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Advances in Theory and Technology Research of Low Temperature Combustion (LTC) for Diesel Engines

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Abstract: The increasingly stringent emission regulations and the oil crisis have promoted the research and development of engine technology. As an advanced combustion technology, low temperature combustion has been attracting attention from all walks of life in recent years. This paper analyzes the deficiencies of traditional combustion, and summarizes the research progress of diesel engine low temperature combustion from three aspects of combustion system parameters, injection strategy and fuel characteristics.

Keywords: Low temperature combustion, Diesel engine, Review.

1. Introduction

Diesel engine has higher compression ratio and less throttling loss than gasoline engine, so its thermal efficiency is higher [1]. The traditional diesel engine adopts the diffusion combustion method, the emission of HC and CO is low, but the generation of PM and NOx is high and it is difficult to improve at the same time. According to the diesel engine combustion process model (Fig. 1) studied by Dec J.E[2], when the oil jet penetrates into the combustion chamber, hot air is entrained into the oil jet, and the fuel cracks to form the precursor of soot. The combustion reaction starts in the premixed region with an equivalence ratio of about 4, at which point air continues to be entrained into the partial combustion reaction region until a thin flame front forms around the periphery of the oil jet. The temperature of this flame front is around 2700K, part of the soot is oxidized in the high temperature flame area, and NO is produced in large quantities in the area close to the diffusion flame front where N2 and O2 exist. Therefore, from the perspective of the combustion process of a diesel engine, the generation of NOx and PM is unavoidable, and the characteristics of different formation conditions of NOx and PM and the characteristics of spray combustion of direct-injection diesel engines make the measures to reduce NOx emissions often increase PM emissions and reduce PM emissions. PM emission technologies will also increase NOx emissions, and the control of the two presents a contradictory situation.

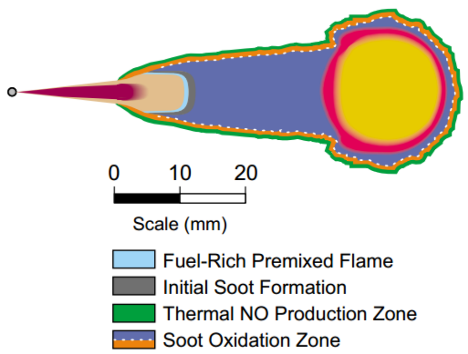

Figure 1. Typical diesel engine flame structure[2]

In order to improve the emission of diesel engines, various advanced technologies have emerged at home and abroad. For example, Selective Catalytic Reduction (SCR), which uses ammonia as an inert substance in the catalyst system to reduce the level of nitrogen oxides, and converts pollutants into nitrogen, water and trace carbon dioxide by reducing NOx[3] . The other is to combine exhaust gas recirculation technology (Exhaust Gas Recirculation, EGR) and particle capture system (Diesel Particulate Filter, DPF), while reducing NOx and soot emissions. However, the complex post-processing technology will lead to increased back pressure to reduce thermal efficiency, and additional system components also reduce the economy [4].

A homogeneous gas mixture can eliminate the formation of soot, and a lower equivalence ratio can reduce NOx emissions. Based on this concept, researchers have done more in-depth research on the emission mechanism of pollutants, and have turned their attention to low-temperature combustion technology to avoid the generation of pollutants from the combustion level [5,6].

2. Low Temperature Combustion Technology Principle

According to the research in literature [7,8], in the traditional diesel engine combustion process, the change and development process of the local equivalence ratio (Φ) and temperature (T) in the cylinder will inevitably pass through the area that meets the conditions for NOx and soot generation, so that As a result, NOx and soot emissions will inevitably be generated during the combustion process, as shown in Figure 2. When the in-cylinder temperature is lower than 1650 K, no matter how the Φ and T in the cylinder change and develop, the combustion process can avoid the area that satisfies the generation conditions of NOx and soot emission, and ultra-low NOx and soot emission can be realized simultaneously . Common LTCs include homogeneous charge compression ignition [9] (HCCI), premixed charge compression ignition [10] (PCCI), and reactivity controlled compression ignition [11] (RCCI). These techniques are the same in terms of fundamentals, but differ in approach.

