STUDY ON COLD STARTING PERFORMANCE OF A LOW COMPRESSION RATIO DIESEL ENGINE BY USING INTAKE FLAME PREHEATING

Chao ZHANG[1], Bolan LIU[1,*], Jingchao HU[1], Xiyang YU[1], Xiaogang WANG[1]

[1]School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, PR China

[*]Corresponding author; E-mail: liubolan@bit.edu.cn

Power density improvement is one the main techniques for engine thermal efficiency promotion. For turbocharged diesel engine, low compression ratio (LCR) in normally adopted for safety consideration under high power density operation. However, LCR tends to lead cold starting problem. In this study, the influences factors and performances of a 10-cylinder turbocharged diesel engine was investigated. An intake flame preheating model was built and validated by series of bench tests. The optimization of starting parameters and flame heating was conducted eventually. Based on the study, the basic performance flame preheating system under different conditions was disclosed. The cold starting boundary parameters of the diesel engine was found. Moreover, the best starting fuel injection parameters were acquired. The research is beneficial for diesel engine power density promotion based on cold starting ability.

Keywords*: low compression ratio, cold start, intake flame preheating*

Introduction

Thermal efficiency improvement is one of the driving forces for the development of internal combustion engines [1-3]. It is well known that increasing power density can beneficially improve thermal efficiency [4]. Thus, in order to promote engine power density, it needs to do more work in unit time or get more air into the cylinder to burn more fuel [5-6]. The two-stage turbo charging is used as a common method, which can improve the Indicated Mean Effective Pressure (IMEP) of diesel engine effectively. From the aspect of structure and material, enhancing the body strength and stiffness of engine can improve the power and economic performance. However, there is always a limit of strength and stiffness, with the absence of great progress in material and technology of diesel engine manufacturing [7-9]. By ultra high boosting pressure, it is necessary to use some method to restrict the improvement of maximum pressure, to ensure that with the increase of IMEP, the thermal load and mechanical load remain at the same level, the usual method is to reduce the compression ratio [1-3].

Therefore, the development trend of diesel engine technology to improve power density is to reduce the compression ratio. The compression ratio of the direct injection diesel engine is about 18-22, and it can even be reduced as low as 12 after adopting the high turbocharging technology [10-11]. Under normal temperature and running conditions, it has little effect on the working of diesel engine, but when the engine running in the extremely cold weather, the temperature at the end of compression stroke can't reach the spontaneous combustion temperature of diesel fuel, which will cause the engine can't start up and work normally [12-13]. Besides, the performance of the storage battery will reduce owing to the low temperature, which will cause the performance reducing of the start-up system [14-15]. Low temperature has great influence on the cold start performance of diesel engine. The maximum speed of a diesel engine depends on the power provided by fuel combustion and the friction torque of diesel engine [16].When the ambient temperature is low, the viscosity of the lubricating diesel is larger, and the friction torque of the diesel engine is increased, more fuel is needed to overcome the friction resistance and pump loss. with the decrease of temperature, the temperature at the end of compression stroke will decrease, the time of spontaneous combustion is postponed, which leads to misfire, and the number of the misfire cycle will increases with the decrease of the speed [17]. To solve this problem, it is necessary to add various kinds of auxiliary starting measures, many scholars have done a lot of researches on this problem.

In this paper, a 10-cylinder diesel engine model was built and validated, the limit boundary conditions of diesel engine cold start was studied based on the model. An intake flame preheating system model was built and validated by several sets of bench test. Based on the simulation and test, the effects of the ignition performance, combustion stability, air preheating characteristics and gas composition on the preheating system were studied under the condition of variable wind speed, variable temperature and variable preheating fuel supply. This research provides an effective basis for the reliability of the intake flame preheating system, which makes it more reliable to increase the power density by reducing the compression ratio.

2. Experimental set up and test methodology

2.1 Experimental set up

The main purpose of the preheating test bench is to improve the temperature of the intake air through the combination of the circuit path and the fuel path to burn the fuel in the intake pipe, and achieve the best preheating effect, through the matching and optimization of fuel and electricity.

