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Analysis of the Influence of Working Rate and Energy Consumption of Air Compressor in EMU Air Supply System Considering Leakage

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Abstract

Under different operating conditions, the frequency of utilization of electric multiple units (EMU) air equipment is different. If the air consumption of equipment cannot match with the air supply, the air compressor will be underutilized, resulting in compressor oil emulsification. In engineering, the working rate is usually improved by increasing compressor working time to avoid emulsification, but this also leads to higher energy consumption. For this problem, based on the composition and principle of the EMU air supply system, models of air supply system considering leakage effect are established, and the influence of different air compressor start-stop pressure and air storage cylinder volume on the compressor working rate are analysed under two typical working conditions of initial air charging and normal line running. The results show that when the starting pressure of the air compressor is 8.5 bar or above, the working rate is positively correlated with the stopping pressure. When the starting pressure is low and the stopping pressure is high, the energy consumption of the air compressor is low. When the volume of the air storage cylinder is between 160 L and 190 L, the energy consumption of the air compressor is low, but the working rate is higher than 30%. The research results provide a fundamental basis for the parameter design and selection of train air supply system.

Keywords: train, air compressor, air supply, working rate, leakage, energy consumption.

1 Introduction

The air supply system is an important part of the EMU, which provides a continuous power source for the air brake system, air spring and other wind equipment to ensure the safe and smooth operation of the EMU. As the core component of the air supply system, the working condition of the air compressor is very important. At present, air compressors used by rail vehicles are generally divided into oil-lubricated air compressors and oil-free air compressors. Due to the high manufacturing cost, oil-free air compressors are used in a small range on rail vehicles, so oil-lubricated air compressors occupy most of the market on rail vehicles, but the ensuing problem is the oil emulsification of air compressors [1]. The performance of lubricating oil after emulsification are reduced, which makes the wear of the air compressor aggravated and affects the life, which needs to be avoided. The main reason for the emulsification of lubricating oil is that the air compressor inhales humid air while the operation time of the air compressor is low, the temperature of lubricating oil cannot rise to the appropriate range normally, and the condensed water precipitated by compressed air cannot be gasified and discharged, which is mixed in the lubricating oil, resulting in emulsification of lubricating oil [2-3]. Generally, oil emulsification can be avoided when the working rate of screw air compressors is not less than 30% [4]. Shi et al. [5] proposed the load/unload working mode of air compressors. In the unloading mode, the air compressor does not output compressed air while idling. The ground experiment and positive line experiment verified the effectiveness of this working mode. Tian et al. [6] proposed a set of intelligent control scheme of air compressor working rate based on a train control and management system, which automatically opened or closed the exhaust device on the main air duct to maintain the working rate of air compressor. In general, in order to improve the working rate of the air compressors, most measures are to keep the air compressor running and extend the working time, but at the same time, it also causes a certain amount of energy waste.

For air compressors, the initial investment of equipment accounts for 15%, the maintenance and management costs account for 15%, and the proportion of energy consumption is as high as 70% [7]. In order to reduce compressor energy consumption, scholars have made a lot of efforts. Yu et al. [8] studied the variation rule of air compressor function efficiency under different ambient temperatures, and obtained the temperature corresponding to the optimal air compressor function efficiency. Shen [9] et al. designed an inspiratory pre-treatment system and obtained the law of influence of cooling tower parameters on energy consumption of air compressor. Lin [10] designed a new compressed air system control algorithm, and the engineering pilot application results show that the energy consumption of the air compressor unit is reduced by 4.91%. It can be seen that at present, there are separate studies on the emulsification of air compressor oil and the compressor energy consumption, but there are few reports on the analysis of the air supply system that considers the influence of the leakage of air supply system and balances the oil emulsification prevention and low energy consumption of air compressor.

