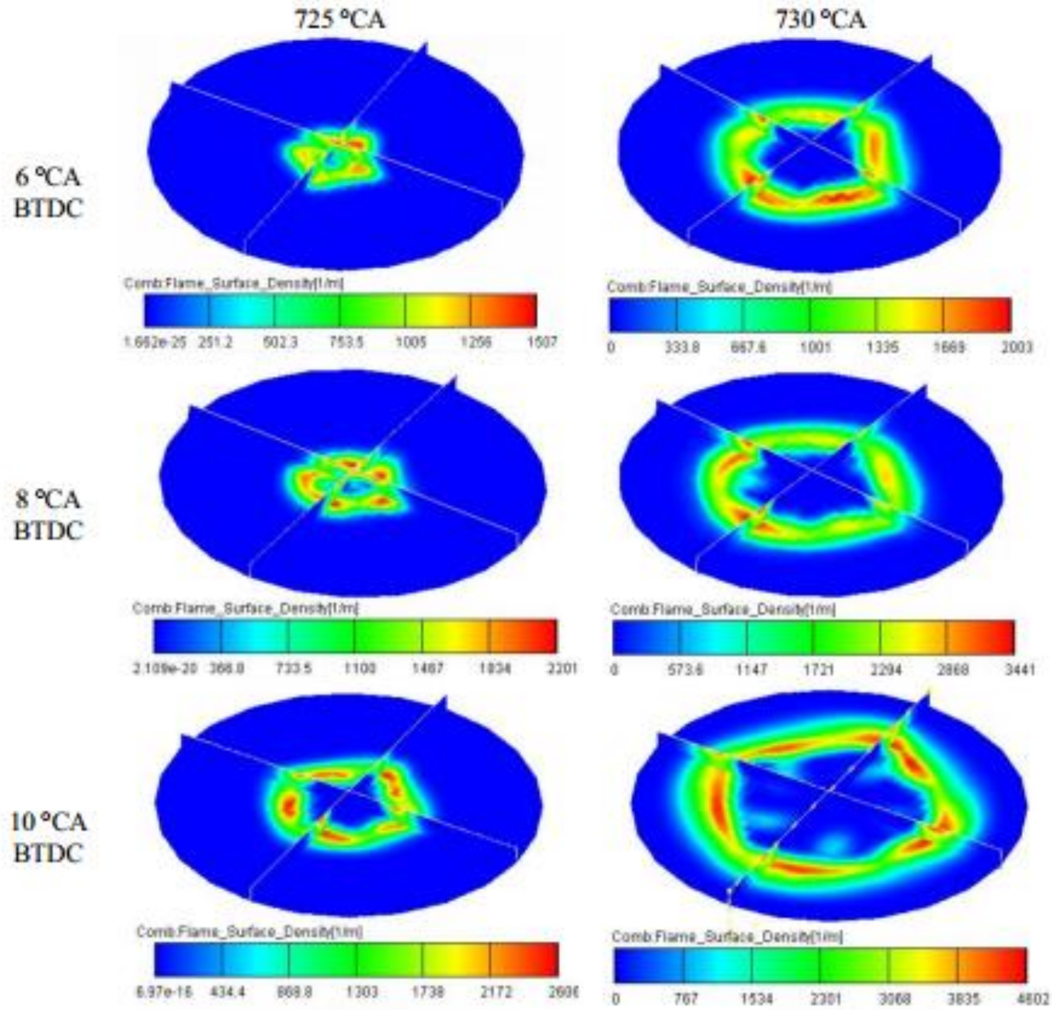
Figure 3: Comparison of simulation and experimental results

4. Effect of ignition diesel injection advance angle

Under the condition that the amount of ignition diesel fuel is R=7% and the fuel injection duration is 10 °CA, the influence of 6 °CA BTDC, 8 °CA BTDC, 10 °CA BTDC, 12 °CA BTDC, and 14 °CA BTDC on combustion and emission in the cylinder is explored by taking the injection advance angle as the research variable.

