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The Influence of Plateau Environment on Diesel Engine Starting Process

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Abstract: In view of the difficulty of a diesel engine starting in a plateau environment, this paper analyzed three factors that affect diesel engine starting by literature review and theoretical analysis, deeply analyzed the mechanism of the plateau environment on the diesel engine starting process, and introduced auxiliary measures for diesel engine starting in a plateau environment so as to further study how fast and reliable starting has laid a solid theoretical foundation.

1. Introduction

In southwest China, the average sea wave height is 4500 m. Compared with the Central Plains, its environmental characteristics are mainly cold weather, thin air, low oxygen content, a large temperature difference, and low air pressure. Due to its special geographical and climatic characteristics, it is difficult to start the diesel engine of heavy vehicles, and it cannot be started in serious cases. In addition, if the diesel engine is forced to start in a cold state, it will aggravate the wear of the cylinder liner, piston, crankshaft, and other key components of the diesel engine, which will cause diesel engine failure for a long time, affecting the working performance and service life of the diesel engine. Through consulting relevant literature, it is found that when the diesel engine starts at an altitude of 4000 m and an ambient temperature of -25 °C, its starting difficulty is equivalent to the starting condition at -40 °C in plain areas [1-3]. Therefore, it is of great significance to further study the influence mechanism of plateau environment on the starting process of diesel engines and continuously develop the auxiliary device for starting diesel engines at low temperatures in a plateau environment to improve the adaptability of heavy vehicle diesel engines to a plateau environment.

2. Influencing Factors of Diesel Engine Starting Process

The starting process of a diesel engine refers to the whole process from the crankshaft starting to rotate under an external force until the diesel engine starts to automatically rotate. At the initial stage of a diesel engine's starting, the starting motor drives the crankshaft to rotate, forcing the piston to move up and down in the cylinder and compressing the fuel in the cylinder, and the gas expansion works to push the piston to move up and down, thus driving the crankshaft to rotate. When the diesel engine speed reaches the specified starting speed range, the expansion of the combustible mixture in the cylinder works to make the crankshaft rotate. At this stage, the diesel engine's working cycle can be completed automatically, enabling it to work on its own. In the process of a diesel engine starting, whether the engine can start smoothly is mainly determined by the following three factors.

2.1 Impact of Temperature and Pressure in the Cylinder at the End of the Compression

To ensure that the diesel injected into the cylinder can ignite automatically, the temperature of the mixture in the cylinder at the end of compression is required to be about 200 °C higher than the fuel spontaneous ignition point. The auto-ignition point of diesel oil is about 335 ℃ under normal pressure. When the gas pressure at the end of compression in the cylinder reaches 2.0–2.8 MPa, the temperature is 200–235 °C. Therefore, the diesel engine can be started quickly and reliably only when the mixture temperature reaches a high temperature above 400 °C.

In a plateau environment, there are two main characteristics of a diesel engine starting. One is that when starting the diesel engine, the end temperature of air compression in the cylinder often cannot reach the auto-ignition point temperature of diesel; second, the end compression pressure in the cylinder is lower than the normal value.

2.2 Influence of Mixture Uniformity and Concentration Suitability in Cylinder

The precondition for diesel fuel to self-combust in the cylinder is whether the mixture in the cylinder is uniform

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and the concentration is appropriate. If the amount of diesel fuel injected into the cylinder is too small or the quality of the spray is poor, the engine cannot form self-combustion conditions or work continuously. To characterize the concentration of the mixture, it is usually expressed by the excess air coefficient. For a supercharged diesel engine, the excess air coefficient is usually 1.8–2.2 under the maximum power working condition, which is called the ignition limit of the diesel engine. If the mixture is too rich or too thin, it is not conducive to the ignition of the mixture.

2.3 Effect of Minimum Starting Speed of Diesel Engine

Through the analysis of the above two starting conditions, it can be found that the diesel engine starting is related to the starting speed. Under normal conditions of oil and gas supply, to ensure that the diesel engine can start normally, the starting speed should always be greater than or equal to the minimum starting speed. If the starting speed of the diesel engine is less than the minimum starting speed, the fuel injection pressure is insufficient, the atomization quality of diesel fuel is poor, and the compression time becomes longer, which increases air leakage and heat loss and makes it difficult to reach the autoignition temperature of the fuel, so the diesel engine cannot be started.