The schematic diagram of the test bench system is shown in Fig. 1. The system mainly includes mechanical part, circuit part, fuel line part, data acquisition part and control system, which can be seen in Table 1. The axial flow fan blows the air into the intake manifold. The ECU controls the on-off of the relay and the solenoid valve, thereby controlling the on-off of the circuit path and the fuel path.

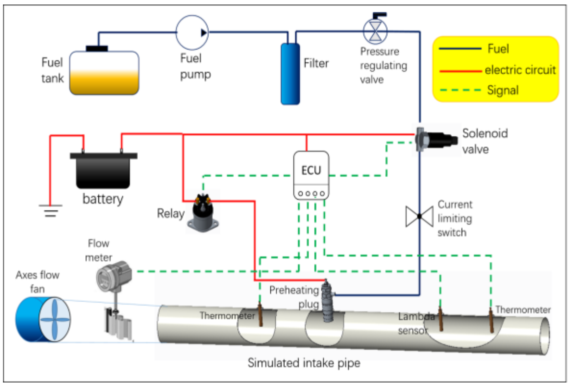


Fig. 1 The schematic diagram of the test bench system

Table 1. The compositions of the test system

Subsystem	Composition

Mechanical part	Brackets , Intake pipe , Axial flow fan
Circuit part	Storage Battery , Relay , Solenoid valve , Preheating plug
Fuel line part	Tank , Fuel pump , Fuel filter , Preheating plug , Pressure regulating valve
Control system	Control box
data acquisition part	Vortex flow sensor , Thermometer , Lambda sensor , Fuel pressure meter, Image equipment

2.2 Test methodology

The main purpose of this test is to provide validation for the intake preheating model. The test was carried out under different environment conditions, and the preheating effect mainly includes the preheating temperature rise, the oxygen content after preheating, the ignition performance, and the combustion stability and so on. The air velocity in the simulated intake pipe is adjusted by adjusting the speed of the fan, which simulates the air velocity in the intake pipe at different starting speeds of diesel engines. The fuel supply can be changed by adjusting the opening of the limiting valve, the maximum adjustable range of fuel flow is from 1ml/min to 30ml/min. The fuel pressure can be changed by regulating the opening of the regulating valve, the range of pressure in the test is 2-4 bar. The electric heating time, ignition time and flame preheating time can be controlled separately by changing the power up time of relay and solenoid valve. The ambient temperature during the test period is between 0-10 degrees, which meets the temperature condition of cold start preheating.

3. Intake preheating system model and the whole engine model

3.1 Mathematical model of Intake Preheating

The preheating plug is installed on the head of the simulated intake pipe, which is mainly composed of three components, injector, igniter (electric heating column) and shell. When the system begin to work, the electric resistance wire is heated until the temperature of heating column raise to the spontaneous combustion temperature of diesel fuel. Diesel fuel is injected to the electric heating column and begins to burn, which generates a lot of heat. Heated air, unburned fuel and combustion products get into the cylinder. The combustion process can be expressed by the following chemical equation (excluding combustion by-products):

$$C_{11}H_{21}+16.25\left(O_2+3.773N_2\right)\Rightarrow 11CO_2+10.5H_2O+61.31N_2 \tag{1}$$

This process can make the following assumptions: the gas in the intake pipe is simulated as one-dimensional steady flow, and the variation of intake pressure can be ignored. For the process of heating a flow of gas by a flame, according to the conservation of energy:

$$\frac{dU}{dt}=\frac{dW}{dt}+\frac{dQ}{dt}+h\frac{dm}{dt} \tag{2}$$

Where U is Internal energy of air intake, W is the work done by the system, Q is the quantity of heat supplied to the system by its surroundings, m is the mass of intake air in unit time, and h is specific enthalpy.

