# Research on Clean Combustion Technology of EGR-based Flameproof Diesel Engine

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**Original Article**

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# Research on Clean Combustion Technology of EGR-based Flameproof Diesel Engine

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**Abstract:** In view of the serious pollution of NOx emissions from flame-proof diesel engines used in coal mines and its direct and indirect hazards that cannot be ignored, the combustion process of flame-proof diesel engines is analyzed and a combustion mathematical model is established. Subsequently, the clean combustion method based on exhaust gas recirculation (EGR) is adopted, and an EGR clean combustion device is designed, which meets the requirements of the coal mine standard *Safety Regulations on Coal Mine*. The design content involves: (i) Composition and structure design of EGR system meeting the requirements of flame-proof standards; (ii) The closed forced cooling cycle design of the EGR system. Specifically, the clean combustion process of flame-proof diesel engine based on EGR system is simulated and analyzed by fluid simulation analysis software, and the effects of EGR system on the performance and emission of flame-proof diesel engine under 15 operating modes of three rotational speeds and five loads are obtained. Then, the control strategy and control program of the EGR system of flame-proof diesel engine are compiled based on the mathematical model and simulation results. In addition, the bench test of the flame-proof diesel engine equipped with EGR device is carried out by using this control program in the laboratory, and the control program of EGR system is modified by analyzing the experimental data. Finally, the optimized bench test is carried out by selecting the control program that optimal matches the flame-proof EGR device and the flame-proof diesel engine. The test results suggest that: (i) Under the external characteristic working mode: after installing the EGR system, the power of the flame-proof diesel engine is 58.9kW under the optimized EGR opening, and the highest output torque is 252.3 Nm, and the power performance is slightly lower than that of the original engine; (ii) Under eight operating mode: after installing the EGR system, the weighted average CO emission of the flame-proof diesel engine under the optimized EGR opening is 0.0045%, and the volume concentration is increased by 0.0045% compared with that without the EGR system; the weighted average NOx emission of the flame-proof diesel engine under the optimized EGR opening is 93.35ppm, which is 56.17% lower than that without the EGR system, indicating that the EGR system technology has significantly improved the reduction of NOx emissions of the flame-proof diesel engine; (iii)Under eight operating mode: after installing EGR system, the HC emission of flame-proof diesel engine under optimized EGR opening is basically unchanged compared with that without EGR system, and the soot emission is slightly increased; and (iv) The EGR system meets the requirements of the coal mine standard, and this method and technology can improve the basis for reducing the NOx emission from the tail gas of the underground vehicles in the coal mine.

**Keywords:** Trackless Auxiliary Transportation; Flame-proof Diesel Engine; Exhaust Gas Recirculation (EGR); Clean Combustion; Control Strategy

## 0 Introduction

Trackless auxiliary transportation is a key component in the underground material transportation system of coal mine at present, which has the advantages of high transportation efficiency, strong power, fast traveling speed and good adaptability. [1-3] With the great-leap-forward development of the coal industry, the type and number of auxiliary transport equipment are increasing. Among them, trackless auxiliary transport vehicles (including flame-proof personnel transport vehicles, flame-proof material transport vehicles, flame-proof sprinklers, multi-function support trucks, flame-proof cement mixers, etc.) have been extensively used in coal mines. In trackless auxiliary transport vehicles, flame-proof diesel engines are broadly used because of their strong power and good economy. However, when the trackless auxiliary transport vehicle is running in the roadway, a large number of waste gas and dust emitted by its power plant flame-proof diesel engine are concentrated in the roadway, which can not be discharged through the ventilation system in time because many old mines underground roadway width is narrow, the height is low, the road surface quality is poor, the ventilation condition is not good. Once the harmful components and particles in the exhaust gas are inhaled by the workers working underground, nausea and vomiting, dizziness, chest tightness, wheezing and coughing will occur, which will cause great damage to the health of the miners. [4-6]This kind of exhaust gas is mainly composed of harmful components such as hydrocarbons (HC), nitrogen oxides (NOx), soot particles and carbon monoxide (CO) [7] [8]. Among these components, the volume concentration of NOx is relatively high, and the harm is great. The main component of this NOx is nitric oxide (NO). Although NO is colorless, tasteless and less toxic when its concentration is low, it will paralyze people's nerves and cause blood poisoning when its concentration is high, resulting in nerve paralysis and physical convulsion, and NO will react with oxygen in the air to form NO2. NO2 is generally reddish brown and has a strong pungent smell. After entering the miners' lungs, it reacts with water quickly to produce irritating soluble nitric acid, and a large number of high concentrations of NO2 will cause

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emphysema, which directly indicates the urgency and importance of solving the NOx pollution in coal mine exhaust.

Nowadays, EGR technology is one of the important methods for domestic and foreign scholars to study and explore to reduce NOX in diesel engine exhaust. The main research results are as follows: Zhou Yucai[9] simulated the changes of engine advance angle, air-fuel ratio and EGR rate by means of numerical simulation, and explored the effect of EGR system on engine emission nitrogen oxides through bench experiments. FU Jiping [10] designed an electronically controlled EGR system by theoretically studying the mechanism of EGR technology to reduce NOX emissions from diesel engines, and carried out matching tests between electronically controlled EGR systems and electronically controlled diesel engines in the laboratory. Through the analysis of the test results, the balance relationship between EGR rate and diesel engine power performance, fuel economy and particulate emissions was clarified. Liu Ming [11] explored the NOx emission of diesel engine under different injection advance angles and different EGR rates through experiments, and found the optimal control operating mode point of the electronically controlled EGR system. Based on these operating mode points, the MAP diagram of the EGR system was drawn. Wu Xiaojiang [12] deeply probed into the effects of different EGR rates on diesel engine power, fuel economy and emission performance under different load conditions, and proposed that small EGR rate should be selected for diesel engine under heavy load, otherwise large EGR rate should be selected. Zhang Xiangzhen [13] applied the EGR technology to the turbocharged diesel engine and studied the effect of this technology on the emission of turbocharged diesel engine through experiments. The experimental results show that the application of EGR technology can effectively reduce the NOx emission of diesel engine under medium and medium load conditions. Xi Duanliang [14] simulated the EGR system with fluid mechanics simulation software, explored the effects of several EGR rates on diesel engine combustion process and engine performance and emissions through experiments, and constructed the optimal 3D EGR rate MAP diagram. Hu Junyi [15] theoretically analyzed the principle of EGR and designed the EGR electronic control system. Through experiments, the emission characteristics of the diesel engine with different EGR rates were studied, and the two-dimensional map diagram which best matched the performance of the electronically controlled EGR system and the diesel engine was obtained. Liu Haifeng [16] confirmed the effect of EGR rate on NOx emission of diesel engine at several operating mode points at the same altitude, and deeply studied the optimum EGR rate of the diesel engine at different operating mode. WANG Hu [17] considered the combustion control technology based on EGR and explored the national V emission through experiments. Li Aijuan [18] verified the influence of EGR cooling temperature on diesel engine emission and performance in the cooling system of electronically controlled EGR device through experiments, and discovered the optimal cooling temperature range of electronically controlled EGR system under different operating mode of diesel engine. Guo Liang et al. [19] discussed the application of low pressure EGR system in diesel engine, and made clear the inflection point of diesel engine NOx emission with the peak combustion heat release rate through experiments. Xie Wei'an et al. [20] confirmed the influence of adding biodiesel and in-engine EGR purification technology on diesel engine emissions through experiments, and pointed out that in-engine EGR technology is effective in reducing NOx emissions of diesel engines.

In the past, most of the road diesel engines were taken as the research object, and the research of EGR technology was carried out by means of simulation and experiment, but the flame-proof diesel engine is different from the road diesel engine, and it is a special power plant which can be used in the dangerous environment of combustible gas. During normal operation, the high temperature and high pressure gas in the combustion chamber shall not be transmitted to the outside of the body. In addition, the exposed outer surface temperature should not exceed 150 ℃, which can be used as the ignition source of combustible gas, and the final exhaust temperature should not exceed 70 ℃. In order to meet these requirements and underground use in coal mines, flame-proof diesel engines need to be redesigned in accordance with the coal mine standard MT990-2006 *General Technical Requirements for Flame-proof Diesel Engines*. This suggests that it is urgent to study the new technology of flame-proof diesel engine used in coal mine to control and purify the NOx emission of flame-proof diesel engine.

## 1. Mathematical model of diesel engine combustion

### 1.1. Assumptions of calculation conditions for the combustion process of flame-proof diesel engines

For simplicity, the following assumptions are made on the combustion process of flame-proof diesel engine.