3. Influence of Plateau Environment on Diesel Engine Starting Process

3.1 Influence of Plateau Environment on Temperature and Pressure in the Cylinder at the End of Compression of Diesel Engine

The plateau environment is characterized by low air pressure, low temperatures, thin air, and low oxygen content. With the increase of altitude, atmospheric pressure Pa and atmospheric density ρ reduce. The corresponding reduction is shown in Equations (1) and (2) [4]:

$$P_a = P_0(1-0.02257\,H)^{5.256} \tag{1}$$

$$\rho = \frac{1.293}{1+0.00376(T_a-273.15)} \times \frac{P_a}{0.101325} \tag{2}$$

where P_0 is the atmospheric pressure at sea level, MPa; H is the altitude, km; ρ Is the atmospheric density, kg/m^3; and T_a is the ambient atmospheric temperature, K.

The temperature and pressure at the end of compression of the diesel engine can be calculated by Equations (3) and (4):

$$T_{co} = T_{ca}\varepsilon_{cc}^{n_1-1} \tag{3}$$

$$P_{co} = P_{ca}\varepsilon_{cc}^{n_1} \tag{4}$$

where T_{ca} is the compression starting point temperature, K; T_{co} is the compression endpoint temperature, K; ε_{cc} is the effective compression ratio, ε cc = (0.8–0.9) ε_c, ε_c is the compression ratio; N_1 is compression polytropic index; P_{ca} is the starting point pressure of compression in the cylinder, Pca = (0.8–0.9) Pa, Pa is the atmospheric pressure, MPa; and P_{co} is the final compression pressure of the cylinder, MPa.

It can be seen from Equations (3) and (4) that the final compression temperature and pressure of a diesel engine are mainly determined by ambient temperature, pressure, and the compression polytropic index. The polytropic index of a diesel engine is mainly affected by the heat exchange between the working fluid and the cylinder wall and the cylinder leakage. When the ambient air temperature is low, the intake air temperature decreases, which increases the oil viscosity, deteriorates the fluidity, and reduces the starting speed, leading to longer compression time, increased mixture leakage, reduced polytropic index of the diesel engine, and reduced temperature and pressure in the cylinder at the end of compression. When the temperature and pressure in the cylinder at the end of compression drop to a certain extent, the mixture will not reach the minimum ignition critical temperature, the mixture will not ignite, and the diesel engine will not start normally.

3.2 Effect of Plateau Environment on Diesel Engine Mixture Characteristics

Three conditions are required for fuel combustion. In addition to temperature and pressure, there is also mixture concentration. These three factors are not independent but interact with each other. See Figure 1 [5]. With the decrease in temperature and pressure, the concentration limit of combustion narrows.

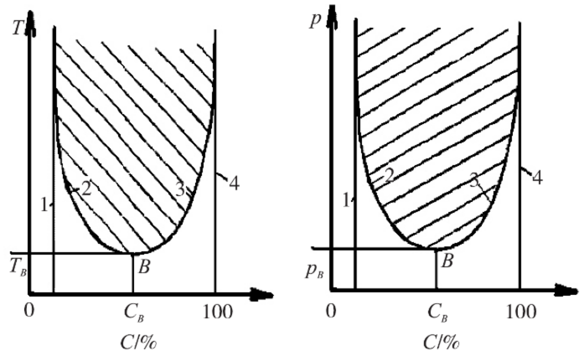

Figure 1. Relationship between ignition temperature, pressure, and ignition limit of mixture

In Figure 1, 1 is the lean oil limit, 2 is the lean oil lower limit, 3 is the rich oil upper limit, 4 is the rich oil limit, TB is the limit temperature, PB is the limit pressure, CB is the concentration value of combustible mixture under the limit temperature and pressure, and the shadow area is the ignition area.

It can be seen from Figure 1 that with the increase in altitude and the decrease in temperature, the temperature and pressure of the diesel engine at the end of compression show a downward trend, and the corresponding ignition mixture concentration range gradually decreases. Therefore, the mixture concentration is likely to exceed the ignition concentration range due to the reduction of the atmospheric density in the plateau, resulting that the mixture in the diesel engine cylinder cannot be ignited.

3.3 Impact of plateau environment on diesel engine starting speed

The starting speed of a diesel engine is mainly affected by the starting power and starting torque. The higher the starting power is, the smaller the resistance torque is, and the higher the starting speed of the diesel engine is, on the contrary, the lower it is.

3.3.1 Effect of low temperature on starting power of diesel engine

The output power of the heavy vehicle starting system directly affects the starting speed of the diesel engine. The greater the output power, the higher the starting speed is, and the diesel engine can start at a lower temperature, which can improve the low-temperature starting performance of the diesel engine. However, with the continuous drop in ambient temperature, the power supply device of the starting system, namely, the battery, will discharge with a large current under low-temperature conditions, resulting in a sharp drop in battery capacity and output power, a decrease in starting speed, and poor starting performance.

In addition, with the temperature decreasing, the viscosity of the electrolyte (diluted sulfuric acid solution) in the battery will increase, which will increase the resistivity of the battery. It can be seen from Table 1 that when the temperature of the electrolyte drops from 30 °C to 40 °C, the resistivity of the electrolyte increases 7.36 times.