The work done by the system and the energy change caused by mass exchange can be neglected, and the following formula can be obtained:

$$\frac{dU}{dt}=\frac{dQ}{dt}=\frac{dQ_B}{dt}-\frac{dQ_w}{dt} \tag{3}$$

Where Q_B is the heat released from diesel combustion, Q_w is the heat dissipated by air through the intake pipe wall to the environment. Neglecting the effect of excessive air coefficient ($dU = d(mu)$), the following formula can be obtained:

$$\frac{d\left(mu\right)}{dt}=u\frac{dm}{dt}+mC_v\frac{dT}{dt} \tag{4}$$

Where C_v is the specific heat. Due to the volume of pipe is a constant, the specific heat is considered as C_v (Specific Heat at Constant volume).

Then the temperature rise after preheating in the intake pipe is:

$$\frac{dT}{dt}=\frac{1}{mC_v}\left(\frac{dQ_B}{dt}-\frac{dQ_w}{dt}\right) \tag{5}$$

It can be seen from the formula, the preheating temperature rise and the airflow velocity in intake pipe are related to the flow of fuel and the amount of heat lost to the environment.

The heat released from diesel combustion is:

$$\frac{dQ_B}{dt}=H_u\eta_u\rho_u\frac{dV_f}{dt} \tag{6}$$

Where H_u is the Lower Heat Value (LHV) of the diesel fuel used, η_u is the combustion coefficient of diesel fuel, ρ_f is the density of diesel fuel, V_f is the volume flow of diesel in unit time.

The wall heat dissipation of the intake pipe is:

$$\frac{dQ_w}{dt}=\alpha_A A\left(T-T_w\right) \tag{7}$$

Where α_A is the heat dissipation coefficient of wall, A is the total surface area of the heat dissipation of the simulated intake pipe, T_w is the inner wall temperature of the intake pipe,

Suppose the gas is ideal gas, then:

$$mC_v\frac{dT}{dt}=\left[H_u\eta_u\rho_f\frac{dV_f}{dt}-\alpha_A A\left(T-T_w\right)\right] \tag{8}$$

The amount of air consumed by diesel combustion is:

$$\frac{dV_a}{dt}=\frac{\rho_f l_0}{\rho_a}\frac{dV_f}{dt} \tag{9}$$

Where V_a is the volume of consumed air, ρ_a is the density of air, l_0 is the theoretical air fuel ratio of diesel combustion.

Fig.2 shows the model of intake preheating system, and Fig.3 shows the whole engine model, which are built by GT-POWER. The whole diesel engine model contain six independent subsystem, Intake and exhaust system, cylinder system, turbocharging system, cooling system, leakage model and starting system.

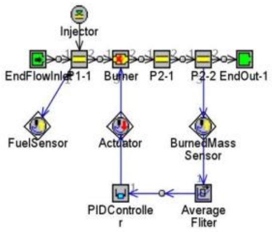


Fig.2 Simulation model of intake preheating system

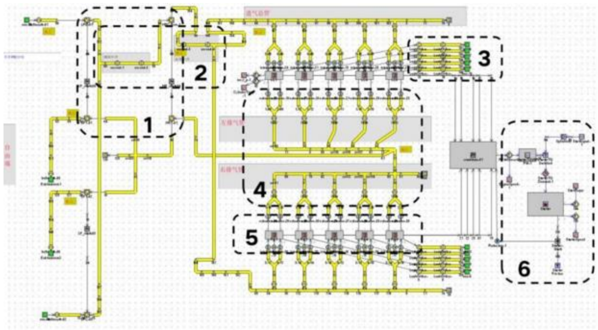


Fig.3 Simulation model of 10-cylinder diesel engine

3.2 Model validation

By conducting some intake flame preheating tests under different ambient temperature, wind speed and preheating fuel supply, the intake flame preheating model was validated under different running conditions. For all these working points, the model accuracy is controlled within 8% error range, which is the guarantee of the prediction for starting assist under different flame preheating support for the low compression diesel engine. The flame preheating test parts can be found in section 4.1.