Burning flame areal density

The flame areal density cloud with crankshaft rotation angles of 725 °CA and 730 °CA was selected to study the influence of the pilot diesel injection advance angle on the areal density of the combustion flame, as shown in Figure 4. With the increase of the injection advance angle, the distribution range of the flame surface becomes larger, indicating that the range of already burning and burning gradually increases with the increase of variable values. It can be concluded that when the piston reaches near top dead center, the value in the case of early injection is greater than that of late injection, which indicates that the earlier the injection time, the longer the hysteresis period, the more sufficient the time to form a homogeneous combustible mixture, and the more adequate the combustion. With the progress of the combustion reaction, it can be judged from the flame density distribution range that the earlier the fuel injection, the earlier the combustion ends, which can also be verified at the 730 °CA crankshaft angle moment, the fuel injection advance angle is 12 °CA, 14 °CA when the flame density value is verified, according to the change law of the previous sets of values, the earlier the fuel injection, the larger the value, the more vigorous the combustion, but when the fuel injection advance angle is selected 14 °CA, the value becomes smaller, indicating that the combustion is no longer a peak state.



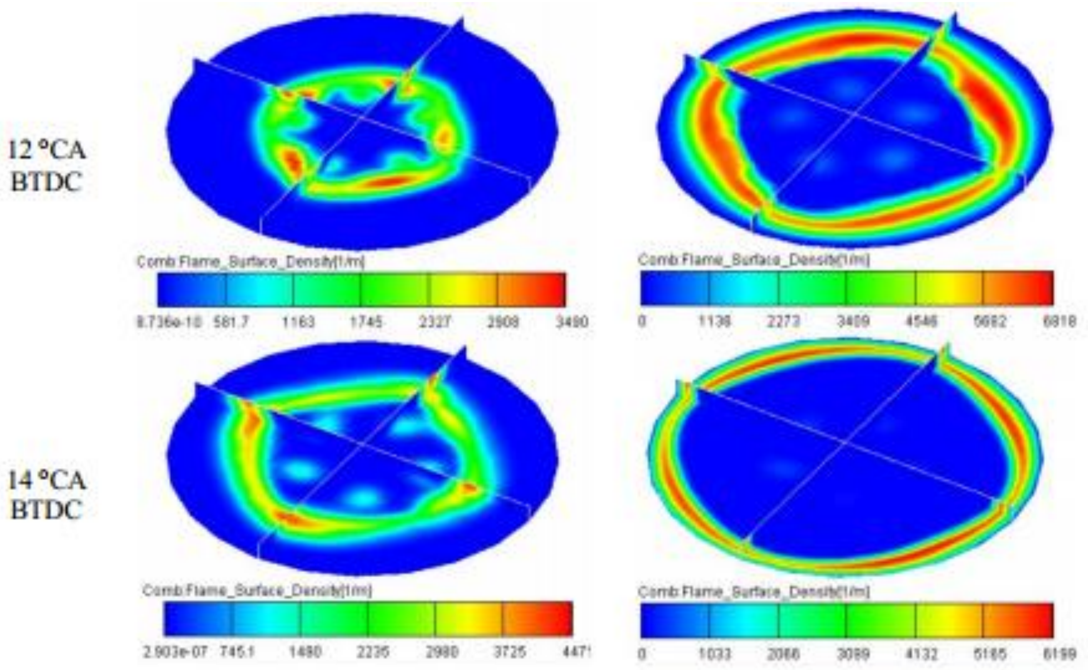
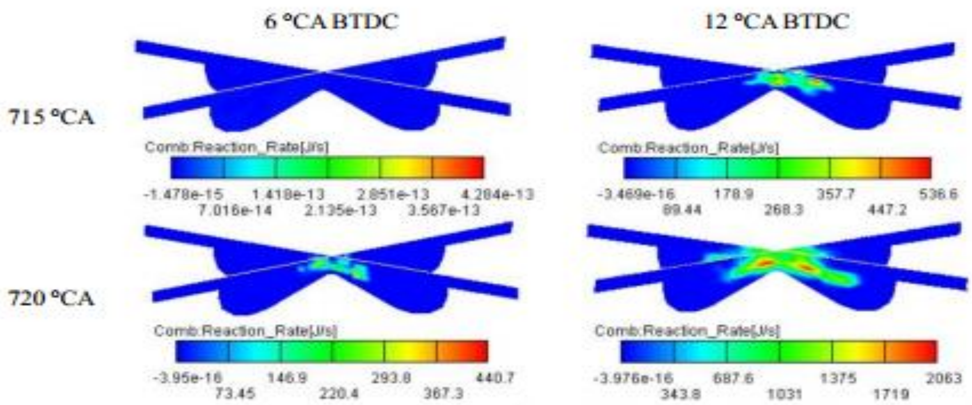