(1) The temperature, pressure and composition of the working fluid in the cylinder of the flame-proof diesel engine are the same, and the fresh air in the cylinder is completely integrated with the residual exhaust gas during the intake stroke.

(2) The working medium in the cylinder of flame-proof diesel engine is an ideal gas, and the internal energy and specific heat of the gas are only related to its own temperature and composition.

(3) The fuel is injected into the cylinder and burned immediately.

(4) The ratio of fresh air to fuel decreases gradually in the process of combustion.

### 1.2. Characteristics of working medium

The characteristic of working medium refers to the relationship between the specific heat and constant of mixture and its temperature, pressure and composition. The composition of mixture is often described by air-fuel ratio. The air-fuel ratio of flame-proof diesel engine refers to the mass ratio of fresh air to the fuel used. It is assumed that when calculating, the air-fuel ratio of pure air is infinitely large, and when there is a mixture of air and waste gas in the cylinder, the air-fuel ratio of the mixture is the average air-fuel ratio of air and waste gas. This rule is effective only when the excess air coefficient of the exhaust gas in the cylinder is greater than 1.1.

$$\mu_{air} = (1 - \mu_{FV} - \mu_{CP}) \times 100\% \quad (1)$$

Wherein: $\mu_{air}$ -- Mass percentage of air;

$\mu_{FV}$ -- Mass percentage of fuel steam;

$\mu_{CP}$ -- The mass percentage of combustion products.

Air-fuel ratio of combustion products in cylinder of flame-proof diesel engine:

$$AF_{CP} = \frac{\mu_{CP} - \mu_{FB}}{\mu_{FB}} \quad (2)$$

Wherein: $AF_{CP}$ -- Air-fuel ratio of combustion products;

$\mu_{FB}$ -- Mass percentage of fuel burned.

### 1.3. Combustion model

The performance of flame-proof diesel engine, that is, power, fuel economy and emission, is determined by the heat release law of fuel combustion in the cylinder, and the heat release law of fuel combustion is mainly reflected in in-cylinder pressure, combustion rate and temperature. Therefore, the accuracy of the calculation results is determined by the accuracy of the combustion heat release law. The law of combustion heat release is expressed as follows:

$$\frac{dQ_B}{d\varphi} = H_u \cdot g_f \cdot \frac{dx}{d\varphi} \quad (3)$$

Wherein: $H_u$ -- low calorific value of the fuel, in kJ/kg;

$dx / d\varphi$ is related to the physical and chemical reaction process and change of fuel combustion of flame-proof diesel engine and the structural parameters of components.

The combustion model built in the fluid simulation software mainly involves the quasi-dimensional model and the zero-dimensional model, while the quasi-dimensional combustion model AVL MCC model is adopted in this paper. The model changes the exothermic characteristics by controlling the quality of the mixed fuel and the turbulent kinetic energy density in the cylinder, and mainly predicts and calculates the emission of the engine. The main parameters that can be set in the model are the diameter of the injector, the number of injection holes, the injection angle, the injection law and the pipeline pressure. According to the input parameters, the fuel injection rate and kinetic energy are calculated, and the premixed combustion and diffusion combustion are comprehensively considered. The heat release rate formula is as follows:

$$\frac{dQ_F}{d\varphi} = \frac{dQ_{MCC}}{d\varphi} + \frac{dQ_{PMC}}{d\varphi} \quad (4)$$

$$\frac{dQ_{MCC}}{d\varphi} = C_{Comb} \cdot f_1(m_F, Q_{MCC}) \cdot f_2(k, V) \quad (5)$$

$$f_1(m_F, Q_{MCC}) = (m_F - \frac{Q_{MCC}}{H_u}) \cdot (w_{Air,available})^{C_{EGR}} \quad (6)$$

$$f_2(k, V) = C_{Rate} \cdot \frac{\sqrt{k}}{\sqrt[3]{v}} \quad (7)$$

$$\frac{(dQ_{PMC} / Q_{PMC})}{d\varphi} = \frac{6.908}{\Delta\varphi_c} \cdot (m+1) \cdot y^m \cdot e^{-6.908 \cdot y^{(m+1)}} \quad (8)$$

Wherein, $Q_{MCC}$, $Q_{PMC}$ -- Total heat release rate of diffusion and premixed combustion, in kJ;

$C_{Comb}$ -- Combustion constant, in kJ/kg/°CA;

$m_F$ -- Quality of fuel evaporation, in kg;

$w_{Air,available}$ -- Initial effective air mass fraction of combustion

$k$ -- Local turbulent kinetic energy density, in $m^2/s^2$;

$C_{EGR}$ -- EGR influence coefficient;

$C_{Rate}$ -- Fuel mixing coefficient;

$\Delta\varphi_c$ -- Extension of premixed combustion of fuel in cylinder; in °CA.

## 2. Flame-proof structure design of EGR system for flame-proof diesel engine

The standard MT990-2006 *General Technical Requirements for Mine Flame-proof Diesel Engines* [21] puts forward requirements for flatness, dimension width, surface temperature and bearing strength of underground flame-proof diesel engine and its parts. Consequently, the design of EGR system and its parts need to meet the requirements of the standard. In general, the flame-proof design of the EGR system is divided into the flame-proof design of the parts of the EGR system itself and the flame-proof design of the intake and exhaust system connected to the EGR system.

**2.1. Flame-proof design of EGR system components**

The EGR system that meets the flame-proof design requirements is called flame-proof EGR system, which is mainly composed of EGR control system, EGR cooler, EGR valve, throttle (integrated on the ECU of flame-proof diesel engine), sensor, water-cooled exhaust gas drainage line and waste gas introduction pipeline. For the selected products, its flame-proof design means that the selected parts are placed in a special shell with the arc or spark that may be produced by the parts in the shell and separated from the flammable and explosive materials outside the shell. When the explosive mixture in the shell explodes, it should not be deformed or destroyed by the explosion pressure, and there should be no out-of-explosion phenomenon, that is, when the material in the shell explodes or burns, it should not cause the explosion and combustion of flammable and explosive materials outside the shell. The shell that prevents the spread of Mars is called a flameproof shell. Before the flame-proof design of key components are shown in Fig.1. After the flame-proof design of key components are shown in Fig.2.

Fig. 1 Before the flame-proof design of key components

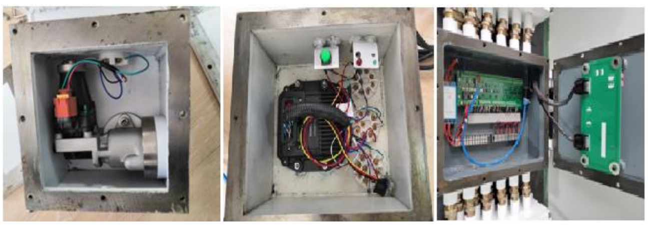


Fig. 2 After the flame-proof design of key components

**2.2. Flame-proof design of intake and exhaust system connected to flame-proof EGR system**

Water-cooled exhaust bellows is one of the most important components in flame-proof design of flame-proof diesel engine. The water-cooled exhaust bellows are generally designed as double-layer exhaust bellows with exhaust gas passage inside and cooling water between the interlayers. The purpose of this cooling water is to ensure that the surface temperature of the outermost layer of the exhaust bellows is not more than 150 ℃ to meet the requirements of coal mine standards. The EGR system needs to extract exhaust gas from the water-cooled exhaust bellows, and these lines also need to meet this requirement.

The intake bend is used to connect the flame-proof intercooler and the intake fence in the intake system of the flame-proof diesel engine. A design connecting flange should be added to the intake bend to introduce exhaust gas. Due to the low intake temperature, a single layer stainless steel pipeline connection is used between the connecting flange and the flame-proof EGR valve. The water-cooled exhaust bellows, the exhaust gas introduction bellows, the water-cooled exhaust gas bellows and the intake elbow are shown in Fig.3.