The 10-cylinder model was validated through the cylinder pressure curve under different engine working points. As can be seen from Fig.4, the rated point was illustrated as an example, though there are some differences in the decline section of the explosion pressure, the maximum error is less than 4%, except this, the simulation cylinder pressure curve at other stages is well matched with the test cylinder pressure curve. The study of the intake flame preheating on the LCR diesel engine start ability can be performed by using the combined model.

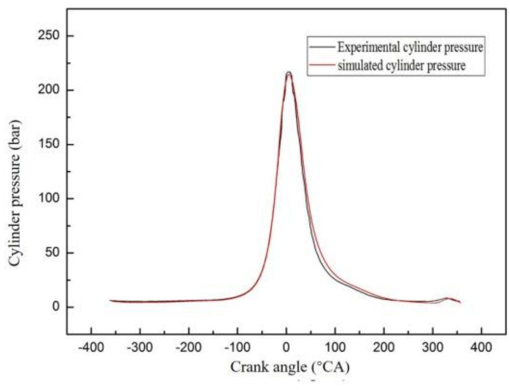


Fig.4 Validation of the 10-cylinder diesel engine model at rated point

4. Results and discussion

4.1Intake flame preheating performance

A series of the intake flame preheating tests was conducted on the test bench. Both the bench structure and modulating parameters are designed to simulate the possible running conditions of the real operations. The tests of different ambient temperature were conducted to simulate different engine starting thermal environment. The varied intake manifold mass flow rate is simulated by different channel wind speed according to engine idle speed. The flame preheating fuel supply is adjusted by adjusting the opening of limiting valve and the appropriate level of fuel supply is evaluated based the photography of the flame combustion status.

The temperature rise (TR) of preheated air under different ambient temperatures, different wind speed and different preheating fuel supply are shown Fig.5, Fig.6 and Fig.7 respectively. There are 3 parameters were investigated, at each figure, the fixed other 2 parameters was chosen as follow, ambient temperature: 8.2°C; wind speed: 7m/s; fuel supply: 8ml/min.

As can be seen from Fig.6, under different ambient temperature, the higher the ambient temperature is, the temperature of air at the rapid-raise period and the stabilization period is higher, but the final temperature raise is all between 40-50°C. 10°C of intake can be promoted for every 5°C environment increment. A similar trend can be seen from Fig.8, the greater the fuel supply, the higher the temperature rises. However, at different wind speeds, which can be seen from Fig.7, the initial temperature rise of 9m/s wind speed is slightly faster than that of 7m/s and 5m/s, and in the later stage, the faster the wind speed, the lower the temperature raise. This is because at beginning of preheating, it is faster that the heated airflow reach the end of the pipeline at higher wind speed. However, in later stage, the higher the wind speed, the bigger the volume of air flowing through the preheating plug in unit time, when the preheating fuel supply is fixed, the heat released in unit time is the same, and the larger the flow rate, the more serious the heat is diluted.

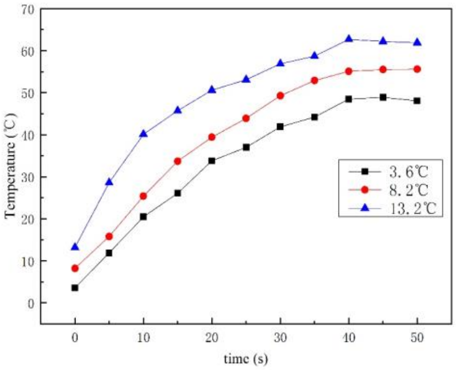


Fig.5 TR under different ambient temperatures

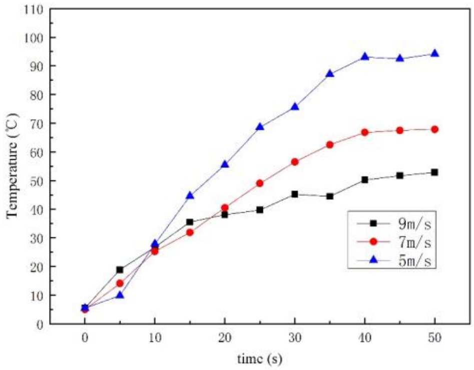


Fig.6 TR under different wind speed

During the testing, there was some dripping liquid fuel below the flame preheating plug and Outflow at the end of the pipe. Measuring the flow at the end of the pipeline with the measuring cylinder, and that is called ‘residual fuel’.Fig.8 shows the residual fuel situation under different preheating fuel supply. It can be seen that when the fuel supply exceed 8ml/min, the greater the fuel supply is, the more the residual fuel is, which should be avoided as far as possible.