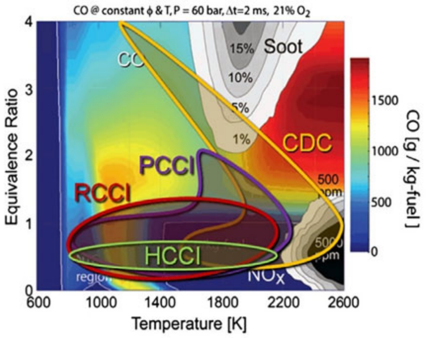

Figure 2. Contour plots of emissions depicting the operating regions of LTC modes compared to the conventional diesel combustion (CDC) model[7]

HCCI has two distinct advantages over conventional diesel combustion. First of all, its mixture is lean, which effectively avoids the generation of NOx and soot. Secondly, its specific heat capacity is relatively high, which is beneficial to improve the thermal efficiency of the engine [12]. The Southwest Research Institute of the United States [13] used low-pressure injection to inject diesel into the intake port, and at the same time used intake heating to promote the mixing of diesel and air to ensure the formation of a uniform mixture. The research results show that NOx emissions can be reduced by more than 98%, and PM emissions are reduced by 27% compared with the original machine. However, the control of combustion phase and pressure rise rate under high load is one of the difficulties of HCCI [14]. For this reason, scholars have proposed to realize premixed charge compression ignition (PCCI) by means of high EGR rate and early injection in cylinder, which can effectively control the combustion phase, but high EGR rate under high load will affect combustion stability[15].

RCCI injects low-activity fuel into the intake port to form a lean homogeneous mixture, and cooperates with direct injection of high-activity fuel in the cylinder to form active stratification, thereby controlling the combustion rate. Kokjohn [16] explored the performance of gasoline/diesel RCCI and achieved a thermal efficiency of 50%, while NOX and soot emissions were close to zero. Splitter [17] optimized the active stratification in the cylinder by increasing the activity difference between direct injection fuel and premixed fuel, and at the same time adopted a leaner mixture and a piston with low heat transfer, achieving a thermal efficiency of nearly 60%, NOX And soot emission is also controlled at an extremely low level. However, due to the large amount of pre-mixed fuel in RCCI, there is more residual fuel in the clearance area, and the HC and CO emissions are higher.

3. Influence of Combustion System Parameters on Low Temperature Combustion

3.1. Effect of EGR on Low Temperature Combustion

Zheng [18-20] conducted LTC bench tests with diesel and two biodiesels. The results showed that when air was used as the oxidant, NOx production was mainly affected by temperature, oxygen concentration and time during the reaction. Therefore, under the steady-state condition of the diesel engine, the NOx emission will monotonically decrease with the increase of EGR, as shown in Fig. 3. This is mainly due to the dilution effect, thermal effect and chemical effect of EGR. EGR dilutes the oxygen concentration in the working fluid while increasing its specific heat capacity, thereby reducing the flame temperature. In addition, the endothermic reaction of EGR components (such as H2O) may also contribute to the reduction of flame temperature.

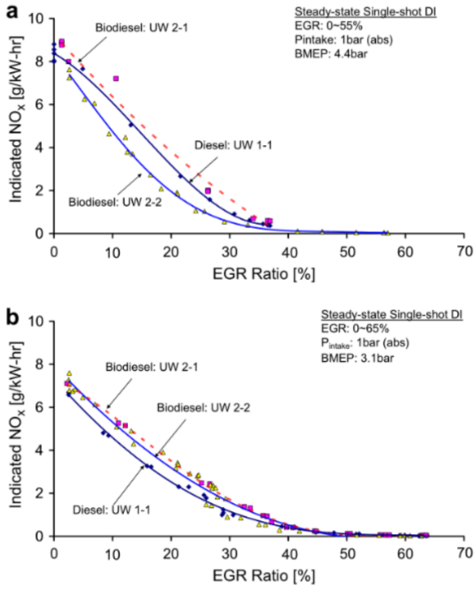

Figure 3. Effects of EGR on engine indicated NOx output under (a) medium load and (b) low load condition[18]