Figure 4: Effect of fuel injection advance angle on flame density

Combustion Reaction Rate

As shown in Figure 5, the instantaneous combustion reaction velocity cloud at the rotation angles of 715 °CA, 720 °CA, 730 °CA, and 740 °CA crankshaft was intercepted taking the two injection advance angles of 6 °CA BTDC and 12 °CA BTDC as the research object. It can be concluded that when the crankshaft angle is 715 °CA, the diesel fuel in the late injection condition has not yet burned, and the combustion speed in the early injection state has reached 536.6 J/s; Before the piston reaches top dead center, the combustion rate in the cylinder in the case of early injection is significantly faster, on the one hand, because the amount of ignition diesel fuel injected in the case of early injection is more (the fuel injection duration is 10 °CA, when the fuel injection is completed), and on the other hand, because the earlier the fuel is injected, the more uniform the combustible mixture formed, the wider the distribution range and easy to burn. When the piston passes the top dead center, the combustion speed is higher than the early injection, and the increase is much greater than the early injection time, which is because the late injection makes the moment when the diesel is compressed and burned closer to the top dead center, at this time, the temperature and pressure in the cylinder are higher, resulting in more intense combustion. At a crankshaft angle of 740 °CA, the combustion speed at the advance angle of 12 °CA BTDC injection is maintained at around 150 J/s, indicating that the combustion process is nearing the end at this time.