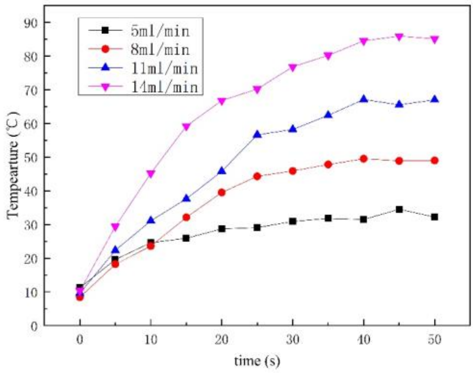


Fig.7 TR under different preheating fuel supply

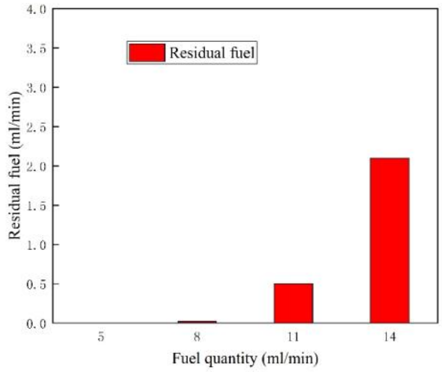


Fig.8 Residual fuel

The flame combustion state in Fig.9 is shown at different preheating fuel supply. In the case of the fuel supply is 5ml/min, the flame is small and red. With the increase of fuel supply, the volume of flame begins to increase. When the fuel supply is above 14ml/min, there are some sporadic sparks appear around the main flame, and unburned small droplets that are visible to the naked eye fall on the pipe wall. This indicates that the dripping fuel can't be completely evaporated and burned at the time, and the white smoke is emitted at the end of the intake pipe. Due to the constantly flowing air, the oxygen is sufficient for the combustion of fuel in the preheating plug. However, the fuel is streaming down but not dropping when the fuel supply is exceed 8ml/min, and there is an area limitation of resistant wire, therefore, not all fuel can be heated and burned.

a. 5ml/min　　b. 8ml/min　　c. 11ml/min　　d.14ml/min

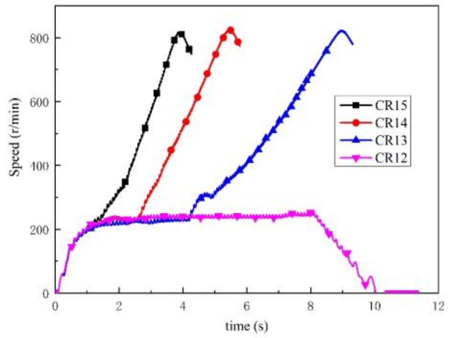
Fig.9 Flame combustion state under different preheating fuel supply

4.2 Cold start characteristics of LCR diesel engine

In order to explore the effect of parameters and environmental conditions on the performance of diesel engine cold start, searching the limit boundary condition of diesel engine cold start under different parameter matching, the simulation of cold start performance of diesel engine was carried out at different compression ratio, intake temperature, altitude and injection quantity.

The starting speed of diesel engine under different compression ratio, different intake temperature, and different altitude are shown in Fig.10, Fig.11 and Fig.12 respectively. There are 3 parameters were investigated, at each figure, the fixed other 2 parameters was chosen as follow, CR: 14; intake temperature: 0°C; altitude: 0m.