Fig. 3 Physical map of pipeline

**2.3. Drainage design of flame-proof EGR system**

There are generally four ways of EGR air extraction and drainage. In Fig. 4, the arrangement of EGR before vortex pressure and before vortex pressure is that the waste gas is drawn from the front or back of the turbine. As the harmful substances in the exhaust gas enter the compressor after passing through the flame-proof EGR valve, the compressor will be corroded and damaged, so these two arrangements are not used. In Fig. 4, the EGR drainage mode after the vortex front pressure is to extract the exhaust gas from the pipeline in front of the turbine, and then introduce the exhaust gas from the pipeline behind the compressor. The interlayer of the turbocharger and exhaust manifold of flame-proof diesel engine is filled with circulating cooling water, that is, there is a water jacket on the outside, and the surface temperature of the internal water-cooled turbocharger and exhaust manifold is less than 150C to meet the requirements of standard MT990-2006, which makes it difficult to take air here and not easy to achieve. Thus, the drainage scheme after vortex post-pressure is selected in this paper. The utility model has the following advantages: (I) the EGR system responds well; (ii) the exhaust gas does not pass through the compressor and the flame-proof intercooler, so that both of them are not damaged by the exhaust gas corrosion; (iii) the space position is sufficient, the arrangement is convenient and the requirement for circulating water cooling temperature is the lowest.

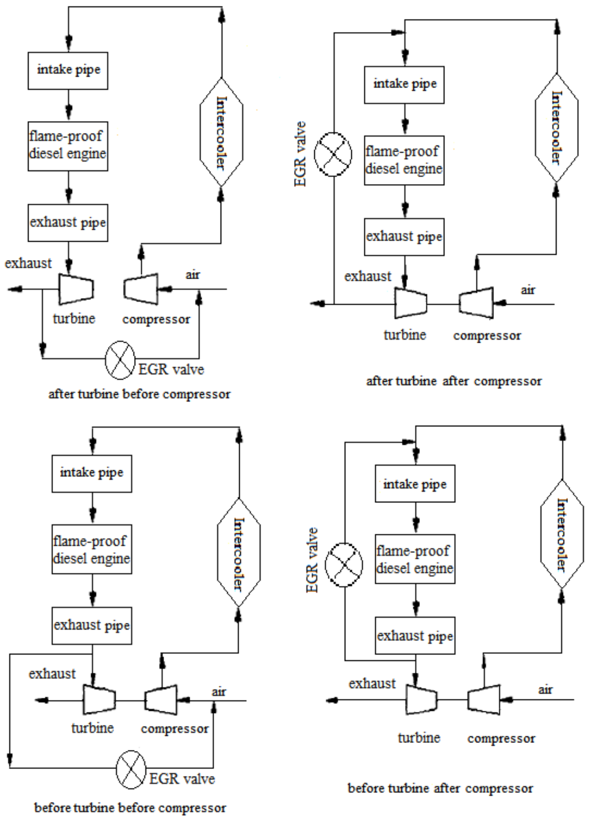



Fig. 4 EGR intake and drainage method

## 3. Cooling design of flame-proof EGR system

According to the different cooling medium, the cooling system of flame-proof diesel engine can be divided into oil-cooled type, air-cooled type and water-cooled type. The cooling of flame-proof EGR system is only a part of the whole cooling system of flame-proof diesel engine. The coal mine standard requires that the surface temperature of flame-proof diesel engine and its ancillary parts should not exceed 150 ℃, but the temperature of exhaust gas is absolutely high. In addition, due to the limitations of underground roadways in coal mines, coal mine vehicles are usually short and narrow, compact space, not easy to dissipate heat, while the specific heat capacity of water is relatively large, and the cooling effect is good. As a result, the water cooling mode should be adopted in the flame-proof EGR system to make full use of the cooling system of the flame-proof diesel engine itself. Moreover, it can greatly reduce the cooling cost of flame-proof EGR system and make the layout of flame-proof EGR system simple and compact.

The cooling system of flame-proof EGR belongs to the cooling system of flame-proof diesel engine, so it is also driven by circulating water pump for water cycle cooling. The temperature of the flame-proof EGR cycle exhaust gas is determined by the amount of water in the cooling system, and the water quantity control is realized by the flame-proof ECU of the flame-proof diesel engine to control the pump speed in real time according to the specific operating mode. Fig. 5 is the schematic diagram of the cooling and cooling of the flame-proof EGR system. The specific circulation route is that the pump sucks a certain amount of cooling water from the outlet pipe of the radiator to pressurize and then sends it into the stainless steel EGR cooler through the cooling pipe (the function of the stainless steel EGR cooler is to reduce the temperature of recycled waste gas). After coming out of the stainless steel EGR cooler, the cooling water flows into the intake pipe of the radiator through the one-way valve and finally into the radiator water chamber. The function of this one-way valve is to avoid the influence of cooling water reflux on the temperature of recycled waste gas. The flame-proof EGR valve should be designed at the front end of the EGR cooler so that the EGR cooler can more accurately control the temperature of the recycled exhaust gas.

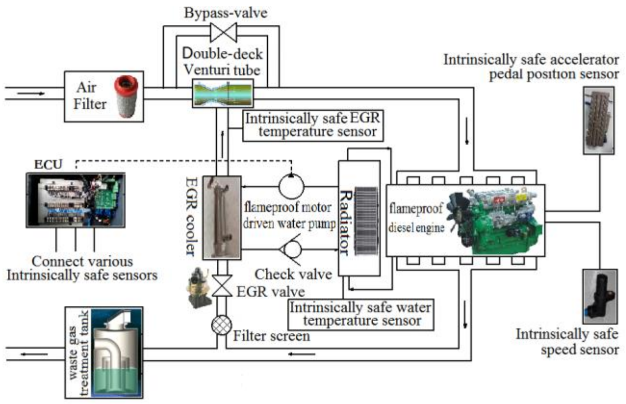



Fig. 5 The cooling principle diagram of the flame-proof EGR system

### 3.1. Calculation of Pump Type Selection for Flame-proof EGR System

The amount of water needed for circulating cooling is determined by the amount of heat brought to the cooling system by the recycling of waste gas in the flame-proof EGR system, so it is necessary to calculate the heat dissipation taken away by the flame-proof EGR cooling system and then calculate the power consumption of the pump.

There are multiple factors affecting the heat $Q_L$ of flame-proof EGR cooling system, which need to be found accurately in order to calculate accurately, which is excessively complicated. Through the bench test in the flame-proof diesel engine laboratory, the maximum heat flux of the flame-proof EGR cooling system appears under the condition that the speed and load of the flame-proof diesel engine is 2200 r / min and 50% load, and its value is 9kW. Therefore, the heat exchange between flame-proof EGR waste gas and its cooling system is approximately 9kW.

The heat $Q_L$ taken away by the known system can be calculated by the following formula to calculate the amount of water in the flame-proof EGR cooling system.

$$V_L = \frac{Q_L}{\Delta t_l \gamma_l c_l} = 2.14\times10^{-4} m^3/s \quad (9)$$

Wherein, $\Delta t_1$ -- The relative temperature difference between the inlet and outlet cooling water of the flame-proof EGR cooling system. A large number of test results suggest that the cooling cycle system of flame-proof diesel engines, the temperature difference is usually taken as $\Delta t_1$=5℃~10℃, and $\Delta t_1$ is taken as 10℃ in this paper;

$\gamma_1$ -- The density of water, approximately $\gamma_1$=1000kg/m$^3$;

$c_1$ -- The specific heat of water, approximately $c_1$=4.2KJ/kg·℃.

The maximum pumping capacity of the water pump can be calculated as follows:

$$V_b = \frac{V_L}{\eta_s} = 15.12 L/min \quad (10)$$

Wherein, $\eta_s$ -- The maximum volumetric efficiency of the pump when it is working, the test measured $\eta_s$=0.8~0.95, and it is taken as 0.85 in this paper.

$V_b$ -- The pumping volume of the flame-proof water pump.

$$N_p = \frac{V_b P_p}{\eta_h \eta_j \eta_v} \approx 0.057 \text{ kW} \quad (11)$$

$P_p$ -- Maximum working pressure of water pump;

$\eta_h$ -- Maximum hydraulic efficiency of pump work;

$\eta_j$ -- Maximum mechanical efficiency of the pump;

$\eta_v$ -- Maximum volumetric efficiency of the pump;

$N_p$ -- The maximum power consumed by the flame-proof motor of the pump.

The cooling system of the flame-proof diesel engine consists of internal and external circulation cooling systems. The cooling system of flame-proof EGR system is only a branch of external circulation cooling system. It is calculated that the maximum power of flame-proof pump for cooling water circulation in other branches is 2.4kW. Finally, this paper selects a cast iron water pump with rated power of 2.5kW, maximum head of 14.5m and maximum flow of 260L/min.