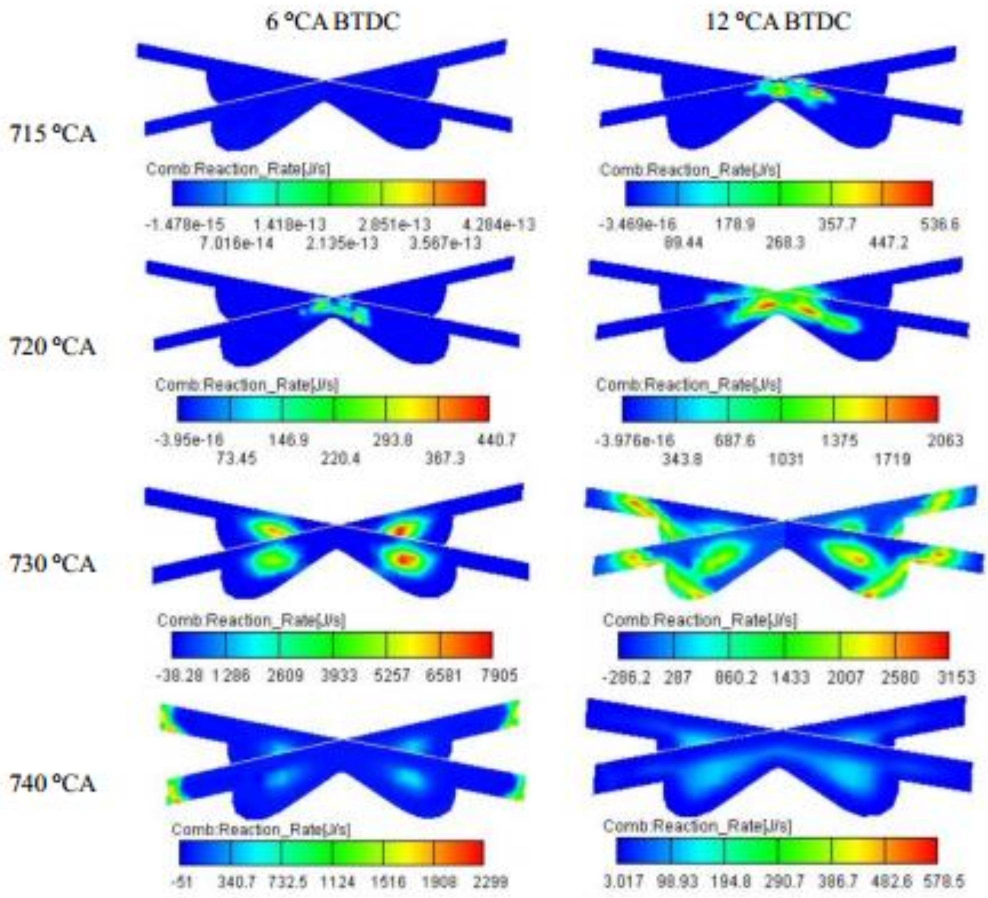


Figure 5: Effect of injection advance angle on reaction rate

Combustion Exothermic Characteristics

Figure 6 shows the change curve of combustion heat release rate with the advance angle of fuel injection. It can be seen from the figure that with the advance of fuel injection timing, the moment of inflection point of heat release in the cylinder is correspondingly advanced, the instantaneous heat release rate shows a trend of first increasing and then decreasing, and the peak of the heat release rate is also advanced due to the advance of fuel injection timing, which is because the fuel is injected before the piston reaches top dead center, and the hysteresis period is extended because of the low temperature and pressure in the cylinder. Diesel fuel in the cylinder air flow under the influence of the formation of combustible mixture increased and more uniform, the first generation of combustible mixture will absorb the surrounding heat for pre-flame reaction, when the temperature in the cylinder reaches a certain extent, diesel fuel is ignited, at this time the number of ignition points increase and disperse, causing a sudden change in the heat release rate.

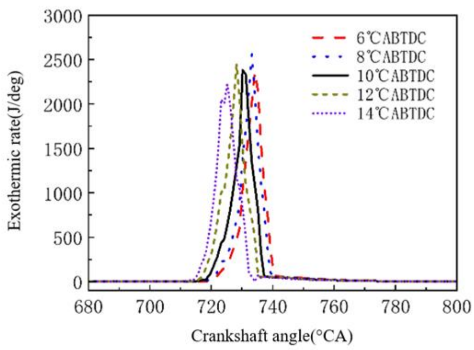


Figure 6: Effect of fuel injection advance angle on heat release rate

NO and CO Emission Characteristics

Figure 7 is the influence of the injection advance angle on the generation of NO mass fraction, it can be seen from the figure that the NO mass fraction is positively correlated with the change of the injection advance angle, because the generation of NO is closely related to high temperature conditions, and the influence of the injection advance angle on the temperature in the cylinder was discussed earlier, and the conclusion that the larger the injection advance angle, the higher the average temperature in the cylinder, which also led to the formation of NO by nitrogen atoms and oxygen atoms at high temperatures.

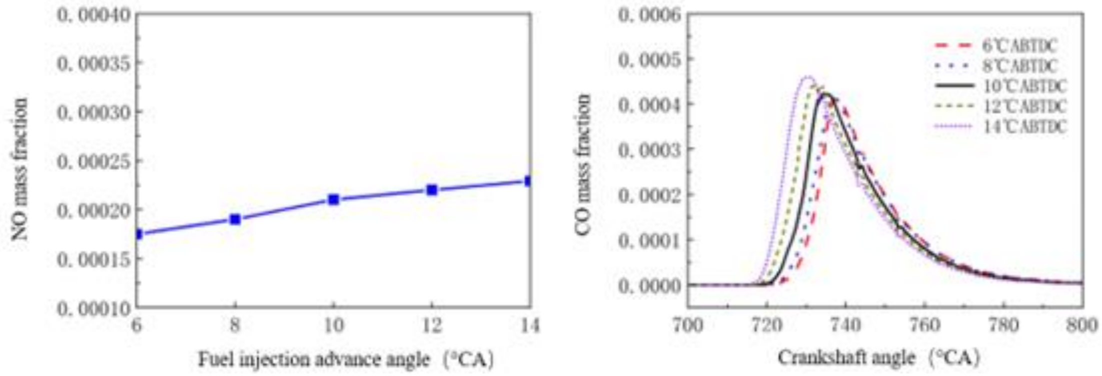


Figure 7: Effect of fuel injection advance angle on NO and CO

5. The effect of the pilot diesel injection duration on the combustion and emission process in the cylinder

This section describes the effects on combustion and emissions in the cylinder with an injection duration of 4 °CA, 7 °CA, 10 °CA, 13 °CA, 16 °CA under the condition of injection volume R=7% and injection timing of 710 °CA.

