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Intelligent Control of Air Compressor Production Process

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Abstract: The air compressor provides not only the required pressure air for the cooling equipment and refrigeration plant, but also the raw material required for the air separation plant. Utilizing the air compressor is extremely extensive in many significant departments such as the metallurgy, oil and chemical industry. The air compressor production process is a time-varying, delay and nonlinear complex system and gas consumption in the industrial field is irregular. Defects in the traditional control method lead to the pressure instability of the compressed air outputted from the air compressor in volatile gas-consumption situations, sometimes a wide range of fluctuation arising. Therefore, the working state of the air compressor becomes unstable. It results in both a waste of resources and greater energy consumption. Therefore, guaranteeing the output pressure of the air compressor system steady is extraordinarily significant for improving efficiency and saving energy for the overall air separation system. DCS control technology applied to the system, the ECS-700 system of SUPCON was utilized into configuring the air compressor system and monitoring real-time values of important parameters in the various components. According to the working characteristics of the air compressor system, a fuzzy pressure controller and an intelligent control method based on the fuzzy PID were proposed. The simulation results showed that the control effect was extraordinarily satisfactory and effective. It can offer a certain meaning of guidance and reference for the control of other equipment in air separation systems.

Keywords: Air compressor production process, Intelligent control, Fuzzy PID control, Nonlinear, Simulation, Fuzzy control, Time-varying

1. Introduction

The air compressor is a device which generates compressed air and conveys air. It not only provides compressed air at the necessarily regulated pressure for the cooling equipment and refrigerating machinery, but also transports the necessarily raw air to the separation equipment. With the development of the national economy, the air compressor becomes the vital equipment indispensable for the metallurgy, ore mining, machinery, manufacture, petrochemical, national defence and communications industry. In addition, it gradually forms one of important power sources for a great many enterprises.

In general, electric energy consumption of the air compressor system working in the stable state counts up to about twenty percentages of the total energy consumption in the enterprise. Moreover, energy consumption in the unstable state is more. The air compressor is one of key system devices in the overall air-separation process flow. It directly influences the entire air-separation system efficiency whether important parameters of the air-separation system are controlled effectively or not. It is uncommonly tough to obtain its accurate mathematic model by virtue of the air compressor system characteristics, such as time-varying, delay and nonlinearity. Moreover, the traditional controller is based on the accurate mathematical model of the controlled object. Therefore, it is extremely difficult to achieve the satisfactory control effect by adopting traditional control approach to dominate the air compressor system. Bomei Yang designed a new air-compressor controller based on the single chip microcomputer and intelligent control technology. The controller possessed small volume, high reliability, stable control, and easy manipulation. Moreover, parameters could be set, the human-computer interaction was achieved and control accuracy was rather high, which was

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less than 0.01MPa. Fluctuation during the device operation is less and energy consumption was lower. Consequently, the production cost decreased [1]. Xueyan Zhang had researched the PLC-based variable velocity variable frequency system of the air compressor for guaranteeing air-compressor operation steady and outlet pressure stable. He conducted transformation of the variable frequency system on the control system of the original air compressor to make it combined with the PID demodulator. Stable gas pressure was obtained and important parameters as well as the operation condition of the frequency converter during the air-compressor operation could be monitored [2].However, the fuzzy control technology which possesses features of the simple design, convenient application, strong anti-interference ability and powerful robustness for system parameter variation synthesizes expert experience, not depending on the accurate mathematical model of the controlled object. Furthermore, the fuzzy controller is suitable for the system similar to the air compressor which is nonlinear, time-varying and delay. Therefore, it is of a certain advantages for the fuzzy control technology to be utilized into the air compressor system control.

2. Monitoring System Configuration of Air Compressor Production Process

The monitoring software designed possessed function as follows:

1) According to requirements of the monitoring system, the Windows XP Professional Edition in Chinese version was selected for system software environment as a platform to develop a graphical interface where it was convenient for users to operate effectively.

2) The main control interface showed the real-time data and history records of each primary parameter of air compressors to provide the basis for designing the effective control program.

3) In the monitoring interface, the operation log window, alarm log history window, report window of air compressors could be displayed by switching.

4) The starting mode was divided into soft start and manual start for air compressor control.

Through compiling the relevant program, air compressors were started or stopped by manually clicking a button on the control interface.

The ECS-700 system in the DCS configuration tool was used to develop its monitoring software during designing the monitoring system of air compressors. The system whose characteristics were flexible configuration, perfect control function, convenient data processing, focused display operation, friendly HMI, simple installation specifications, easy debugging, powerful versatility and reliable operation integrated the latest field bus technology, embedded software technology, advanced control technology and network technology. The DCS system generally selected the dual-redundant control unit. When a control unit failed, a relevantly redundant real unit was switched into the working unit without disturbance [3].

For designing the control system of air compressors, working below was completed as a whole:

1) The project operation, structural configuration and engineer authority management set were accomplished in structural design environment. Structural configuration included the control domain, control station, operating field and adding operation nodes.

2)Control configuration and monitoring configuration were achieved in the configuration environment.

