Starting System and Safety Protection of Explosion-proof Diesel Engine for Coal Mine Based on Compressed Air

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Abstract: The starting and safety protection system is an important part of the explosion-proof diesel engine, and there are malfunctions in the explosion-proof diesel engine, such as difficulty in starting and failure in protection. As a gas working medium, compressed air is safe, reliable, and advantageous in acquisition and storage. Therefore, analyzing the starting principle and safety protection requirements of explosion-proof diesel engines and studying the correlation between the two systems, a set of starting and safety protection systems using compressed air as the working medium is designed in this paper. Moreover, the performance requirements of the main components in the system are studied, analyzing and calculating the operating parameters in the system, so that the design plan can be optimized. The problems appearing in starting and safety protection of explosion-proof diesel engines are solved through this system.

1. Introduction

The application of a large number of modern coal mining machinery not only improves the efficiency of coal mining work, but also reduces the work intensity of workers, improving workplace safety. As a special power system device, explosion-proof diesel engines such as monorail cranes, rail locomotives, explosion-proof rubber tire vehicles, special power stations, and mobile pumping stations are currently widely used in equipment in explosive environments such as coal mines. Moreover, owing to a series of advantages such as strong power, flexible fuel installation and convenient maintenance, explosion-proof diesel engines have been recognized by the majority of users. Additionally, as a branch of the diesel engine group, explosion-proof diesel engines have all the necessary system components as ordinary diesel engines. Meanwhile, due to the particularity that explosion-proof diesel engines work in the environment with explosive gases, explosion-proof diesel engines must have explosion-proof performance avoiding ignition and detonation and blocking the transmission of detonation. In addition, starting system should provide sufficient speed and torque to overcome the frictional resistance when the internal mechanisms of the explosion-proof diesel engine are stationary as well as the compression resistance when the piston compresses the air. Moreover, the protection system must realize self-alarm and shutdown when the operating parameters of the explosion-proof
diesel engine are abnormal and the air exceeds the standard. Nowadays, there are mechanical, pneumatic, and electrical systems in the international and domestic explosion-proof diesel engine starting systems, and for the protection systems, there are air protection and electrical protection, which have not unified the two, separating the internal logical connection of the two systems and resulting in a series of problems such as system mismatch and poor performance. Therefore, in this paper, based on the integrity of the explosion-proof diesel engine system and comprehensively considering the internal logical connection between starting and safety protection, compressed air is used as a unified working medium to design a set of economical, practical, and highly reliable starting and safety protection system of explosion-proof diesel engine, which has explosion-proof performance and can smoothly start the explosion-proof diesel engine.

2. Principles of Starting and Safety Protection of Explosion-proof Diesel Engines

2.1 Principle of Compressed Air Starting

Starting the explosion-proof diesel engine must rely on starting system. When the explosion-proof diesel engine is stationary, external force must be used to drive the crankshaft to rotate, forcing the connecting rod piston to compress air. At the end of the compression stroke, the diesel is injected into the combustion chamber to form gas with high temperature and pressure to start normally. After the normal start, the explosion-proof diesel engine can operate normally. Besides, there must be sufficient starting torque and starting speed during starting. The starting speed refers to the minimum speed of the crankshaft during the normal operation of the explosion-proof diesel engine, which ensures that the explosion-proof diesel engine can inhale a sufficient amount of fresh air and has a certain temperature to meet the necessary conditions for diesel combustion. Starting torque refers to the minimum system torque required to overcome the internal frictional resistance and air compression resistance of the explosion-proof diesel engine during starting. Only when the speed provided by starting system is greater than the starting speed and the torque provided by starting system is greater than the minimum system torque can the explosion-proof diesel engine start smoothly.[1]

In the compressed air starting, the potential energy of compressed air is converted into the rotational kinetic energy of air motor, driving the crankshaft to rotate, so that the explosion-proof diesel engine can start up normally.[2] Fig.1 is a flow diagram of compressed air. When compressed air is started, it should meet the following requirements:

\[ n_s = n_m \geq n_{\text{min}} \]
\[ T_s = T_m \geq T_r \]

\( n_s \) is the output speed of the air motor (rp/m), \( n_s \) is the Starting speed (rp/m), \( n_{\text{min}} \) is the minimum speed of the crankshaft (rp/m), \( T_s \) is the Starting torque (Nm), \( T_m \) is the output torque of the air motor (Nm), \( T_r \) is the Resistance distance of explosion-proof diesel engine (rp/m).