Burning Flame Areal Density

In order to study the effect of injection duration on flame areal density, this section intercepts the flame areal density distribution and size clouds at 725 °CA and 730 °CA crankshaft angles for five injection duration conditions, as shown in Figure 5.10. It can be seen from the figure that with the increase of the fuel injection duration, at the corner of the 725 °CA crankshaft, the propagation range of the flame areal density is gradually shrinking, and its value is also decreasing, because in the case of a certain amount of ignition diesel, the shorter the injection cycle, the more diesel fuel injected into the combustion chamber in the same time, the greater the amount that can be compressed and burned, the easier it is to catch fire, and the temperature and pressure of the surrounding combustion environment can be quickly increased, so that natural gas has sufficient combustion conditions, and it is more conducive to the spread of flame to the cylinder head and the edge of the cylinder wall. At a crankshaft angle of 730 °CA, the flame surface with a fuel injection duration of 4 °CA has reached the cylinder wall.

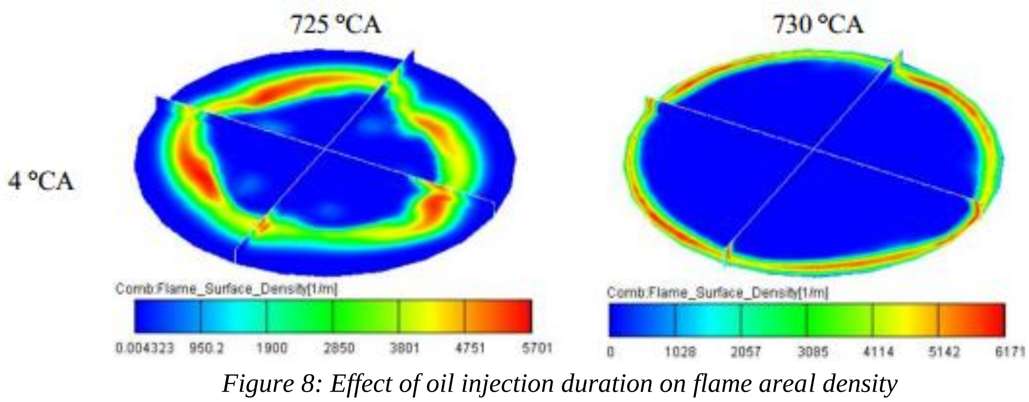


Figure 8: Effect of oil injection duration on flame areal density