**3.2. Selection of cooler for flame-proof EGR system.**

Flame-proof EGR cooler is a kind of heat exchange device. Because it needs to be used in coal mine, it must not only meet the requirements of heat exchanger standards, but also meet the flame-proof requirements of coal mine standards. If the temperature of the cooling system is too low, the water vapor in the exhaust gas from the flame-proof diesel engine will absorb heat and form acid with the sulfides in the exhaust gas. These substances will corrode the cooler and its various pipes, greatly reducing the reliability and service life of the cooler, so the temperature of the cooling system should not be too low. Flame-proof EGR coolers shall meet the above requirements, specifically as follows:

(1) The effective width from the inner edge of the connecting flange to the inner edge of the bolt hole at both ends of the cooler should not be less than 9mm.

(2) The structure of cooler should not only meet the strength requirements, but also be resistant to corrosion, high temperature and vibration.

(3) The cooling efficiency of the cooler should ensure that the surface temperature does not exceed 150 ℃ at the maximum load.

(4) On the basis of ensuring the heat dissipation efficiency, the volume is as small as possible, the pressure loss is as small as possible, and the channel blockage should be stopped.

## 4. Simulation calculation of flame-proof EGR system

### 4.1. Basic parameters of flame-proof diesel engine

The EGR technology and system studied in this paper are applied to an electronically controlled flame-proof diesel engine emitted by a certain type of country III in coal mine, and its main technical parameters are shown in Table 1.

Table1 basic parameters of a certain type of national III mine flame-proof diesel engine

| Parameter Name | Parameter value |
|---|---|
| Type | Four-stroke, water cooling, exhaust gas turbocharging,<br>Air-air cooling, in-line, EFI |
| Pressurization Method | Exhaust gas turbocharging and intercooling |
| Number of Cylinders × Bore × Stroke | 4×105 mm×124 mm |
| Displacement | 4.3L |
| Rated Power (Speed) | (65±5%)kW（2200rpm） |
| Torque (Speed) | (330±5%）N.m（1400-160r/min） |
| Compression Ratio | 17.5 |

| | |
|---|---|
| Work Order | 1-3-4-2 |
| Rated Power Fuel Consumption Rate | ＜（245±3%）g/ kW.h |
| Surface Temperature | ≤150℃ |
| Noise | ≤114dB |

### 4.2. Establishment of simulation model

In this paper, the working process simulation model of mine flame-proof diesel engine is built by using fluid simulation software, and its working process, power performance, economy and emission are analyzed deeply. The control strategy of EGR system of mine flame-proof diesel engine and its influence on the performance and emission of flame-proof diesel engine are studied deeply. The working process simulation model of an electronically controlled flame-proof diesel engine used in a mine is shown in Fig. 6. The simulation model mainly includes water-cooled intake and exhaust system, cylinder, water-cooled turbocharging and air-air intercooling device, flame-proof EGR valve and its cooling device, etc.

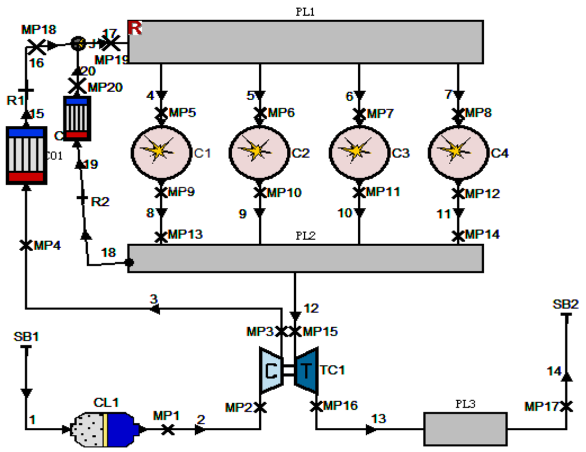


Fig. 6 Simulation model of the working process of an flame-proof diesel engine

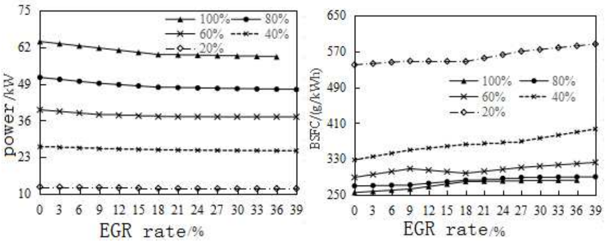
### 4.3. Simulation results analysis

EGR control strategy directly affects the power economy and emission of flame-proof diesel engine, so it is necessary to accurately calculate the amount of recycled waste gas introduced into the cylinder of flame-proof diesel engine under different operating mode, and the recycled waste gas is expressed by EGR rate. EGR rate refers to the ratio of the mass flow rate of exhaust gas recycled by flame-proof diesel engines to the total mass flow rate of mixed gas inhaled in the cylinder, which is generally expressed as a percentage. Calculating the influence degree of EGR rate on power economy and emission of flame-proof diesel engine is of great significance to analyze and study how to control EGR valve under different operating mode, so that the opening value of EGR can be quickly and accurately controlled in the optimal state of engine operation, and it is the basis for formulating EGR control strategy. Through the simulation calculation of the working process of the flame-proof diesel engine under 15 operating mode points(three speeds (2200r/min, 1600r/min, 1000r/min), five loads (100%, 80%, 60%, 40%, 20%)), this paper analyzes and studies the influence of the EGR rate on the power, BSFC(brake specific fuel consumption) and emission performance(NOx, soot (smoke)) of the mine flame-proof diesel engine under 15 operating mode. The results play a guiding role in the formulation of the control strategy of the EGR system of the mine flame-proof diesel engine.

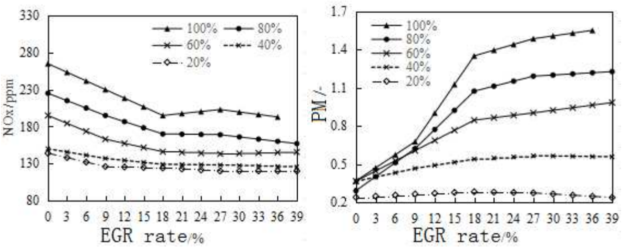
#### *4.3.1. Effect of EGR rate on the performance and emissions of flame-proof diesel engines at the rated speed operating mode points*

Fig. 7 proves the variation of the performance and emission of flame-proof diesel engine with EGR rate at rated speed (2200r/min) at each load. According to the diagram, at each load of rated speed, the power of flame-proof diesel engine gradually decreases with the increase of EGR rate, on the contrary, BSFC increases gradually, and the dynamic performance and economic performance of flame-proof diesel engine worsen with the increase of load. Among them, the maximum decrease of 100% and 20% load power is 8.4% and 4.8% respectively. The maximum increase of BSFC is 10.86% and 8.6% respectively. The main reason is that the increase of EGR rate leads to the decrease of fresh air in the cylinder of flame-proof diesel engine, which leads to the suppression of the combustion of high-pressure mixture in the cylinder, the decrease of the maximum combustion temperature in the cylinder and the lower oxygen concentration in the cylinder under heavy load. The increase of EGR rate will further worsen the combustion, so compared with the operating mode with zero EGR rate, the output power decreases, and the deterioration of combustion also makes the fuel economy worse and BSFC increases gradually. Due to the sufficient excess air coefficient in the cylinder, the increase of EGR rate leads to the decrease of oxygen concentration, but it has little effect on in-cylinder combustion, so the change of power and BSFC is relatively smooth. Consequently, in view of this EGR system, the control strategy of higher EGR rate for medium and low load conditions and lower EGR rate for high load conditions can be adopted. In addition, it should be considered to close the flame-proof EGR valve under heavy load or full load conditions to ensure sufficient power performance of the flame-proof diesel engine at rated speed.

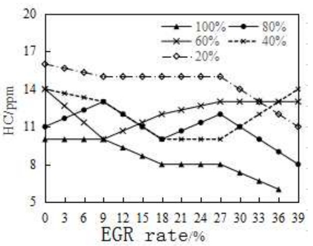
At each load of rated speed, NOx emission of flame-proof diesel engine decreases rapidly at first and then slowly with the increase of EGR rate. When the engine load is less than 40%, the oxygen concentration in the cylinder decreases, the ignition delay period is prolonged, and the lower combustion temperature in the cylinder even suppresses the soot formation reaction, resulting in particularly small soot emissions and slow changes in soot and NOx emissions. The reason for the low soot emission is that the fuel injection quantity of the flame-proof diesel engine under low load is less and the fuel atomization effect is good, and the oxygen in the cylinder is relatively sufficient, so the in-cylinder combustion is more sufficient, and the effect of EGR rate on soot emission is relatively small. When the flame-proof diesel engine works at medium and high load, with the sharp increase of fuel injection, the decrease of oxygen concentration quickly suppresses the combustion of the mixture, resulting in the formation of a large number of soot particles at the initial stage of combustion. On the other hand, it will also cause local high temperature and hypoxia in the cylinder, which suppresses the oxidation reaction of soot in the later stage of combustion, so the soot emission increases significantly when the load is more than 60%, and increases rapidly with the increase of EGR rate. Accordingly, from the perspective of soot and NOx emissions, the control strategy of selecting higher EGR rate under low load conditions and lower EGR rate under medium and heavy load conditions should be adopted.