To sum up, in order to improve the working rate and energy consumption economy of air compressor, this paper takes the air supply system of EMU as the research object, and analyses the working rate and energy consumption of the compressor with different start-stop pressure and storage cylinder volume. In this paper, the basic structure of the EMU air supply system is first introduced, and then the AMESim software is used to model and simulate the system, and the working rate and energy consumption trend of the air compressor under different parameters are obtained.

2 Methods

2.1 Composition and principle of air supply system

The structure of the air supply system for CR400AF EMU is shown in Figure 1. The air supply system is composed of air source, pipeline and air equipment.

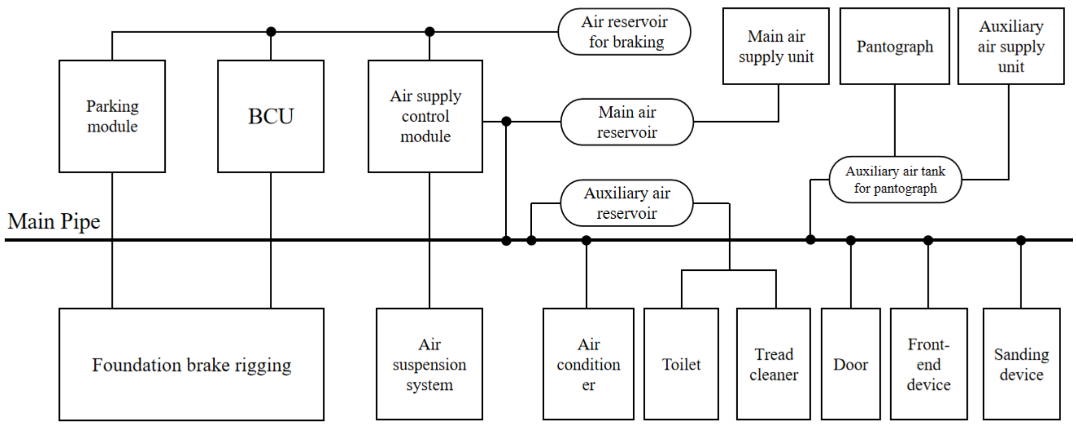

Figure 1 Schematic diagram of air system for EMU.

The air source equipment is the main air supply unit and the auxiliary air supply unit, which are installed in the third and sixth vehicles. The two main air supply units are defined as the main and secondary air supply units according to the time or the direction of train travel. During normal running, when the total air pressure exceeds 950 kPa, the air compressor stops working, and when the total air pressure drops below 800 kPa, only the main air supply unit starts to supply air to the train. When the total air pressure drops to 750 kPa, the main and secondary air supply units start to supply air to the train at the same time. In the initial air charging, the main and slave air supply units run at the same time to supply air to the train. The auxiliary air supply unit is driven by the battery and only starts when the EMU does not raise the bow and the total wind pressure is insufficient to provide the compressed air required for the bow. Therefore, the auxiliary air supply unit is not considered in this paper. As shown in Figure 2, the main air supply unit consists of a drive motor, compressor host, safety valve, dryer, oil-water separator, check valve and other components. This unit inhales, compresses and filters air from atmosphere, and provides compressed air with a certain pressure to the train.

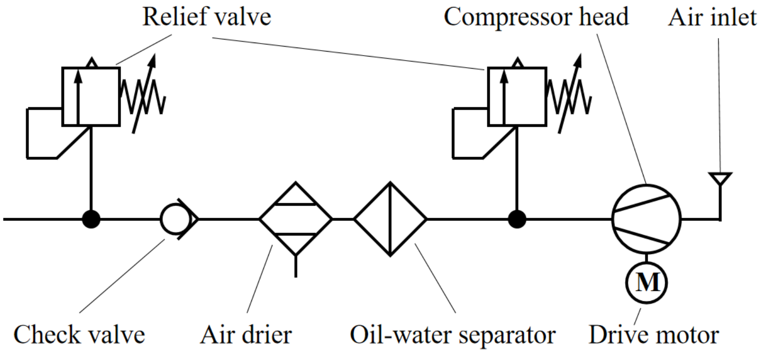

Figure 2 Schematic diagram of the main air supply system.