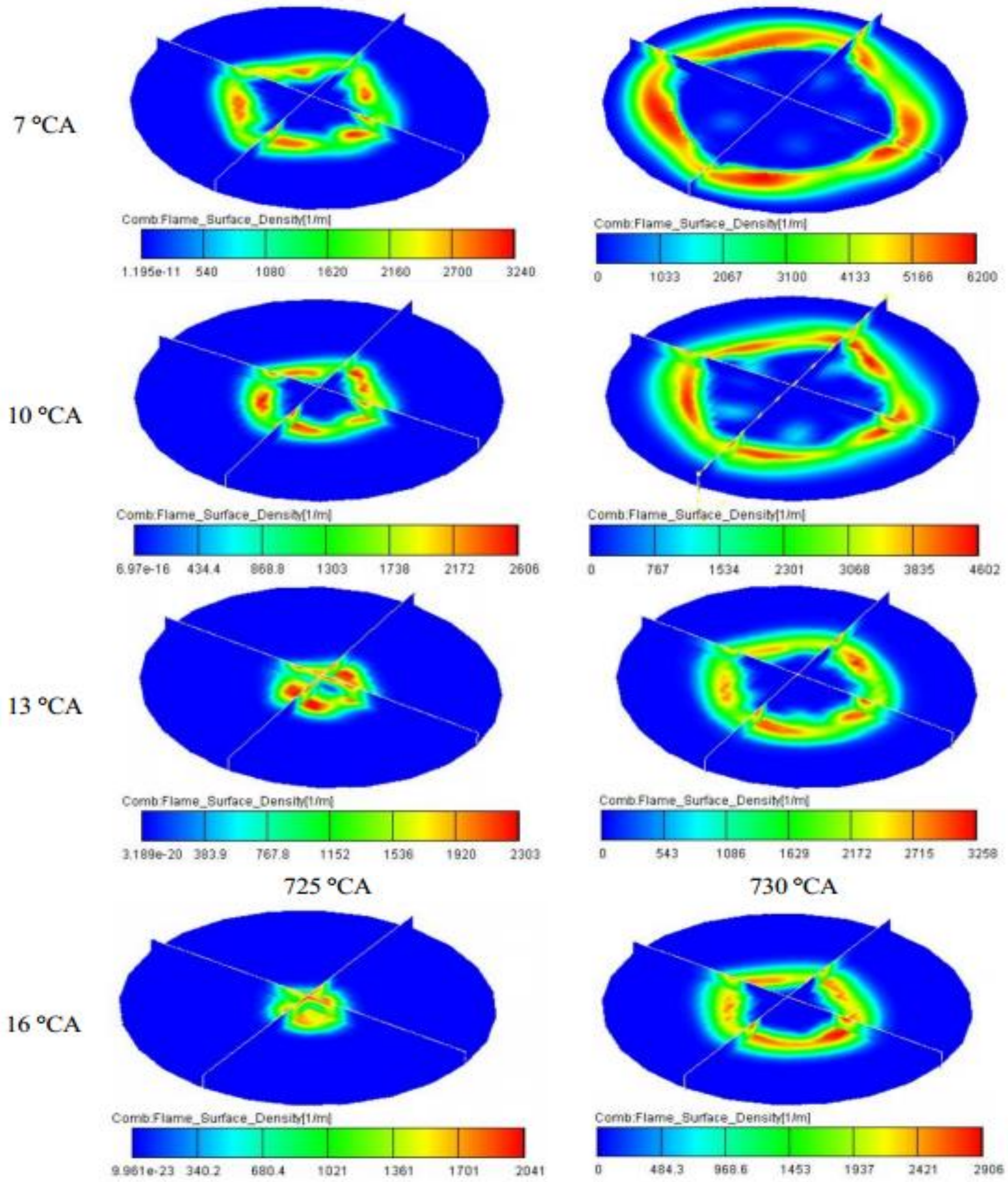


Figure 8: Effect of oil injection duration on flame areal density (continued)

Burning Flame Areal Density

In this part, the flame areal density distribution and size clouds at 725 °CA and 730 °CA crankshaft angles were intercepted for the five injection duration conditions, as shown in Figure 9. It can be seen from the figure that with the increase of the fuel injection duration, at the corner of the 725 °CA crankshaft, the propagation range of the flame areal density is gradually shrinking, and its value is also decreasing, because in the case of a certain amount of ignition diesel, the shorter the injection cycle, the more diesel fuel injected into the combustion chamber in the same time, the greater the amount that can be compressed and burned, the easier it is to catch fire, and the temperature and pressure of the surrounding combustion environment can be quickly increased, so that natural gas has sufficient combustion conditions, and it is more conducive to the spread of flame to the cylinder head and the edge of the cylinder wall. At a crankshaft angle of 730 °CA, the flame surface with a fuel injection duration of 4 °CA has reached the cylinder wall.