(a) Changes in Power with EGR rate (b) Changes in BSFC with EGR rate




(c) Changes in NOx emissions with EGR rate (d) Changes in smoke degree with EGR rate



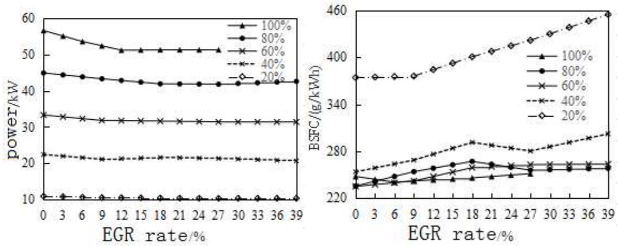

(e) Changes in HC emission with EGR rate

Fig.7 Flame-proof diesel engine speed 2200r/min

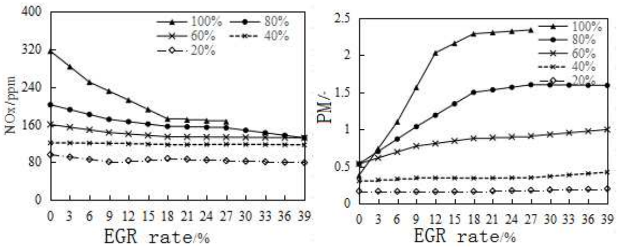
At rated speed and each load, the HC emission of flame-proof diesel engine increases with the decrease of load, and the wall temperature of flame-proof diesel engine is lower under low load conditions. The quenching effect of wall results in a large amount of HC generation. Nonetheless, after entering the medium and high load conditions, the quenching effect on the wall of flame-proof diesel engine gradually disappears with the gradual increase of in-cylinder temperature, and the amount of HC emission decreases gradually. HC emissions decrease with the increase of EGR rate under low load and full load conditions. Although the change law of HC emissions is not greatly obvious under medium load conditions, it tends to increase on the whole. From the perspective of HC emissions, it is not appropriate to adopt a higher EGR rate control strategy to avoid excessive HC emissions of flame-proof diesel engines under medium and medium load conditions.

*4.3.2 Effect of EGR rate on the performance and emissions of flame-proof diesel engines at the maximum torque speed operating mode point*

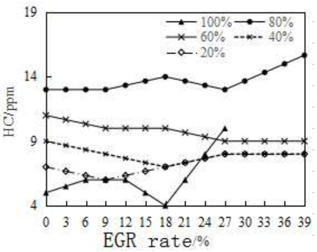
Fig. 8 reveals the variation of performance parameters of flame-proof diesel engine with EGR rate at maximum torque speed (1600r/min). It is suggested that the power and effective fuel consumption of flame-proof diesel engine deteriorate gradually with the increase of EGR rate, and this trend becomes more obvious with the increase of load, and the maximum power decreases of 9.4% and 5.5% respectively under 100% and 20% load. Thus, a smaller EGR rate should be selected for flame-proof diesel engines under medium and heavy load conditions.




(a) Changes in Power with EGR rate (b) Changes in BSFC with EGR rate




(c) Changes in NOx emissions with EGR rate (d) Changes in smoke degree with EGR rate




(e) Changes in HC emission with EGR rate

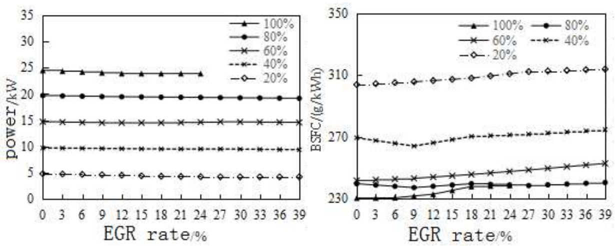
Fig. 8 Flame-proof diesel engine speed 1600r/min

With the increase of EGR rate, NOx emissions gradually decrease and soot emissions show an increasing trend, and the change trend is more significant when the load is more than 60%, and the change is gentle at low load. At this time, the effect of EGR rate on NOx and soot emissions is relatively small, and the trend is basically similar to 2200r/min operating mode. For HC emissions, when the EGR rate of medium and low load is small, there is a decreasing trend of HC emissions, and under heavy load conditions, HC emissions are flat or even decrease when the EGR rate is less than 18%, and then worsen with the increase of EGR rate. Accordingly, the formulation of EGR strategy should consider reducing NOx emissions and taking into account power, economy and soot emissions.

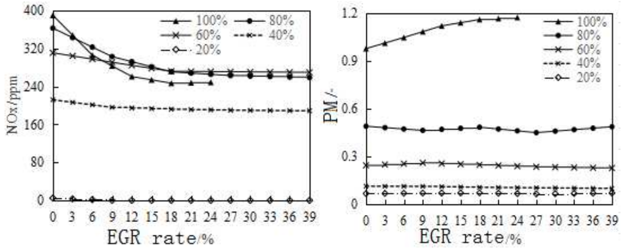
*4.3.3. Effect of EGR rate on the performance and emissions of flame-proof diesel engines at 1000r/min operating mode point*

Fig. 9 manifests the variation of the performance and emissions of the flame-proof diesel engine with the EGR rate at the 1000r/min speed operating mode points. According to the diagram, the power and BSFC of each load deteriorate with the increase of EGR rate, and this trend is more obvious with the increase of load, but the influence of EGR rate on power performance and economy is smaller at low speed condition than that at high speed condition, so the higher EGR rate can be selected for flame-proof diesel engine at low speed condition.

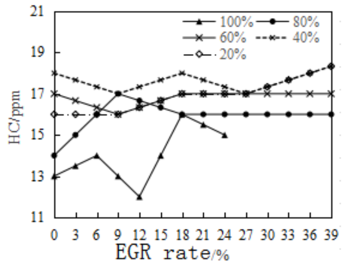
Under 20% load condition, when the EGR rate is less than 9%, the NOx, soot and HC emissions all decrease with the increase of the EGR rate, while the NOx emissions under this operating mode are all truly low under the 0%-39%EGR rate. Considering the comprehensive power performance, economy and emission of the flame-proof diesel engine, it is appropriate to choose the EGR rate of less than 9%. There is still no fixed trend in the change law of HC emissions. Under medium and heavy load conditions, the NOx emission of flame-proof diesel engine decreases with the increase of EGR rate, and the decreasing process is first fast and then slow. Under 80% load, the soot emission does not change obviously with the increase of EGR rate. However, soot emissions gradually increase with the increase of EGR rate at 100% load, so it is appropriate to choose a larger EGR rate for flame-proof diesel engines under medium and high load conditions, but it is not suitable for flame-proof diesel engines under full load conditions.




(a) Changes in Power with EGR rate (b) Changes in BSFC with EGR rate




(c) Changes in NOx emissions with EGR rate (d) Changes in smoke degree with EGR rate




(e) Changes in HC emission with EGR rate

Fig. 9 Flame-proof diesel engine speed 1000r/min

## 5. EGR control strategy for flame-proof diesel engine

The control of EGR rate of flame-proof diesel engine is a multi-objective optimization problem. The traditional EGR rate control method based on empirical mode control can not realize the function of on-line real-time control. In this paper, the comprehensive real-time control of EGR rate is carried out according to the parameters of flame-proof diesel engine speed, surface temperature, circulating water temperature, throttle opening, EGR valve opening, EGR rate, inlet flow rate and load power.

### 5.1. EGR control strategy simulation model

Fig. 10 point outs the simulation model of the flame-proof EGR closed-loop real-time control strategy based on the simulation calculation data of the flame-proof diesel engine under various operating mode.