The brake system and air suspension system are closely related to vehicle safety, so the main air cylinder will give priority to these two systems. A check valve is arranged between the total air cylinder and the brake cylinder to prevent the compressed air of the brake cylinder from reversing, so as to ensure the wind demand of the brake system. When the total air pressure exceeds a certain value, the relief valve opens, and the compressed air of the total air cylinder supplies air to the air suspension system through the pressure-reducing valve to prevent the air spring pressure from being too high. In the process of vehicle operation and passengers getting on and off, the height of the car body will change in real-time due to the change of the body load. At this time, the height valve will automatically charge or exhaust air to the spring air bag and the additional air chamber according to the height of the car body, and adjust the height of the car body.

The toilet and tread cleaning device are supplied by the auxiliary air cylinder. Only when the total air pressure is higher than a certain value, the relief valve is opened and the auxiliary air cylinder can be filled with air. The air priority of the toilet and tread cleaning device is lower than that of the brake system and the air suspension system, so the opening pressure of the auxiliary air cylinder relief valve is slightly higher than that of the air suspension relief valve. Other air equipment such as doors, bagpipes, couplings, etc. are supplied directly by the main air pipe and the main air cylinder.

The above air equipment can be simplified as compressed air through the control valve assembly, charging and venting into the chamber or cylinder to complete the operation and function of the equipment.

2.2 Model of air supply system

2.2.1 Leakage model

The supply air equipment is usually connected by soft and hard pipes, and sealed by sealing materials, but there will still be a certain amount of leakage in the system. Pipeline leakage detection methods include listening method, bubble detection method and pressure detection method [11]. Listening method and bubble detection method can detect the location of leakage, but the accuracy is poor and the specific leakage amount cannot be given. The pressure detection method can be used to detect the leakage of components in the industry, and the pressure detection method is also called the pressure drop method. The leakage amount of the gas under the current pressure can be calculated by measuring the gas pressure in the seal for a period of time. The formula for calculating leakage per unit time using the pressure drop method is as follows:

$$\frac{\Delta P}{\Delta t} = \frac{P - P'}{\Delta t} \tag{1}$$

In the equation: P is the rated working pressure; P' is the pressure of the cavity after Δt; $\frac{\Delta P}{\Delta t}$ is the average pressure drop during the measurement period.

When ΔP is very small, $\frac{\Delta P}{\Delta t}$ can be regarded as the leakage amount of the seal in the rated state.

The main parameters and allowable leakage of equipment related to the EMU air supply system are shown in Table 1.

Equipment	Dimension parameter	Working pressure	Leakage rate
Main air reservoir	Volume 125L	950kPa	2kPa/min
Air reservoir for braking	Volume 125L	950kPa	2kPa/min
Auxiliary air reservoir	Volume 125L	950kPa	2kPa/min
Main pipe	Inside diameter 24mm	950kPa	4kPa/min
Air spring bag	Volume 55L	350~550kPa	2kPa/min
Additional chamber	Volume 110L	350~550kPa	2kPa/min

Table 1 Leakage parameters of air supply system

The model shown in Figure 3 is built in AMESim, and the throttle hole element is used to simulate the leakage of the cavity. First, the working pressure and volume of the cavity are set, the leakage amount is taken as the optimization objective, and the equivalent cross-sectional area of the throttle hole corresponding to the leakage amount under the working pressure of the cavity is calculated through the parameter optimization function, and the obtained cross-sectional area is applied to the model. The leakage of the chamber under working pressure can be accurately simulated.