Control and starting system is the core subsystem of starting system, which must be given priority at the beginning when designing starting system. It ensures a smooth start, and prevents gear collision as well as secondary start-up. In addition, it can also realize air acquisition and compression, filter processing, shunt control, power output, etc.[3] Fig.2 is a control and starting system.
Fig. 2 Control and starting system

Compressed air flows out of the storage device. After processing, the water and other impurities are discharged, which is divided into two paths, namely power source and control air source. Then, the air is intervened to flow to various pneumatic control valves, controlling the meshing state of the pinion in the air motor and the ring gear of the explosion-proof diesel engine. Therefore, the engagement before starting and the separation after starting can be realized, so that the normal starting can be controlled. Moreover, the power air source flows to the air motor, which drives the motor to rotate to start the explosion-proof diesel engine.

2.2 Safety Protection Principle of Explosion-proof Diesel Engine

The Gas explosion is one of the most serious disasters in coal mines, which is destructive and sudden. It must meet three conditions at the same time. In other words, for gas concentration, \(5\% < \text{concentration gas} < 16\%\); for ignition source, ignition temperature > 650; for combustion-supporting agent (oxygen) concentration, oxygen > 12%. In addition, explosion-proof diesel engines are prone to backfire in the intake air during operation, and there are residual sparks in the exhaust gas. The exhaust temperature reaches 600 degrees. The surface of the body is prone to form high temperatures, etc. Therefore, the basic principle of explosion-proof diesel engine protection is to block the ignition source and reduce the surrounding temperature changes. Table 1 is a list of factors that cause the gas explosion and the normal operation of explosion-proof diesel engines.

| Factor Method | Air inlet | Air vent | The machine surface | Between the parts | Exhaust gas temperature | Engine oil | Coolant |
|---------------|-----------|----------|---------------------|-------------------|-------------------------|-----------|---------|
| Manifestation method | Tempering ignite | Sparks ignite | High-temperature ignition | Fire in the gap | High-temperature ignition | Abrasion | High temperature |
| Processing method | Flame arrester | Flame arrester | Cooling and insulation | Structural transformation | Purification device | Pressure control | Temperature control |

According to Table 1, when dealing with explosive factors, structural modifications to the body can be used. For example, in the design, for the component gap factor, the surface roughness of the part can be increased, and the edge thickness can be greater than 13mm, so that the explosion can be
avoided. In addition, special devices can also be added for direct explosion protection, such as factors including the air inlet and the air vent. Usually, an air intake flame arrester or exhaust fence is added. Moreover, it is also feasible to monitor the operation of the explosion-proof diesel engine in real time through monitoring means. Usually, the monitored information is converted into a pneumatic signal, hydraulic signal, or voltage signal, controlling the actuator to stop the explosion-proof diesel engine when an abnormal state such as oil pressure monitoring and water temperature monitoring occurs[4].

3. Compressed Air Starting and Protection System Composition of Explosion-proof diesel engine

Analyzing principle, the system composition is distinguished by functional form, which is mainly composed of air source acquisition and storage, air source cleaning, status sensing, logic valve group, actuator and supporting joint pipelines, as is shown in Fig.3.

![Fig.3 Compressed air starting and protection system diagram of explosion-proof diesel engine](image)

Air source acquisition and storage are mainly composed of air pumps, air storage tanks, one-way valves, safety valves, ball valves, and drain valves. The function of the air pump is to compress the external air that will be stored in the air storage tank to supply the system air source when the explosion-proof diesel engine starts and works normally, which can be driven by gearboxes, hydraulic motors, air motors, and explosion-proof motors. In addition, due to the need for explosion-proof, the air pump casts water channels in the pump body and uses circulating water for forced cooling. The maximum temperature of the shell is less than 150°C.

One-way valves and safety valves restrict the direction of air flow and control the maximum pressure of the air storage tank. Air can only enter the air storage tank from the air pump inlet without reverse flow. What is more, when the pressure at the outlet of the air pump reaches 0.8MPa which is set by the unloading valve, the pressure will be relieved, and the pressure in the air storage tank cannot exceed the maximum pressure of 1MPa so that the two together protect air source acquisition and storage module.

The air storage tank is a pressure vessel that stores high-pressure air compressed by the air pump, which must have a certain degree of corrosion resistance and rust resistance, and the pressure level...
should meet the design requirements. Additionally, the drain valve is installed at the bottom of the air storage tank to discharge the water formed by air cooling and condensation, since the condensed water will squeeze the effective volume of the air storage tank. Meanwhile, low temperatures will freeze and block the air path, which is harmful to the entire system.

Air source cleaning is mainly composed of different filters impurities such as water and dust that enter the system, cleaning the air source, so that the entire system can work safely and effectively.

The state perception is mainly completed by four necessary sensors, namely water temperature sensor, water level sensor, exhaust temperature sensor, and surface temperature sensor.

The logic valve group is mainly composed of pneumatic valves with different functions. According to the control mode, it can be divided into manual button valves, pneumatic control valves, hydraulic control valves, etc. Besides, the start and protection of explosion-proof diesel engines are controlled by combining different valves.