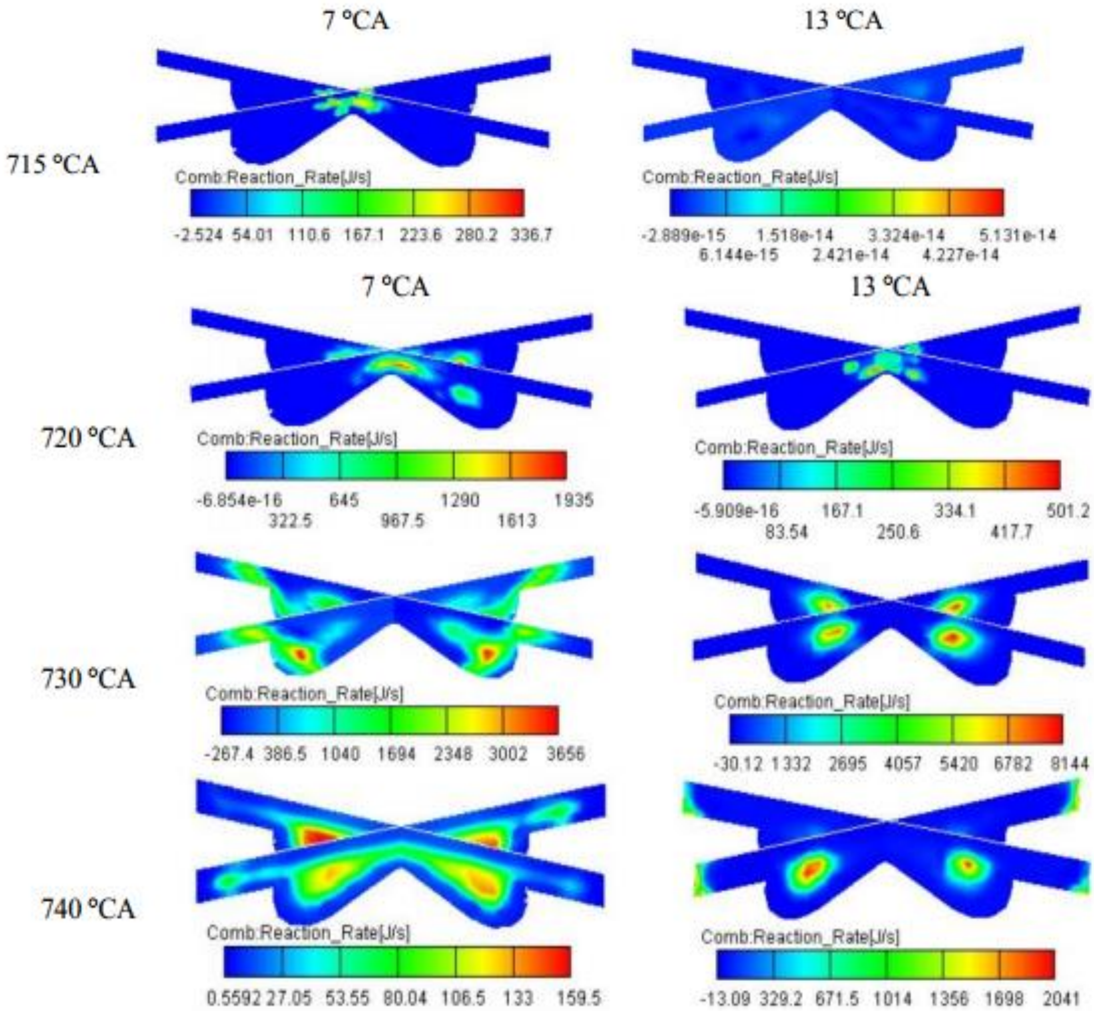


Figure 9: Effect of injection duration on reaction rate

Combustion Exothermic Characteristics

Figure 10 shows the effect of the pilot diesel injection duration on the combustion exothermic rate. It can be seen from the figure that the heat release rate curve under different injection duration periods has certain fluctuations, and it can be intuitively seen that with the increase of variable value, the more lagging the time point of the peak of the heat release rate curve, the reason for this phenomenon is that the longer the diesel injection time, the less ignition diesel fuel injected in the same time, the thinner the combustible mixture formed, the less likely it is to be compressed. Conversely, the shorter the duration period, the easier it is to compress ignite the ignition of the diesel fuel, and the sooner the heat release occurs in the cylinder. Although the short injection duration can make the combustion in the cylinder more concentrated, it is necessary to be vigilant that the concentrated heat release in a short period of time can easily lead to a sudden increase in pressure and temperature in the cylinder, resulting in rough work and other phenomena, which is not conducive to engine work.