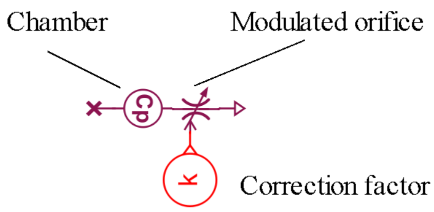

Figure 3 Leakage model

The cross-sectional area of the orifice calculated by the above method is shown in Table 2:

Equipment	Cross-sectional area of the orifice
Main air reservoir	0.022mm²
Air reservoir for braking	0.022mm²
Auxiliary air reservoir	0.022mm²
Main pipe	0.004mm²
Air spring bag	0.024mm²
Additional chamber	0.043mm²

Table 2 Leakage orifice parameters

2.2.2 Main air supply system model

The wind source system is a complex nonlinear system coupled with "machine-electric-gas-liquid", so it is difficult to obtain a precise and accurate model of the wind source system [12]. This paper focuses on the airflow properties of the wind source system and establishes the main air supply unit model according to the principle diagram of the main air supply unit (Figure. 2), as shown in Figure. 3.

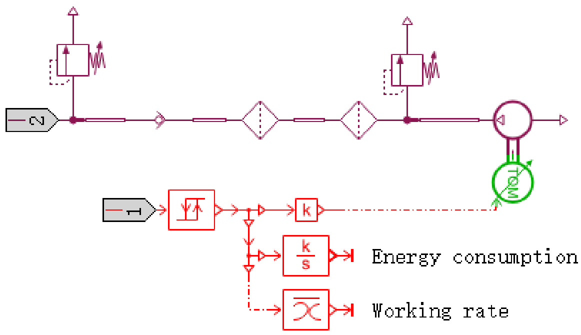

Figure 4 Main air supply system model

The trigger element in the model can output high or low level by the value of the input signal, input the signal of the pressure sensor of the total air duct to the trigger, set the starting and stopping pressure threshold, and then control the start and stop of the air compressor. The displacement of the air compressor in the model is 1300 L/min. From the daily start of the vehicle to the power failure at the end of the daily work, the proportion of the accumulated operating time of the air compressor and the entire working day during this working period is defined as the working rate of the air compressor [6]. The working rate calculation formula of the air compressor is shown in Equations (2) and (3).

$$t_{CYCLE} = t_{ON} + t_{OFF} \tag{2}$$

$$DC_{COMP} = \frac{t_{ON}}{t_{OFF}} \quad (3)$$

In the equation: t_{ON} is the running time of the air compressor; t_{OFF} is the rest time of the air compressor; t_{CYCLE} is the working cycle of the air compressor; DC_{CYCLE} is the working rate of the air compressor.

In the model, the energy consumption and working rate of the air compressor can be calculated by integrating components and mean components respectively, which are expressed by the equation as follows:

$$f(P_t) = \begin{cases} 1, & P_t < P_{\text{stop}} \\ 0, & P_t \geq P_{\text{start}} \end{cases} \quad (4)$$

$$DC_{COMP} = \frac{\int_0^{t_{CYCLE}} f(P_t)}{t_{CYCLE}} \quad (5)$$

$$E = P_R \int_0^{t_{CYCLE}} f(P_t) \quad (6)$$

In the equation: $f(P_t)$ is the compressor start and stop signal; P_t is the current main wind pressure; P_{stop} is the air compressor stop operating pressure; P_{start} is the starting pressure of the air compressor; E is the energy consumption of air compressor; P_R Is the rated power of the air compressor.

2.2.3 Model of air supply system for EMU

In the process of initial air charging, the two main air supply units jointly supply air to the brake air cylinder, the total air cylinder, the auxiliary air cylinder and the air suspension system of the whole train. When the above equipment reaches the working pressure, the initial air charging of the train is completed. When the train runs on the main line, the main air cylinder supplies air to the air suspension system to ensure the dynamic use of air spring. The air brake system is separately supplied by the brake cylinder. The rest of the air equipment is supplied by the main air pipe and auxiliary air cylinder. Because of the low pressure of the toilet air cylinder, the leakage effect is small, only the filling and exhaust air model is established, and the leakage model is not established. Other equipment such as bagpipes, couplings, headcovers and other equipment due to low wind frequency, ignore its wind consumption. Thus, the wind system model for a single vehicle is shown in Figure 5.