As can be seen from the figures, with the decrease of compression ratio, the decrease of intake temperature and the increase of altitude, the starting time of diesel engine increases rapidly. The compression ratio decreases leads to the thermal efficiency decreases, resulting in insufficient utilization of fuel and gas. Under the same fuel supply, the total energy of combustion heat release decreases, and the output power decreases. It can also be seen from the figures that, when compression ratio is below 12, the temperature is below 0°C and the altitude is above 1000m, there is a faltering at speed rise period, which is an important factor affecting the speed stability and starting time of diesel engine cold start. When the compression ratio is lower than 12, the intake temperature is below -20°C and the altitude is higher than 2000m, the diesel engine can't start normally without auxiliary starting measures.



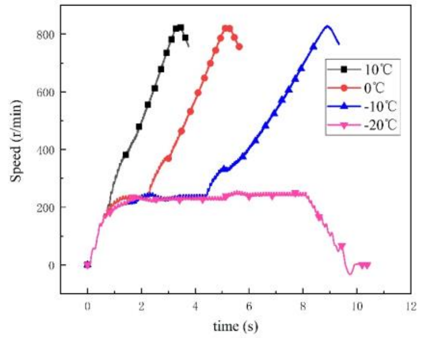
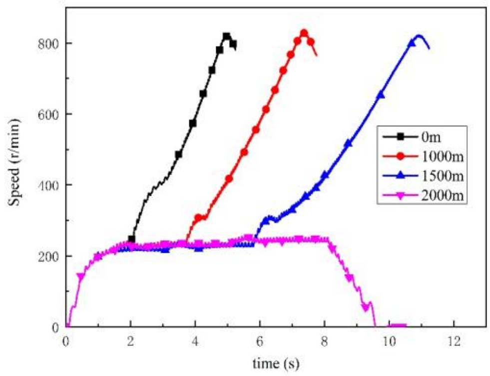


Fig.10 Starting speed under different CR **Fig.11 Starting speed under different temperature**

Fig.13 show the starting speed of diesel engine and the first ignition cycle under different injection quantity, the compression ratio is 14.5, the intake pressure is 1bar, and the ambient temperature is 10°C. As can be seen, the ignition time reduced to the minimum with the injection quantity increased near 60mg/ (cyc·cyl), only 1.6s. Therefore, the optimal injection quantity for cold start is 60mg/ (cyc·cyl). When the amount of the main fuel injection continues to increase, the ignition time increases again, and the first ignition cycle postpone again, however, once ignition occurs, the increase rate of diesel engine speed under heavy injection quantity will be higher than that of small injection quantity.



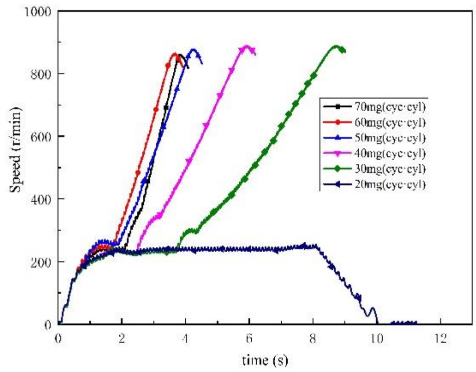


Fig.12 Starting speed under different altitude **Fig.13 Starting speed under different injection quantity**

Pilot injection is an effective measure to improve the cold start performance of diesel engine, the pilot injection can bring the cold flame effect, which can improve the temperature in cylinder before main injection, activate the heating atmosphere of mixed gas in cylinder, Improve the combustion conditions, shorten the ignition time [18-19]. Fig.14 show the starting speed of diesel engine and the first ignition cycle under different pilot injection quantity. At each cases, the wind speed is 7m/min, the ambient temperature is 0°C, and the fuel supply is 8ml/min. As can be seen from the figure, an appropriate pilot injection quantity can shorten the ignition time. However, the starting performance will be reduced when the pilot injection quantity is too high, because the cold flame reaction time is insufficient, which is not conducive to the improvement of the combustion thermal atmosphere in the cylinder. The optimal pilot injection quantity is 5 mg/ (cyc·cyl), which the ignition time is the least.