The actuator is composed of the motor body and the delay valve, which converts the potential energy of the compressed air in the air storage device into kinetic energy to start the explosion-proof diesel engine. In addition, the selection of the air motor is controlled by the starting requirements of the explosion-proof diesel engine.

4. Explosion-proof Diesel Engine Starting and the Selection Calculation of Safety Protection System Component

When designing the system, due to safety and performance requirements, the compressed air pressure of the air storage tank is usually set to 0.8MPa, the control air pressure is generally lower than 0.7MPa, and the pressure safety factor of each component is 2. Besides, the opening temperature of the water temperature sensor is 100°C, the opening temperature of the exhaust temperature sensor is 70°C, and the opening temperature of the surface temperature sensor is 150°C. In addition, the water level of the water level sensor is determined according to the design requirements of the exhaust air treatment box. Meanwhile, in the selection process, the working pressure of the pneumatic valve is generally 0-8MPa, the ambient temperature is 10-80 degrees, and the flow rate is 10L/min. The flow rate of the safety valve is greater than the flow rate of the air pump.

4.1 Motor Starting Torque

The output torque, displacement, and working pressure of the air motor are necessary parameters when selecting the appropriate model from the product catalog. In theory, the necessary and sufficient condition that the explosion-proof diesel engine can smoothly start is that the starting speed and torque of the air motor are greater than the minimum starting speed and torque of the explosion-proof diesel engine \[5\]. The minimum torque of the explosion-proof diesel engine is calculated by the formula (3):

\[
T_{\text{min}} = \frac{9550P_{\text{min}} n_{\text{min}}}{\eta_{\text{s}}} \tag{3}
\]

\(P_{\text{min}}\) is the minimum starting power of explosion-proof diesel engine.

Considering the transmission friction and internal leakage loss of the air motor, the output torque of the air motor is:

\[
T_m = T_{\text{min}} / \eta_{\text{s}} = \frac{9550P_{\text{min}} n_{\text{min}}}{\eta_{\text{s}}} \tag{4}
\]

\(T_m\) is the output torque of air motor, \(\eta_{\text{s}}\) is starting transmission efficiency.

When the high-pressure pneumatic motor, the pressure will be reduced, and the air potential energy will be transformed into the rotational kinetic energy of the air motor so that the starting is completed. The displacement calculation formula is as follows:

\[
V_m = 2\pi T_m / p_w \tag{5}
\]

\(V_m\) is the displacement of air motor, \(p_w\) is the rated working pressure of air motor, which is less than 0.8MPa.
4.2 Design of the Air Storage Tank  
As the core component of air acquisition and storage, the air storage tank belongs to the category of pressure vessels, which are usually welded by stainless steel. Moreover, the volume is determined by the number of starts. The amount of air consumed at one start is calculated by the formula (6):

\[ m_k = \rho_k n_t V_m = \frac{2\pi \rho_k n_t T_m}{p_{w}} \]  

(6)

\( m_k \) is the air consumption at \( k \) times of starting, \( \rho_k \) is the air density at \( k \) times of starting, \( t \) is the starting time, which is usually 5 seconds.

After starting \( k \) times, the remaining amount of the compressed air in the air storage tank is:

\[ m_0 - \sum_{k=1}^{n} m_k = \frac{p_k V_L}{RT} \geq 0 \]  

(7)

\( m_0 \) is the initial air volume in the air storage tank, \( V_L \) is the air tank volume, \( R \) is the air constant, \( p_k \) is the air pressure at \( k \) times of starting, \( T \) is the temperature of the air in the air storage tank, which remains unchanged in a steady status.

It is assumed that the compressed air in the air tank container changes with constant volume and temperature, namely

\[ \frac{p_k}{p_0} = \frac{m_k}{m_0} \]  

(8)

From formulas (6), (7), and (8) it is obtained that

\[ V_L = \left( m_0 - \sum_{k=1}^{n} m_k \right) = \frac{m_0 RT}{m_1 p_0} \]  

(9)

5. Conclusions  
As one of the important systems in explosion-proof diesel engines, the starting and safety protection system is difficult to be designed. In this paper, considering the requirements of the explosion-proof diesel engine in starting and operation protection, the starting and safety protection system of the explosion-proof diesel engine are jointly analyzed to study the principle of compressed air starting and safety protection and calculate the main component parameters.

Based on the results and discussions presented above, the conclusions are obtained as below:

1) It is revealed that the start-up process of explosion-proof diesel engines must be carried out under the premise of meeting safety.

2) It is designed a set of explosion-proof diesel engine compressed air starting and protection systems that meets the use of coal mines

The compressed air starting and protection systems can be applied to equipment that uses explosion-proof diesel engines as power sources in coal mines, such as electric locomotives, monorail cranes, trackless rubber-tired vehicles, etc. In addition, when designing a specific system, the differences between different products should be considered to unify and harmonize the generality and differences and intelligence is the direction of its development.

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