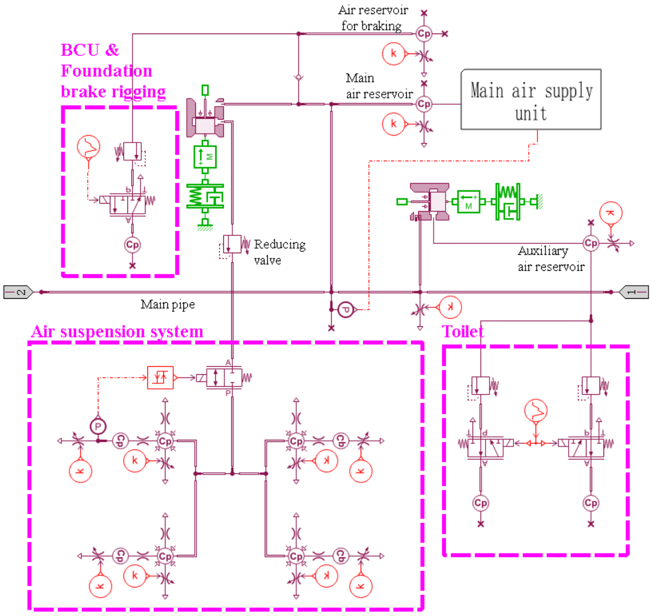

Figure 5 Model of wind system for one carriage

In the air suspension system module, the pressure sensor and trigger are used to control the opening and closing of the solenoid valve. When the pressure measured by the sensor is lower than the working pressure of the air spring, the solenoid valve opens and the total air cylinder supplies air to the air spring; When the pressure measured by the sensor reaches the working pressure, the solenoid valve is closed and the wind supply ends. The maximum air consumption of the air suspension system of each car is about 44 L/min, and the maximum air consumption of each air spring is 11L/min. According to the leakage model in Section 2.1, an additional flow sensor is added, and the parameters of the dynamic exhaust aperture of the air spring are optimized by using this model. The optimized cross-sectional area of the exhaust hole is 0.251 mm^2. Through the opening and closing of the solenoid valve and the exhaust hole, the process of charging and venting the air spring by the height valve can be simply simulated. So far, the model can complete the air supply and exhaust function and leakage of the air suspension system without considering the influence of longitudinal load on the air spring. For the brake system and the toilet, it is simplified to give the working pressure, and the air source is controlled by the solenoid valve to supply and exhaust air to the chamber.

3 Results

3.1 Influence of different start-stop pressure on working rate and energy consumption

3.1.1 Initial charge

When the train is initially charged, the pressure of the air spring rises from 0 to the corresponding pressure of AW0, and the pressure of the air storage cylinder rises from

0 to the stopping pressure of the air compressor. When the pressure of the air storage cylinder is stable, the train is initially charged. The braking system and the connecting pipe of the toilet in the model shown in Figure. 5 are cut off, and the rest parts are connected end to end, and the train air supply system model is established, and only the third and sixth cars were equipped with main air supply units. Under different stopping pressures, the simulation results of the initial air charge model with and without leakage are shown in Figure. 6. Under different stopping pressures, when there is leakage in the system, the initial air charging time is higher than that in the non-leakage model. Since the leakage aperture in the model remains unchanged, the flow rate of the leak hole also increases gradually with the increase of pressure, resulting in an increase in the initial air charging time difference. When the stopping pressure is 8bar, the initial air charging time difference is 32s. When the stopping pressure is 11bar, the initial charging time difference is 45s.