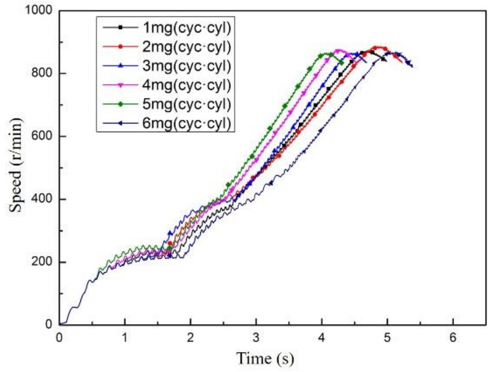


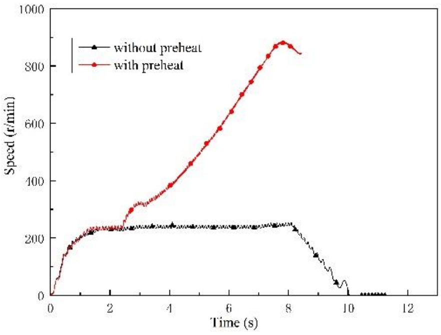
Fig.14 Starting speed under different pilot injection quantity

4.3 Optimization of diesel engine cold starting by intake flame preheating

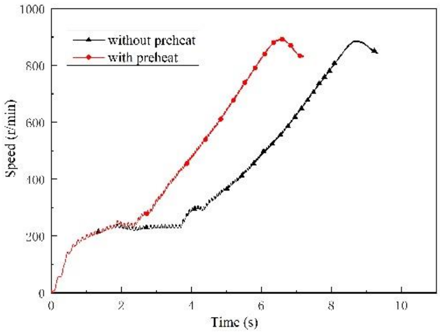
The difficulty of cold start could be relieved by optimize the injection strategy, but there is no fundamental change in combustion and emissions, even could increase fuel consumption. According to the starting performance mentioned above, the optimization of the cold starting control parameters was performed by using validated flame preheating model and diesel engine model.

Comparison of diesel engine cold start speed with preheat and without preheat is shown in Fig.15. At each cases, the wind speed is 7m/min, the ambient temperature is 10°C, and the fuel supply is 8ml/min. The performance of cold start is greatly improved with preheating. Under the same starting injection quantity, the ignition time is obviously shortened, and the first ignition cycle is obviously reduced. In the case of the injection quantity is 30-70mg/(cyc·cyl), the ignition time is reduced about 0.4-2.2s, the first ignition cycle is reduced about 0-3. Without preheating, when the injection quantity is less than 20 mg/(cyc·cyl), the engine can't start normally, but when the preheating system is added, it can start normally.

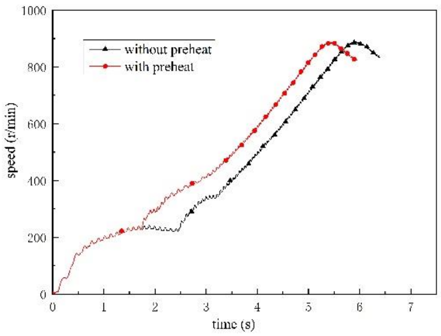
Without preheating, as mentioned above, the best starting performance appears at the injection quantity is 60 mg/(cyc·cyl), when the preheating system is added, as can be seen from the figure, the best point appears at the injection quantity is 50 mg/(cyc·cyl), which the ignition time is the least. The addition of the preheating system makes the atomization, evaporation and mixing of diesel fuel more rapid, the suitable mixture concentration can be reached at lower injection quantity, the fuel consumption and emissions may be improved as a result.