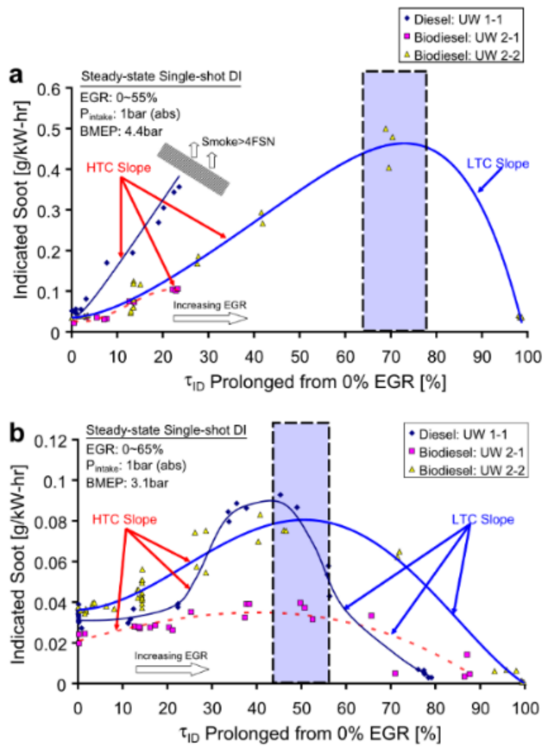

Figure 4. The effect of EGR on the indicated output of engine soot under (a) medium load and (b) low load conditions[18]

Under steady-state conditions, increasing the EGR rate results in an increase in the ignition delay period. Figure 4 shows the effect of ignition lag (caused by increasing EGR rate) on engine soot. Two distinct slopes were observed for the soot vs. ignition delay curve. At the first slope, the soot concentration increases with EGR until the ignition delay is extended by 50-70%. After that, with the increase of EGR, that is, with the further extension of the ignition delay period, the soot gradually decreases. Judging from the two slopes, the former is consistent with the high temperature combustion mode (HTC), so it is called the HTC slope. The latter reduces both NOx and soot, hence the name LTC slope. The HTC slope shows that with the increase of EGR, soot will increase, especially in the high temperature and oil-rich environment, the precursor of soot will be generated, while the low oxygen environment will hinder the oxidation of soot in the next stage. While the LTC slope indicates that the high rate of EGR and the reduction of cylinder temperature during the expansion stroke will increase the ignition delay period, resulting in better fuel-air mixing. Therefore, the low temperature premixed combustion stage will dominate the heat release rate while reducing NOx and soot levels. In order to extend the applicability of EGR, air intake throttling is used to increase the pressure difference between exhaust and intake air, especially at low load conditions, because the CO2 concentration generated under such conditions is limited [21].

3.2. Influence of Intake Pressure on Low Temperature Combustion

Zhang [22] considered the impact on low-temperature combustion of diesel engines from the perspective of intake pressure. Tests have shown that the increase in pressure will shorten the ignition delay period, and the Soot peak value in the Soot-Bump area will increase. If the EGR rate is increased in this area, the NOx emission will be effectively reduced. Air charge density is an important way of low-temperature combustion of diesel engines; although the trade-off relationship between NOx and Soot is solved in the higher EGR region, the trade-off relationship between fuel economy, CO and THC emissions and Soot is added -off relationship; at the same time, it also pointed out that the main direction of future diesel engine combustion technology is to optimize the medium EGR region before the appearance of Soot-Bump by comparing the performance and emission characteristics of medium EGR rate and high EGR rate.

3.3. Effect of Compression Ratio on Low Temperature Combustion

Alper [23] studied the emissions of low temperature combustion under different compression ratios. Parametric experiments were performed at an engine speed of 800 rpm. It has been determined that as the mixture becomes leaner, the in-cylinder pressure and heat release rate decrease. An increase in the octane rating of the fuel results in a longer burn duration. Combustion duration decreases with increasing compression ratio. It was found that at lower compression ratios, CO and HC emissions were higher, while NOx emissions were lower. As the compression ratio increases, CO and HC emissions decrease, but NOx emissions increase. The maximum thermal efficiency obtained using RON40 fuel at 800 rpm and 12:1 compression ratio is 38.2%. The widest operating zone is obtained with RON20 fuel at a compression ratio of 10:1 and a minimum effective fuel consumption rate of 210 g/kWh.

Zhang [24] believed that low compression ratio has no effect on emission improvement at low load, so high compression ratio is more suitable for low load. When the load is large, although the fuel economy becomes worse, it has a significant effect on reducing the soot emission. And if a higher EGR rate is used, a larger intake pressure is required, and when the compression ratio is larger, the maximum burst pressure in the cylinder will be very high. Therefore, it is advisable to use a low compression ratio when the load is large.