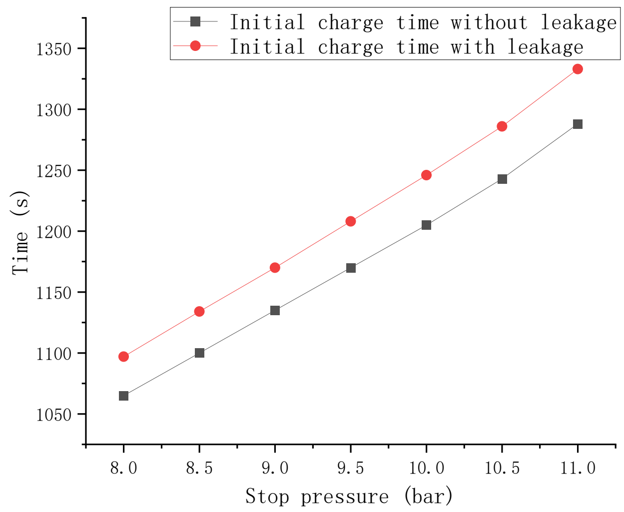

Figure 6 Initial charging time with different stopping pressure

3.1.2 Normal line operation

In order to ensure the operation of each air equipment, a normal line operation condition is set as follows: the train load rises from AW0 to AW2, and then runs for 32 minutes, during which each toilet on the train is used every 4 minutes, and the maximum service brake is applied once when stopping. The starting pressure range of the air compressor is set to 800 kPa to 1100 kPa, and one working condition is set every 50 kPa, 7 working conditions in total. The stopping pressure range of the air compressor is set to 700 kPa to 950 kPa, and one working condition is set every 50kPa, for a total of 6 working conditions. Because the starting pressure of the air compressor must be less than the stopping pressure, a total of 32 groups of combined working conditions. The working rate simulation results of the model hollow press considering leakage under combined working conditions are shown in Figure 7.

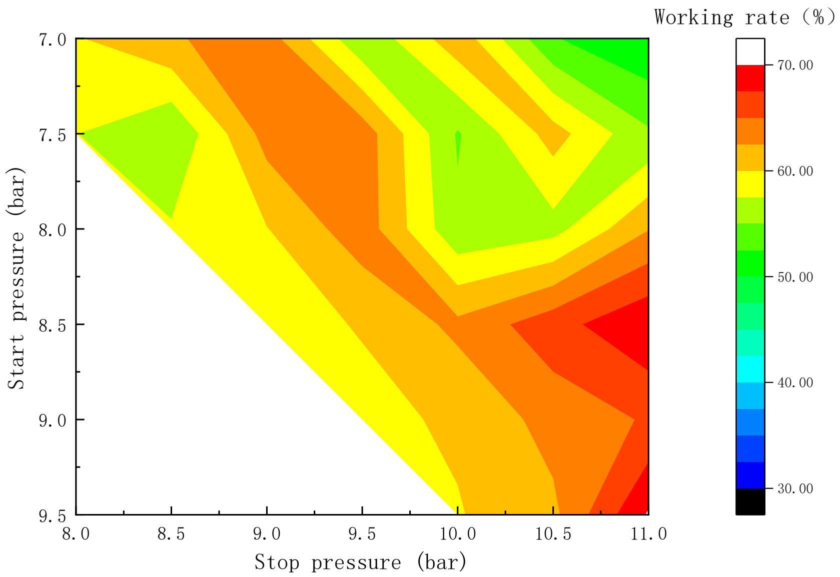

Figure 7 Working rate distribution of air compressors with different start-stop pressures (with leakage)

The simulation results show that the working rate of the air compressor under different working conditions is higher than 30%, which meets the minimum working rate requirement of an air compressor. Under the same starting pressure, with the increase of stopping pressure, the change in working rate is different. When the starting pressure is less than 8.5bar, the relationship between the working rate and the stopping pressure is not obvious, and when the starting pressure is not less than 8.5bar, the working rate of the air compressor increases with the increase of the stopping pressure. Reducing the starting pressure and increasing the stopping pressure can reduce the working rate of the air compressor, while increasing the starting pressure and stopping pressure can increase the working rate of the air compressor.