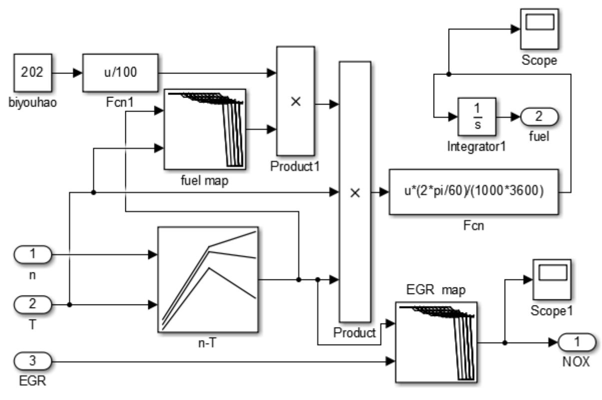
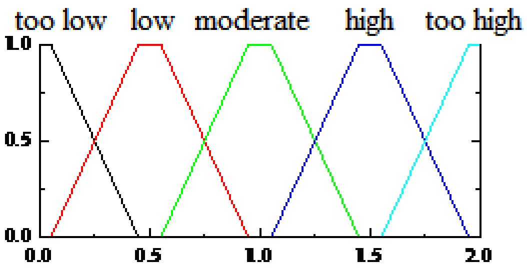



Fig. 10 EGR closed-loop real-time control strategy simulation model of flame-proof diesel engine

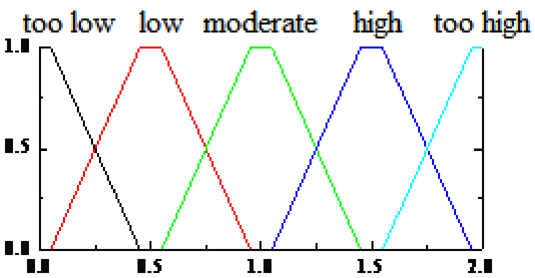
### 5.2. Fuzzy logic feedback modified control model

Control strategy is the core of managing and controlling EGR rate of flame-proof diesel engine. The main goal of this control strategy is to reduce the $NO_X$ emission of flame-proof diesel engine as much as possible on the premise of ensuring the dynamic performance of flame-proof diesel engine. In this study, the real-time data of load demand power and NOx emission are collected on-line and used as the input of fuzzy controller and output control variable, that is, the correction value of EGR rate. Fuzzy logic control does not need accurate mathematical model, it is a rule-based control strategy, which is used to solve nonlinear complex problems in engineering, and has strong robustness, so this method is remarkably suitable for EGR control of flame-proof diesel engine. Specifically, the real-time collected $NO_X$ value and the load required power $P_{rq}$ are used as the two input variables of the fuzzy logic controller, and the EGR rate of the flame-proof diesel engine is controlled by fuzzy logic reasoning and the emission characteristics are optimized.

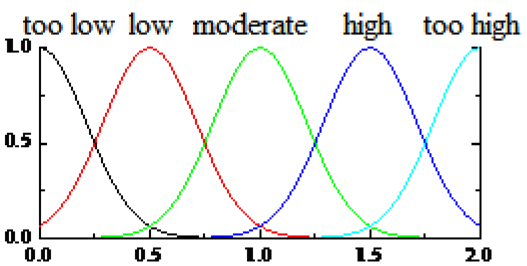
Firstly, the membership functions of the input variable $NO_X$ value and the power $P_{rq}$ and the output variable EGR rate shown in Fig. 11 are established respectively, and the corresponding fuzzy rule sets are established according to the different operating mode of the flame-proof diesel engine.




(a) Input variable $P_{rq}$ membership function




(b) Input variable $NO_X$ membership function




(c) Membership function of output variable EGR rate

Fig. 11 Membership function of the input and output variables of the flame-proof EGR system

Secondly, a fuzzy inference rule composed of several If-Then rules is established. Fig. 12 reports the adjustment rules among $P_{rq}$, NOx and EGR. In order to make full use of the control knowledge of the expert rule base, the Mamdani fuzzy reasoning method is adopted in this paper. Among them, the domain of the input variable $P_{rq}$ is [0, 2], which represents the upper and lower limits of $P_{rq}$, the domain of NOX is [0, 2], which represents the upper and lower limits of $NO_X$ emissions, and the domain of output EGR rate is [0, 2], and the value of EGR rate determines the engine emission performance.

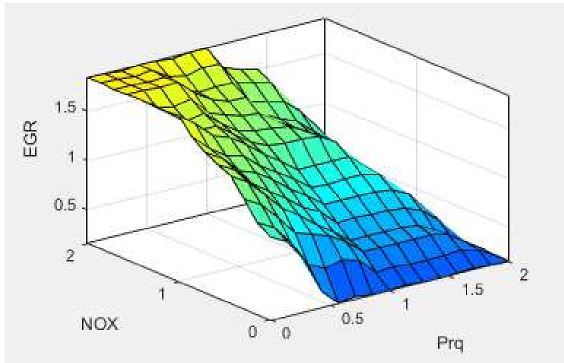



Fig. 12 Adjustment rules corresponding to $P_{rq}$, NOx and EGR in the controller

After establishing the fuzzy logic controller and formulating the fuzzy control rules, the actual parameter set is input into the established model. Considering the initial and boundary conditions, the EGR control simulation model of flame-proof diesel engine is established, and the fuzzy logic controller is loaded into the MATLAB model to study the operating mode, dynamic characteristics and emission performance of flame-proof diesel engine. Fig. 13 indicates the simulation model of fuzzy logic controller for flame-proof EGR system.

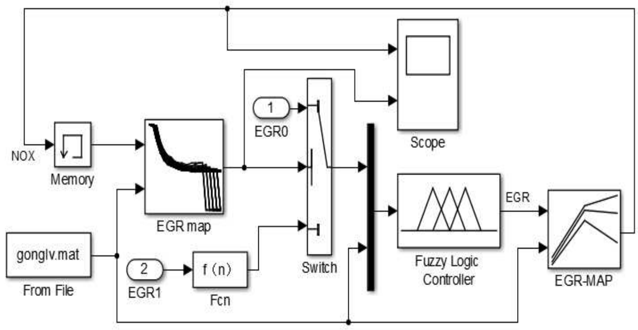



Fig. 13 Controller simulation model

### 5.3. Work flow of flame-proof diesel engine EGR system

Based on the above fuzzy logic control strategy, the control program suitable for flame-proof EGR system of flame-proof diesel engine is compiled. The flow field diagram of the control program is shown in Fig. 14.

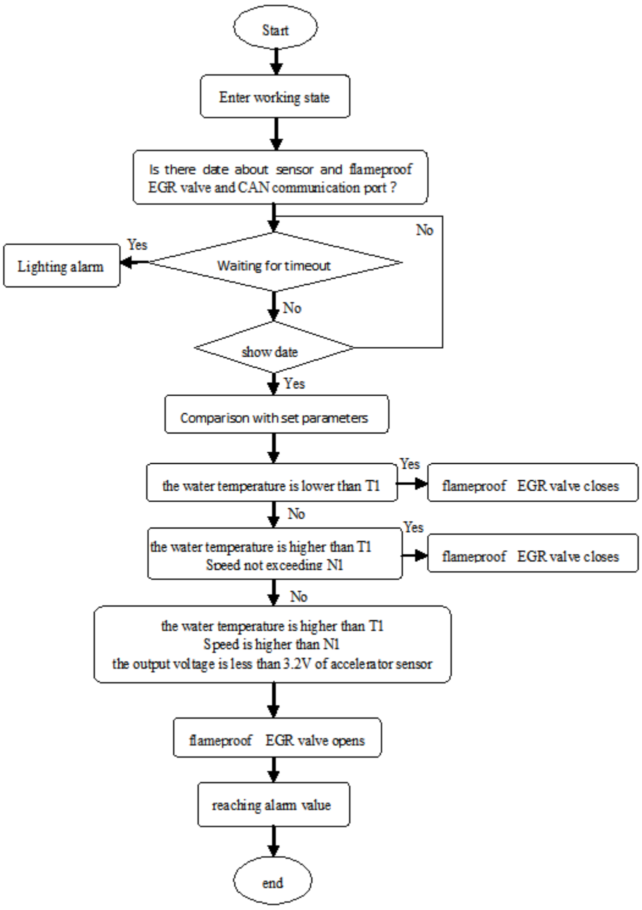



Fig. 14 Control program flow chart

## 6. Test verification

### 6.1. Test equipment and site

Table 2 shows the test equipment of EGR-based flameproof diesel engine.