3.4. Influence of Injection Strategy on Low Temperature Combustion

Bharathiraja [25] studied the control of emissions and combustion phasing of the LTC combustion concept through a dual injection strategy and studied the effects of fuel injection pressure, intake air temperature and pressure. The project is only run on part load with diesel as fuel. LTC's post-injection strategy is employed. The results show that the dual-injection strategy improves thermal efficiency compared to the single-injection strategy. Pilot injection timing and mass fraction play a vital role in controlling emissions and improving thermal efficiency. At all intake temperatures, NO emissions increased and soot, CO, and HC emissions decreased if fuel injection pressure increased resulting in increased thermal efficiency. Also at all intake temperatures and fuel injection pressures, an increase in intake pressure results in increased thermal efficiency, reduced soot and NO, HC and CO emissions. The maximum indicated thermal efficiency achieved was 38%, which is 8% higher than the base reading. The lowest achieved NO emission was 187 ppm, which is 68% lower than the base reading. The lowest soot achieved was 3% of opacity, which is 75% below the base reading. Based on the comprehensive comparison results, the optimized fuel injection pressure is 600 bar, the intake air temperature is 310 K, and the intake air pressure is 107 kPa. In this case, soot was reduced by 23%, NO was reduced to 63%, CO was reduced to 75%, and thermal efficiency increased to 4% compared to the base reading.

4. Influence of Fuel Properties on Low Temperature Combustion

Zheng [26] compared diesel oil with n-heptane liquid, and mainly studied the influence of n-heptane liquid volatility on low-temperature combustion performance. Compared with diesel oil, n-heptane has a smaller liquid-phase penetration distance and better volatility, which promotes the evaporation and atomization of liquid-phase fuel oil, making the final gas-phase penetration distance difference smaller; and the Weber number of n-heptane is larger than that of diesel oil, which is more It is conducive to the crushing of fuel oil and the mixing of gas in the cylinder is more complete. The Soot emission of low-volatility fuel is more sensitive to injection pressure changes than high-volatility fuel, that is, the increase in Soot emission is higher when the injection pressure is reduced, thus improving the volatility of fuel and reducing low-temperature combustion to high injection pressure needs.

The team also studied the effects of different proportions of wide-fraction fuels blended with gasoline and diesel on the low-temperature combustion performance and emissions of diesel engines [27]. The research shows that the cetane number is the main factor affecting the law of combustion heat release in low-temperature combustion of diesel engines, and the wide-fraction fuel has little effect on the indicated thermal efficiency; when the proportion of gasoline in the wide-fraction fuel increases and the volatility increases, the indicated thermal efficiency will decrease. It will increase slightly and reduce Soot emissions. The main factor is the extension of the ignition delay period caused by the reduction of cetane number. When the gasoline blending ratio is high and the EGR rate is large, the improvement of Soot emissions by using wide-cut fuels is more obvious ; The impact of wide fraction fuel on NOx, CO and THC emissions is relatively small, and ultra-low NOx emissions can be achieved under high EGR rate conditions, but the CO and THC emissions problems need to be solved at this time, and the 2.5 homogeneous mixture diesel ignition THC emissions are higher for higher proportions of broad-cut fuels in combination with low-temperature combustion.

Zhu [28] used biodiesel fuel to conduct a low-temperature combustion test in a single-cylinder diesel engine. They mainly studied the impact of biodiesel CO and HC emissions, and analyzed the correlation between these two emission products and basic combustion parameters. The research shows that: when the equivalence ratio is large, the CO emission is mainly related to the equivalence ratio; when the equivalence ratio is low and medium, the CO emission is mainly related to the highest average combustion temperature; the HC emission is mainly related to the ignition delay period and the highest average combustion temperature; CO emissions are similar to those of diesel, but HC emissions are less than those of diesel.

5. Conclusion

It is impossible to avoid the high-temperature oxygen-deficient area and the oil-rich anoxic area at the same time in the traditional combustion method, and one of the ways to reduce the formation of NOx and PM at the same time is to change the combustion curve and adopt a low-temperature combustion method. In order to achieve good combustion and emissions, a reasonable EGR range and compression ratio should be selected. When selecting unconventional fuels, it is necessary to fully consider the influence of the fuel's physical and chemical properties on low-temperature combustion and emissions. Relatively speaking, alcohol fuels have more advantages in achieving low-temperature combustion due to their own fuel characteristics.

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