Under combined working conditions, the simulation results of the working rate of the air compressor under different start-stop pressures without leakage are shown in Figure 8. When there is no leakage in the system, the working rate of the air compressor is low. Compared with the system with leakage, the working rate of air compressor under different working conditions is reduced by at least 8.4%, which can reduce energy consumption by at least 15.4%. The air consumption caused by leakage under different working conditions accounts for about 23.2% of the total air consumption. However, under different start and stop pressures, the working rate of the air compressor is still maintained at more than 30%, and when a higher stop pressure and a lower start pressure are used at the same time, the working rate of the air compressor is low.

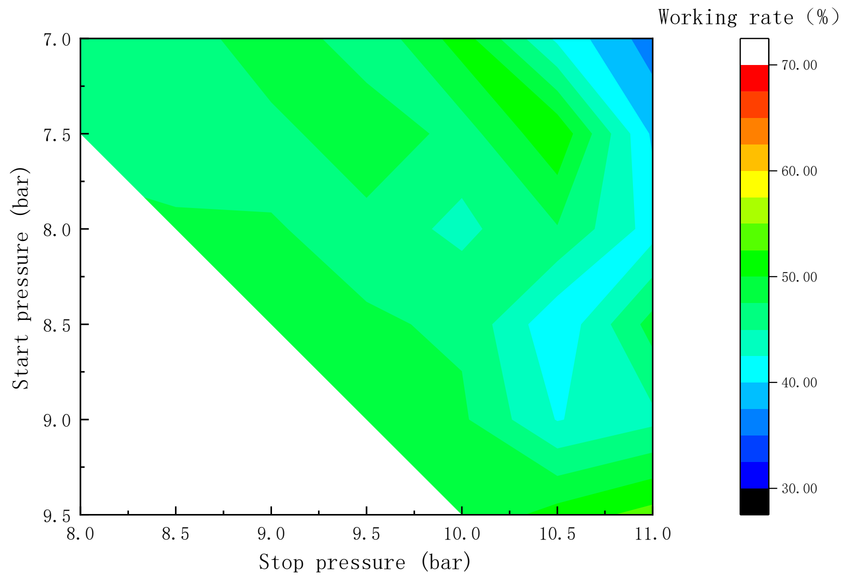

Figure 8 Working rate distribution of air compressors with different start-stop pressure (without leakage)

3.2 Influence of different air reservoir volumes on working rate and energy consumption

3.1.1 Initial charge

The volume of the air storage cylinder is one of the important design parameters of the EMU air supply system. The simulation results of initial air charging when the vehicle is configured with total air cylinder, brake cylinder and auxiliary air cylinder of different volumes are shown in Figure 9.