Table 1. Effect of Temperature on Resistivity of Sulfuric Acid Solution

Temperature/°C	30	20	10	0	-10	-20	-30	-40
Resistivity/（Ω·cm）	1.140	1.334	1.602	1.990	2.600	3.570	5.290	8.390

The increase of the resistivity of the battery increases the internal resistance of the battery, which leads to a sharp drop in the starting output power of the battery.

$$U = E_b - I_{st} \cdot R_b = I_{st} \cdot R_L + I_{st} \cdot R_{st} \qquad (5)$$

where U is the terminal voltage of the storage battery during starting, V; E_b is the electromotive force of the battery, V; I_{st} is the starting current, A; R_b is the internal resistance of the battery, Ω; R_L is the starting line resistance, Ω; and R_{st} is the starter armature resistance, Ω.

Through Equation (5), it can be found that the line resistance and starter armature resistance change little with the temperature drop, while the internal resistance of the battery increases with the temperature drop, so the terminal voltage of the battery will decrease with the temperature drop when starting. On the other hand, the starting current will increase 3–4 times due to the increase in starting resistance during a low-temperature start.

According to the above analysis, under low-temperature conditions, the terminal voltage of the battery and the starting output power decrease due to the increase in the internal resistance of the battery and the rapid increase in the starting current. The starting speed decreases, and finally, the diesel engine cannot be started [6].

3.3.2 Effect of Low Temperature on Engine Starting Resistance Torque

When the diesel engine starts, the actual speed n that the engine crankshaft can reach depends on the starting torque that the starting device gives to the crankshaft and the starting resistance torque that prevents the crankshaft from rotating. Starting resistance torque refers to the torque that needs to be overcome when the diesel engine is dragged from a static state to starting speed, which can be expressed by Equation (6).

$$M_r = M_t + M_j + M_k \qquad (6)$$

where M_t is the friction resistance moment, N·m; M_j is the inertia resistance moment, N·m; and M_k is the compression resistance moment, N·m.

The friction resistance torque of a diesel engine is the main component of starting resistance torque. When the temperature decreases, the friction resistance between various parts increases due to the increase in oil viscosity. Through consulting relevant literature, it is found that when the ambient temperature is 0–5 °C, the friction resistance torque accounts for about 60% of the starting resistance torque, and when the ambient temperature is -20–10 °C, it accounts for about 80%–95% [7].

The compression resistance torque refers to the compression stroke. The piston is formed by the resistance of compressed gas. It mainly depends on the power, displacement, and compression ratio of the engine.

The inertia resistance moment includes the crankshaft, connecting rod, piston, and various auxiliary mechanisms associated with the crankshaft, such as the oil pump, fan, generator, etc. It mainly depends on the inertia force of each component or mechanism in the acceleration process.

Therefore, when the ambient temperature decreases, the oil viscosity will increase rapidly, which will lead to an increase in the friction resistance of the diesel engine and a rapid rise in the starting resistance of the diesel engine, thus affecting the normal starting of the diesel engine.

4. Auxiliary Measures for Diesel Engine Starting at Low Temperature in a Plateau

At present, auxiliary starting measures are used to ensure that the diesel engine can start quickly and reliably when it starts at a low temperature. At present, auxiliary measures for low temperature starting of diesel engines are formulated for plain areas, as shown in Table 2, while those for plateau areas are not ideal.

Table 2. Auxiliary Measures for Low-Temperature and Low-Pressure Starting of Vehicle Diesel Engine

Classification of Starting Aids	Low-temperature Starting Aids	Explanation
Auxiliary Measures for Emergencies Starting	Flame Intake Preheating Device Electric heating preheating device Glow plug	Low atmospheric pressure and low oxygen content in the air in plateau areas make it unsuitable to use air inlet preheating device.
	Cold starting fluid Oil injection in the cylinder	Forced start, serious engine wear, affecting emissions
	Supercapacitor Storage battery heating and insulation device Gelled high-energy battery Low temperature battery	The ideal starting power supply under low temperature and low-pressure conditions needs to be combined with the heating starting auxiliary measures to reduce engine wear.
Auxiliary Measures for Heating and Starting	Coolant heating device Oil and fuel preheating device	It can not only ensure the smooth starting of the diesel engine but also reduce the starting wear.
Other Auxiliary Measures	EGR	Effective in plateau low temperature and low-pressure environment
	Increase cetane number and use additives	High cost, high cost, and limited effect

Given the difficulty in starting diesel engines in a plateau environment, new starting aids currently used mainly include fuel heaters, battery insulation devices, gel high-energy batteries, supercapacitors, etc.