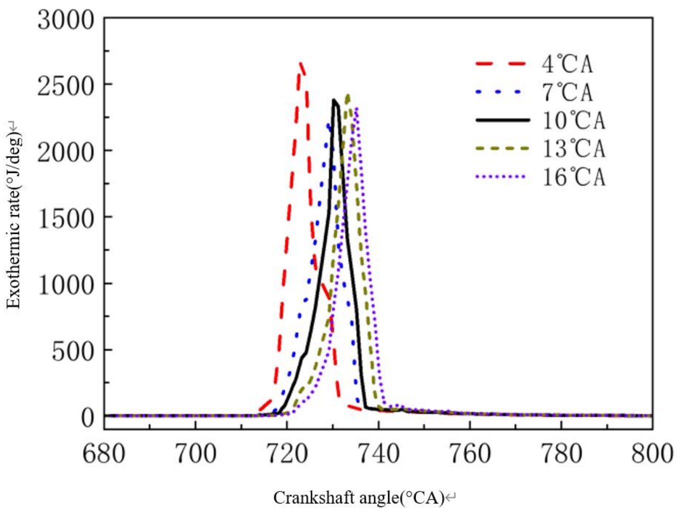


Figure 10: Effect of injection duration on reaction rate

NO and CO Emission Characteristics

Figure 11 shows the effect of different injection durations on NO generation. As can be seen from the figure, the difference in the duration of ignition diesel injection will also lead to the generation of NO in the cylinder is also different, with the extension of the variable value, the amount of NO generation gradually decreases, when the fuel injection duration is 4 °CA, the amount of NO generation is the largest, as can be seen from the temperature curve in the cylinder, the curve under this condition has the highest average temperature in the cylinder, and the generation environment of NO is the best. Figure 5.16 shows the emission of CO under different injection durations, and it can be seen from the figure that the amount of CO generated first increases and then decreases with the change of crankshaft angle. CO mass fraction is negatively correlated with the length of variable values, that is, the longer the injection duration, the smaller the CO mass fraction, and it can also be seen from the curve that the shorter the injection time, the earlier the CO curve falls, the reason for this phenomenon is that with the shortening of the injection duration, the injection rate will increase, so that the oxygen concentration during combustion decreases faster, increasing the generation of CO, but the rate of oxidation will also accelerate, eventually resulting in a decrease in CO generation.

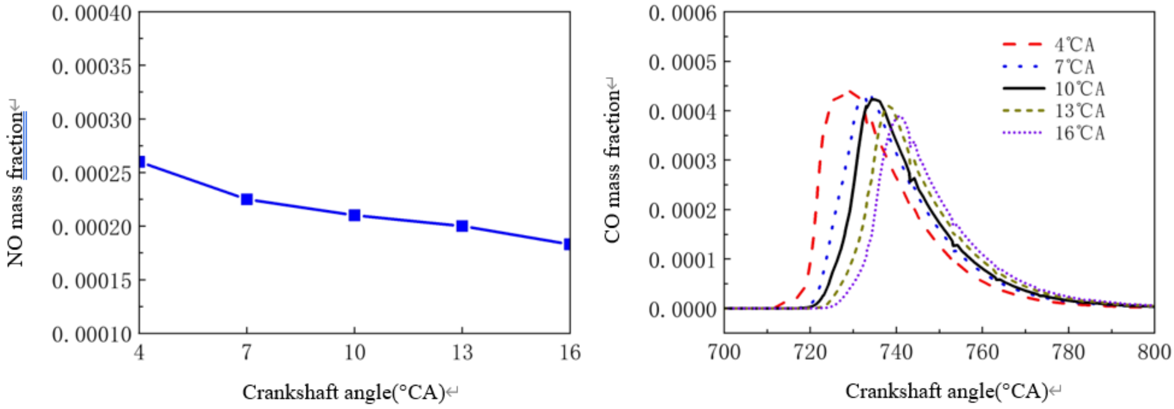


Figure 11: The effect of fuel injection duration on NO and CO emissions

6. Conclusion

This chapter mainly studies the variation of fuel injection advance angle and injection duration on the combustion and emission of diesel-natural gas engines from the perspective of injection strategy.

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