Table 2. Test and test equipment

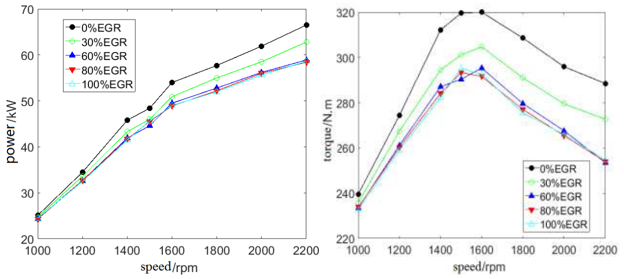
| No. | Equipment name | Manufacturing plant | Specification Model |
|---|---|---|---|
| 1 | Intelligent fuel consumption meter | Sichuan Chengbang Measurement and Control Technology Co., Ltd. | ET4500 |
| 2 | Five-component exhaust gas measuring instrument | Xiamen Haiteng Engine Test Equipment Co., Ltd. | AVL DIGAS 4000 LIGHT |
| 3 | Data collector | Sichuan Chengbang Measurement and Control Technology Co., Ltd. | ET2300A |
| 4 | Engine controller | Sichuan Chengbang Measurement and Control Technology Co., Ltd. | ET4110 |
| 5 | Throttle excitation drive unit | Sichuan Chengbang Measurement and Control Technology Co., Ltd. | ET2600 |
| 6 | Eddy current dynamometer | Sichuan Chengbang Measurement and Control Technology Co., Ltd. | DWD400 |
| 7 | Filter paper smoke meter | Liszt Testing Equipment Co., Ltd. | 415SE |

Fig. 15 Bench test site of the flame-proof diesel engine EGR system

Bench test site of the flame-proof diesel engine EGR system is shown in Fig. 15.

### 6.2. Analysis of test results

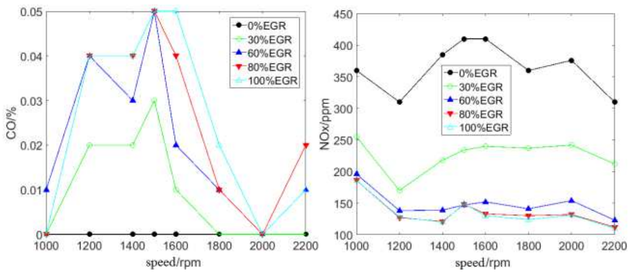
*6.2.1. External characteristic test results of flame-proof diesel engine with flame-proof EGR*




(a) External characteristic power of flame-proof diesel engine

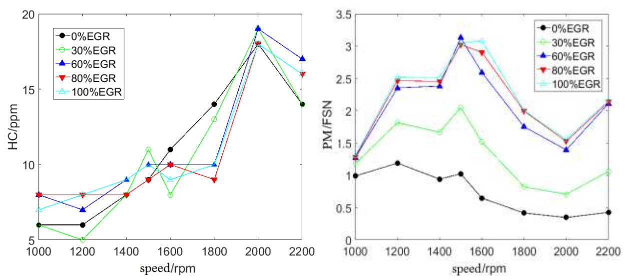
(b) External characteristic torque of flame-proof diesel engine

Fig. 16 External characteristic curves of flame-proof diesel engine at five EGR opening degrees




(a) CO emissions from external characteristics of flame-proof diesel engines

(b) External characteristic NOx emission of flame-proof diesel engine




(c) HC emission of external characteristics of flame-proof diesel engine

(d) Characteristic smoke emission from flame-proof diesel engine

Fig. 17: Exhaust emission curve of flame-proof diesel engine under five EGR opening degrees

Fig. 16 confirms the external characteristic curve of flame-proof diesel engine with flame-proof electronically controlled EGR under five EGR openings. Fig. 17 shows the emission curve of flame-proof diesel engine with flame-proof electronically controlled EGR under five EGR openings.

According to Fig. 16, at operating mode points other than the 1000r/min operating mode point, the power of flame-proof diesel engine with flame-proof electronically controlled EGR system is lower than that without EGR system, and the power decreases gradually with the increase of EGE opening. However, when the opening of the flame-proof EGR system is increased to 60%, the power value tends to be stable and does not change much. At the 1000r/min operating mode point, the power of the flame-proof diesel engine with flame-proof electronically controlled EGR system changes little compared with the system without EGR, suggesting that the EGR system basically does not work at this operating mode point.

At operating mode points other than the 1000r/min operating mode point, the torque of flame-proof diesel engine with flame-proof electronically controlled EGR system is lower than that without EGR system, and the torque decreases gradually with the increase of EGE opening. Nonetheless, when the opening of the flame-proof EGR system is increased to 60%, the torque value tends to be stable and does not change much. When the opening of EGR is 30%, the torque of flame-proof diesel engine with flame-proof electronically controlled EGR system at 1500r/min operating mode point is the largest, which is 5.79% compared with that without EGR system. At the 1000r/min operating mode point, the torque of the flame-proof diesel engine with flame-proof electronically controlled EGR system changes little compared with that without EGR system, indicating that the EGR system basically does not work at this operating mode point.

According to Fig. 17, when the flame-proof diesel engine is running at the four speed operating mode points of 2200r/min, 2000r/min, 1800r/min, 1000r/min when the EGR opening is 30%, the CO emission of the flame-proof diesel engine with the flame-proof electronic control EGR system is basically the same as that of the flame-proof diesel engine without the EGR system. At the four operating mode points of 1600r/min, 1500r/min, 1400r/min, 1200r/min, the CO emissions of flame-proof diesel engines with flame-proof electronically controlled EGR system are increased compared with those without EGR system. Among them, the maximum increase is at the 1500r/min operating mode point, and the volume concentration increases from 0 to 0.03%. Although the increase seems to be large, due to the low base of CO emissions of the original machine, the value of CO emissions after the increase remains significantly low, far less than the value required by the standard. When the EGR opening is 60%, the CO emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system at most operating mode points is higher than that when the EGR opening is 30%. When the EGR opening is 80%, the CO emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system at the 2200r/min, 1600r/min and 1400r/min operating mode points is higher than that when the EGR opening is 60%, and the CO emission at the 1000r/min operating mode point is lower than that when the EGR opening is 60%, and the CO emissions at other operating mode points remain unchanged compared with the EGR opening at 60%. When the EGR opening is 100%, the CO emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system at the 2200r/min operating mode point is lower than that when the EGR opening is 80%, and the CO emission at the 1800r/min and 1600r/min operating mode points is higher than that when the EGR opening is 80%, and the CO emissions at other operating mode points remain unchanged compared with the EGR opening at 80%.

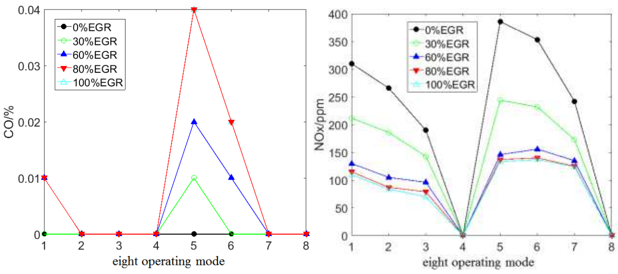
The NOx emission of flame-proof diesel engine with flame-proof electronically controlled EGR system at all operating mode points is lower than that without EGR system, and the NOx emission decreases gradually with the increase of EGE opening. But, when the opening of flame-proof diesel engine EGR system is above 60%, the NOx emission value changes little and tends to be stable. Among them, when the opening of EGR is 30%, the NOx of flame-proof diesel engine with flame-proof electronically controlled EGR system is the largest at 1200r/min operating mode point, which is 45.16%, compared with that without EGR system, and 29.17% at 1000r/min operating mode point, which is the smallest. When the opening of EGR is 60%, the NOx of flame-proof diesel engine with flame-proof electronically controlled EGR system is the largest at 1500r/min operating mode point, which is 64.15%, compared with that without EGR system, and the decrease is 45.56% at 1000r/min operating mode point, which is the smallest.

The HC of the flame-proof diesel engine with flame-proof electronically controlled EGR system changes little compared with that of the system without EGR at all operating mode.