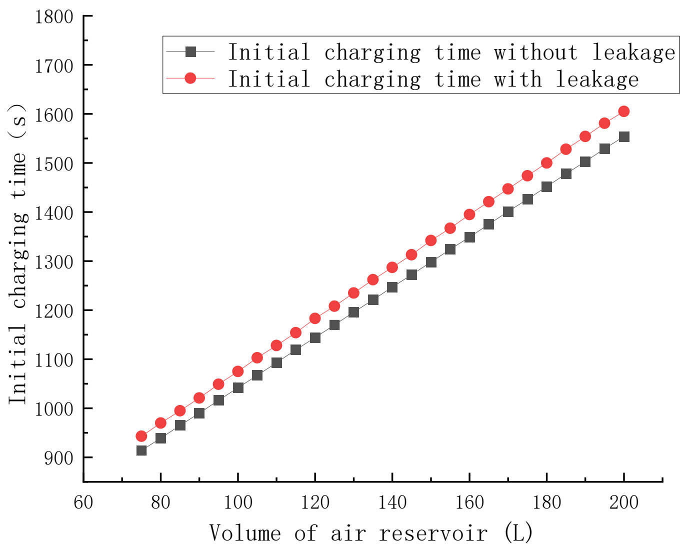

Figure 9 Initial charging time with different air cylinder volume

Regardless of whether there is leakage in the system, the initial charging time has a linear relationship with the volume of the air reservoir. Due to the leakage in the system, the initial air charge takes 29 to 51 seconds more, and the larger the volume of the air storage cylinder, the more time it takes. If the leakage in the system can be completely eliminated, the initial air charging time under different storage cylinder volumes can be increased by at least 3.1%.

3.1.2 Normal line operation

The starting pressure of the main air supply unit is set at 8 bar and the stopping pressure is set at 9.5 bar. The simulation results of different air storage cylinder volumes on the working rate of the air compressor are shown in Figure 10. Under different air storage cylinder volumes, the working rate of the air compressor is higher than 30%, meeting the working rate requirements, when the volume is in the range of 160 L to 190 L, the working rate of the air compressor is low, about 54.7%. If the leakage in the system is eliminated, the working rate of the air compressor can be reduced by at least 4.1% and the maximum is 18.4%.

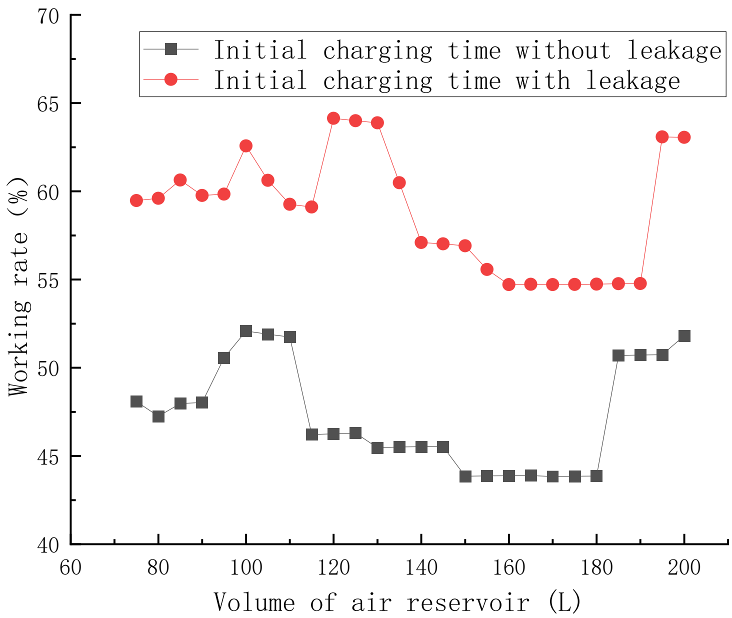

Figure 10 Working rate of air compressors with different volume of air reservoir

4 Conclusions and Contributions

In this paper, according to the structure and working principle of the EMU air supply system, the working performance simulation and analysis model of air compressor in the EMU main air supply unit is established. The accuracy of the model is verified by the initial air charging data of the vehicle, and the leakage models of different cavities are constructed to make the simulation closer to reality. This paper analyses the influence of different start-stop pressure and different air cylinder volume on the working rate and energy consumption of the air compressor in the main air supply unit under the condition of initial air charging and normal line operation. The results show that the working rate of air compressor is higher than 30% under different start-stop pressure. When the starting pressure is 8.5bar or above, the working rate of the air compressor is positively correlated with the stopping pressure. When the starting pressure is low and the stopping pressure is high, the energy consumption of the air compressor is low. Under different air storage cylinder volumes, the working rate of the air compressor is higher than 30%. When the air storage cylinder volume is between 160L and 190L, the working rate of the air compressor is lower, which helps to reduce energy consumption. The research provides some reference for the performance optimization of the supply air system and the reduction of energy consumption.

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