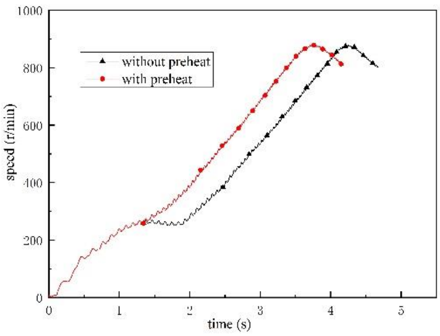
(a) injection quantity = 20mg/(cyc·cyl)



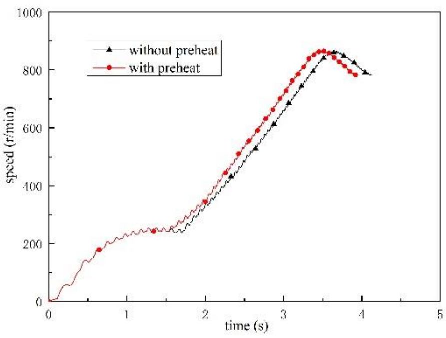
(b) injection quantity = 30mg/(cyc·cyl)



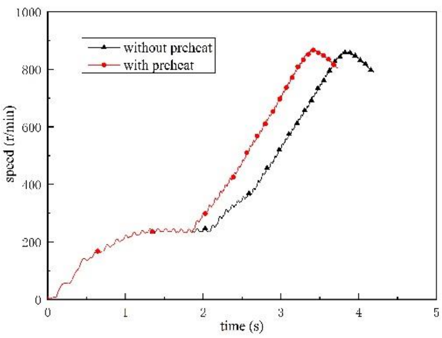
(c) injection quantity = 40mg/(cyc·cyl)



(d) injection quantity = 50mg/(cyc·cyl)



(e) injection quantity = 60mg/(cyc·cyl)



(f) injection quantity = 70mg/(cyc·cyl)

Fig.15 Comparison of starting speed between the engine start with preheat and without preheat

Fig.16 shows the comparison of starting speed between the engine start with pilot injection but without preheat and the engine start with preheat but without pilot injection. At each cases, the fuel supply is 8 ml/min, the wind speed is 7 m/s, and the ambient temperature is 0°C. From the figure, we can see that, although the speed rise rate under the condition of the engine start with pilot injection but without preheat is higher than that the engine start with preheat but without pilot injection, the ignition time of both is basically the same. This means that the intake flame preheating system can replace the pilot injection to improve the starting performance, which can reduces the complexity of fuel injection control, and to some extent, reduces the fuel consumption.

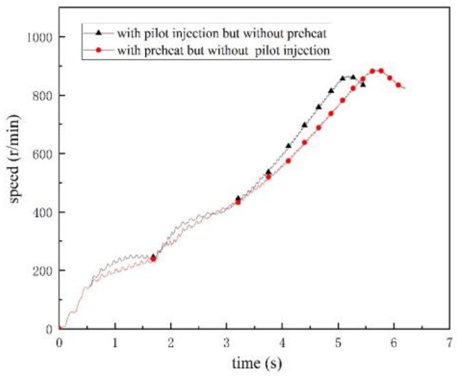


Fig.16 Comparison of starting speed between the engine start with preheat and with pilot injection

5. Conclusion

In order to solve the difficulty of cold start of LCR diesel engine, this paper built a10-cylinder diesel engine model and an intake flame preheating model which validated by several sets of bench tests. Based on the simulation and the test, the limit boundary conditions of diesel engine cold start was studied, the factors affecting the performance of the intake preheating system were studied. The main conclusions can be found as follow,

1. For the 10-cylinder diesel engine intake system, Every 5°C of environment increment can bring average 10°C temperature promotion of intake. Every 2m/s of intake speed increment can bring average 15°C temperature promotion of intake. 8ml/min fuel supply is proper for the combustion of the preheating plug.
2. The self cold starting boundary for the diesel engine is as follow: the CR is 12 (at 0°C intake temperature and 0 m altitude), the intake temperature: -20°C (at 14 CR and 0 m altitude), the altitude: 2000m (at 14 CR and 0°C intake temperature).
3. The addition of intake flame preheating system can reduce the best starting injection fuel quantity from 60 mg/(cyc·cyl) to 50 mg/(cyc·cyl), the preheating system also can replace the pilot injection to improve the starting performance.

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Nomenclature

LCR	-Low compression ratio [-]	IMEP	- Indicated mean effective pressure [MPa]
CR	-Compression ratio [-]	TR	-Temperature raise [°CA]

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