4.1 Fuel Heater

The fuel heater is an auxiliary measure for heating and starting the whole machine and lubricating oil by burning the fuel through the burner and transferring the heat to the coolant and air through the heat exchanger [8]. After the engine is heated, the temperature of the cylinder, piston, piston ring, and bearings increases, and the oil temperature between these friction pairs also increases, reducing the starting resistance and increasing the starting speed, thus increasing the temperature and pressure at the end of the compression and making the engine easy to start. At the same time, the oil viscosity decreases, the lubrication conditions are improved, and the wear on parts is reduced. The fuel heater is a very effective cold-start auxiliary device for diesel engines at low temperatures and is also a commonly used starting aid mode.

4.2 Storage Battery Incubator

The battery insulation box is composed of a box cover, a box, a heating pipe, a sealing strip, fastening bolts, and a battery-fixing device. The basic principle of the battery insulation box is to heat the battery by using the thermal fluid formed by heating the coolant with a fuel heater, then heat the heated battery through the insulation function of the insulation box so that the output power of the battery can meet the needs of the starting system.

4.3 Supercapacitor

The supercapacitor is a new type of energy storage container between traditional capacitors and batteries. The supercapacitor has good discharge ability and reliability in extreme temperature environments, making it an ideal starting power supply for diesel engines in a low-pressure and low-temperature environment. The supercapacitor is characterized by large capacity, small internal resistance, and long life, and can be charged and discharged quickly with a large current. The operating temperature range is 41 to 70 °C. The battery is not suitable for large current discharges, and its low-temperature performance is poor. Due to the limited capacity of the supercapacitor, it cannot provide a long time of large current discharge when used alone, and it is difficult to charge when installed on the vehicle. Therefore, both are not suitable for starting the power supply alone. If the supercapacitor is used in parallel with the battery as the starting power supply, the advantages of the supercapacitor and the battery can be brought into play.

4.4 Colloidal High-Energy Battery

The gelled high-energy battery uses high-energy compounds as an electrolyte, which has the following significant advantages: small self-discharge, good maintenance-free, and easy to be stored for a long time; The excellent charging and discharging characteristics can better meet the operational requirements. Specific energy is high and relative mass is light; No lower limit of discharge voltage is allowed, and deep discharge is allowed. Strong self-recovery ability, which is conducive to emergency use.

The gel high-energy battery has good environmental adaptability. For one thing, the high-energy and environment-friendly battery is different from the lead-acid battery in its mechanism, and there is no gas produced during the charging (discharging) process. For another thing, the battery has very small internal resistance (micro-ohm level), and it will not generate a lot of heat during the charging (discharging) of a large current. The electrolyte usually does not appear gasified, so it is a truly fully sealed battery. Therefore, the high-energy and environment-friendly battery can ensure that the army can use it in any complex environment, such as high temperature, cold, or high altitude, and especially can adapt to the performance requirements of the special vehicle environment. According to the test, it can be used normally in the range of -40 to 70 °C. After being stored at -40 °C for 24 hours, it can be charged (discharged) normally, and its voltage is not lower than 12.5 volts (battery rated at 12 volts).

4.5 Combined Starting Auxiliary Measures

To better improve the starting performance of diesel engines in plateau areas and ensure the service life of diesel engines, two or more starting auxiliary measures can be combined to form a combined starting auxiliary measure. The fuel heater is used as the preheating system of the diesel engine to increase the temperature of the diesel engine body, oil, fuel, or battery by heating the circulating coolant, to realize the starting of the diesel engine under the hot engine state. At the same time, battery insulation devices, gel high energy batteries, or supercapacitor parallel batteries are used as starting power to ensure the starting power of the diesel engine. Combined cold starting auxiliary measures can not only improve the starting ability of diesel engines but also not reduce the reliability and durability of diesel engines, which can completely solve the cold starting problem of diesel engines in plateau-cold regions.

5. Conclusion

(1) The obvious climatic characteristics of the plateau environment are low temperatures and low air pressure, which seriously affect the starting process of diesel engines. The low temperature will reduce the starting power, increase the starting resistance torque, and reduce the engine starting speed, making the diesel engine unable to start normally; low air pressure and low temperature will reduce the pressure and temperature at the end of compression, which cannot reach the autoignition point of the fuel. At the same time, the concentration range of the ignition mixture gradually decreases, which makes the mixture in the cylinder unable to ignite, affecting the starting of the diesel engine.

(2) At present, the starting aids for diesel engines suitable for plateau areas mainly include fuel heaters, battery incubators, supercapacitors, and gel high-energy batteries. The combined cold-start auxiliary measures can not only improve the starting ability of the diesel engine but also increase its reliability and durability.

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