At all operating mode points, the smoke of flame-proof diesel engine with flame-proof electronically controlled EGR system is higher than that without EGR system, and the smoke emission increases gradually with the increase of EGE opening. However, when the opening of flame-proof diesel engine EGR system is above 60%, the smoke emission value changes little and tends to be stable. Among them, when the opening of EGR is 30%, the smoke emission of flame-proof diesel engine with flame-proof electronically controlled EGR system has the largest increase of 148.01% at 2200r/min operating mode point compared with that without EGR system, and the smallest increase is 19.11% at

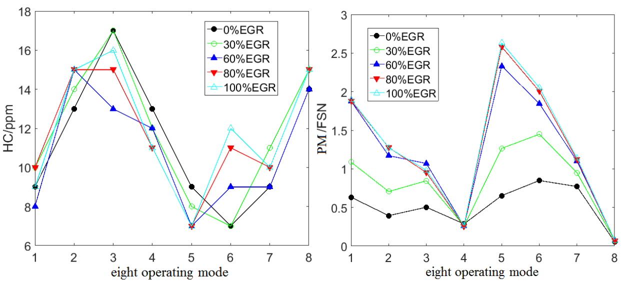
1000r/min operating mode point. When the opening of EGR is 60%, the smoke emission of flame-proof diesel engine with flame-proof electronically controlled EGR system has the largest increase of 394.15% at 2200r/min operating mode point compared with that without EGR system, and the smallest increase is 28.41% at 1000r/min operating mode point.

*6.2.2 Emission test comparison of eight operating mode of flame-proof diesel engine with flame-proof EGR system*




(a) CO emissions from eight operating mode of flame-proof diesel engines

(b) NOx emission of flame-proof diesel engine under eight operating mode




(c) HC emission of flame-proof diesel engine under eight operating mode

(d) Smoke emission from eight operating mode of flame-proof diesel engine

Fig. 18 Emission curve of flame-proof diesel engine under eight operating mode and five EGR opening

According to Fig. 18, the emission characteristic curve of flame-proof diesel engine with flame-proof electronically controlled EGR under eight operating mode and five EGR openings. Among them, the first operating mode point is 2200 r/min, 100% load; the second operating mode point is 2200 r/min, 75% load; the third operating mode point is 2200 r/min, 50% load; The 4th operating mode point is 2200 r/min, 10% load; the 5th operating mode point is 1600 r/min, 100% load; the 6th operating mode point is 1600 r/min, 75% load; The 7th operating mode point is 1600 r/min, 50% load; the 8th operating mode point is idle speed.

According to Fig. 18, when the EGR opening is 30%, the CO emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system at the fifth operating mode point is higher than that without EGR system, and the volume concentration is increased from 0 to 0.01%; there is no change at other operating mode points. When the opening of EGR is 60% and 80%, the CO emission of flame-proof diesel engine with flame-proof electronically controlled EGR system at operating mode points 1, 5 and 6 is higher than that without EGR system, and the volume concentration is increased by 0.01%, 0.02% and 0.01%, 0.04% and 0.02%, respectively. When the EGR opening is 100%, the CO emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system is unchanged compared with the 80% EGR opening at all operating mode.

When the EGR opening of the flame-proof diesel engine is 30%, 60% and 80% respectively, the NOx emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system except the 4th and 8th operating mode point is lower than that without EGR system, among which the EGR opening is 30% and 60% at the fifth operating mode point, which decreases by 36.79% and 62.18%, respectively. When the opening of EGR is 80%, the decrease is the biggest at the second operating mode point, which is 67.29%. When the EGR opening is 100%, the NOx emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system has little change compared with 80% EGR opening at all operating mode points.

The HC emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system except the 3rd and 6th operating mode point has little change compared with that of the system without EGR at 30,60,80% and 100%EGR opening. At the third operating mode point, HC emission is the lowest under 60%EGR opening. At the sixth operating mode, HC emissions increase with the increase of EGR opening. However, on the whole, due to the significantly low content of HC emissions in the emissions, HC emissions generally do not change much under various operating mode.

When the flame-proof diesel engine runs at the EGR opening of 30,60%, the smoke emission of the flame-proof diesel engine with flame-proof electronically controlled EGR system at the operating mode point except the fourth operating mode point is larger than that without EGR system, and the increase is the highest at the second operating mode point, which is 79.19% and 197.21%, respectively. When the opening of EGR is 80% and 100%, the smoke emission of flame-proof diesel engine with flame-proof electronically controlled EGR system has little change compared with 60% EGR at all operating mode points.

*6.2.3. EGR calibration of flame-proof diesel engine*

According to the emission standard GB 20891-2014 *Non-Road Mobile Machinery Diesel Engine Emission Pollutant Emission Limits And Measurement Methods (China Third And Fourth Stage)*, the test data of emission, fuel consumption and power under different opening of flame-proof EGR are shown above. Then the optimal value is selected to get the base curve. The EGR rate is calculated according to the points in the basic curve, based on which the optimal matching is carried out, and several groups of data are obtained through the offset of rotational speed and throttle to generate a flexible control curve. The specific MAP is presented in Fig. 19.

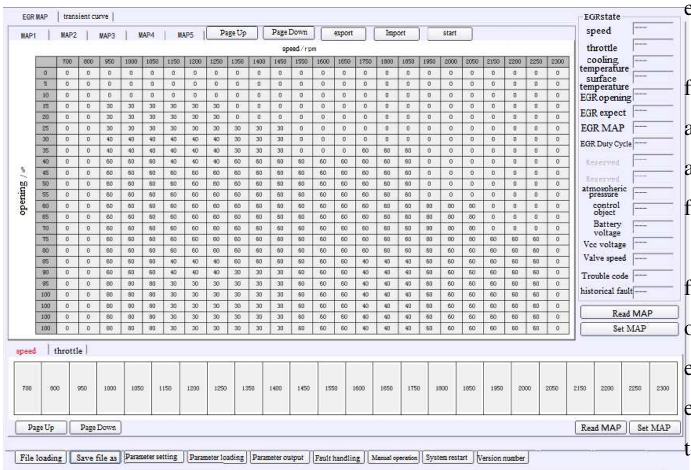



Fig. 19 MAP diagram of flame-proof diesel engine.

*6.2.4. Modification of external characteristics and Emission characteristics of flame-proof Diesel engine.*

According to the MAP diagram of flame-proof diesel engine, the external characteristic curve and eight-mode emission characteristic curve of flame-proof diesel engine are modified and optimized according to the external characteristic test and eight-mode test data of flame-proof diesel engine, respectively, as shown in figs. 20 and 21, respectively.

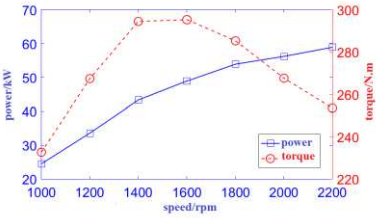
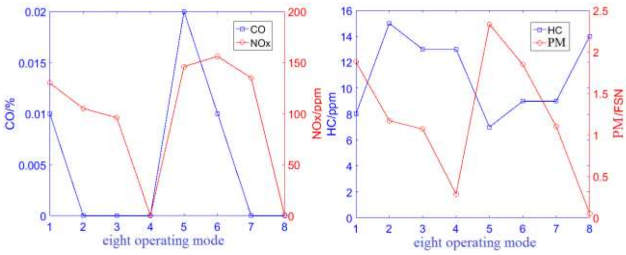



Fig. 20: Optimized external characteristic power and torque curve of flame-proof diesel engine




(a) CO and NOx emissions in eight operating mode after optimization

(b) HC and smoke emission in eight operating mode after optimization

Fig. 21: Optimized emission curve of flame-proof diesel engine under eight operating mode

## 7. Conclusion

1) The EGR technology can extract part of the exhaust gas from the flame-proof diesel engine, and through the flame-proof EGR and control program to participate in the combustion in the cylinder according to the operating mode of the flame-proof diesel engine, the NOx emission is reduced.

2) Under the external characteristic condition, the power of the flame-proof diesel engine installed with flame-proof EGR system and optimized is 58.9kW, and the highest output torque is 252.3 Nm, and the power performance is slightly lower than that of the flame-proof EGR system without flame-proof EGR system.

3) Under eight operating mode: the emission value of the flame-proof diesel engine installed with the EGR system and optimized is calculated according to the weighted coefficient of the emission standard GB 20891 Mel 2014, compared with the original engine: the volume concentration of CO emissions increased from 0 to 0.0045%. The volume concentration of NOx emissions decreased from 213ppm to 93.35ppm, a decrease of 56.17%.

4) The bench test results of flame-proof diesel engine prompt that the water-cooled flame-proof EGR technology is extremely effective in reducing NOx emission of flame-proof diesel engine. The mechanical structure, electrical control system and system materials of the flame-proof EGR system all meet the requirements of the coal mine standard, and can be used in the flame-proof power plant in the coal mine.

**Declarations**

Availability of data and materials：All data generated or analysed during this study are included in this published article.

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