The air compressor control primarily included the motor start/stop and the constant pressure control of outlet pressure, supplemented with an accident interlock protection control during the air compressor operating. The monitoring screen mainly embodied the air compressor start/stop and accident interlock. The air compressor start and stop was divided into the automatic and manual mode. In the constant pressure control process, we should pay attention to preventing compressor surge and outlet flow matching inlet pressure. The low flow or high pressure could lead to the air compressor surge [4, 5]. It could directly damage the air compressor equipment, even causing the air-separation shutdown. Fig.1 showed the operating characteristic curve of the MAN Turbo compressor. The curve was provided by the compressor manufacturer. The offset between the control line and surge line was about 8% to 10% of the flow measurement range value. For some reason, the operating point entering into the control line quickly opened the vent valve and let the operating point leave the control lines. As long as faults existed, the operating point would move around the control line and not enter the surge zone. Faults eliminated, the operating point would leave from the control line and go back to the normal position. The smaller the offset value was, the higher the scan rate required for the system was. However, the larger the offset value was, the greater energy loss was. The offset could be adjusted appropriately after the field configuration, so as to achieve maximum efficiency.

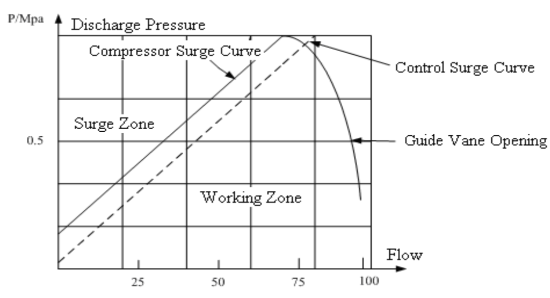

Figure 1 Characteristic Curve

3. Design of Pressure Fuzzy Controller

Determine the domain and membership function. The control structure of the pressure fuzzy controller designed in this paper was shown in Fig.2. The pressure control was rather crucial, since surge in the air compressor occurred when the outlet flow mismatched the discharge pressure in the air compressor. That is to say, the flow was low or the pressure was high. The surge arising would lead to severe consequences: significant deterioration in performance of the air compressor, increased noise and damage to air compressor components. The error deprived from comparison between the actual outlet pressure signal measured by pressure sensors in the air compressor and the prescribed value and the error variation ratio were defined as the input quantity. The output was the opening value of controlling the compressor inlet guide blade. The input quantity was required to be discretized and fuzzified. A certain corresponding relationship between the discretely numerical quantity and the fuzzy quantity indicating the fuzzy language was established to convert the accurate quantity into the fuzzy quantity. The input quantity need be multiplied by the relational quantitative factor during constructing the corresponding relationship. The quantitative factors were indicated by the K. K_e and K_c denoted the deviation and the quantitative factor of the deviation variation, respectively. Ku represented the proportion factor which the output quantity through the defuzzifierion treatment multiplied by the output control quantity made. Their formulas were shown as following [4].

$$K_e = \frac{n}{x_e} \tag{1}$$

$$K_c = \frac{m}{x_e} \tag{2}$$

$$K_u = \frac{y_0}{l} \tag{3}$$

Where X_e and X_c denotes two input values in the basic domain, respectively; y_0 is the accuracy quantity of output of the basic domain; m, n, and l are the corresponding maximums in the discrete domain, respectively.

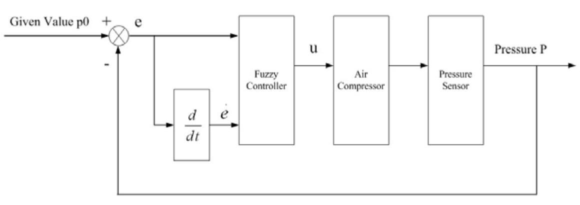

Figure 2 Structure Figure of Fuzzy Control for Pressure

According to control experience of operators on the spot, the deviation E in the basic domain was determined as $-0.5, +0.5$, and the domain was

$$X = -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.$$

Therefore the calculated quantitative factor was $K_e = 12$. Each fuzzy subset possessed many choices of membership functions in the domain X. In general, simpler membership functions such as the trigonometric membership function were adopted in the engineering design. They not only needed less computational effort, diminished memory space but also met common control requirements. The basic domain of the deviation variation ratio E_C was determined as $-0.3 + 0.3$, The domain

$$X = -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6.$$

Calculate the quantitative factor $K_c = 6/0.3 = 20$. The fuzzy controller adopted the incremental output approach. The basic domain of the output variable U was defined as $0, 1$. Apparently, the maximum incremental value of U was $6K_u$. Moreover, two percent of U was preliminarily chosen as the maximum in general. Consequently, $K_u = 0.02/6 = 0.003$ was calculated. Both input and output selected seven linguistic variables which were the negative big, negative medium, negative small, zero, positive small, positive medium and positive big, respectively. They were abbreviated to NB, NM, NS, ZO, PS, PM and PB, respectively.

Establish control rule. According to operator experience as well as expert experience or the fuzzy control rule generated by process knowledge, the rule table was depicted as the sentence forms as follows:

1.If (e is NB) and (ec is NB) then (u is NB)
2.If (e is NB) and (ec is NM) then (u is NB)
3.If (e is NB) and (ec is NS) then (u is NB)
4.If (e is NB) and (ec is ZO) then (u is NB)
5.If (e is NB) and (ec is PS) then (u is NM)
6.If (e is NB) and (ec is PM) then (u is NS)
...
48.If (e is PB) and (ec is PM) then (u is PB)
49.If (e is PB) and (ec is PB) then (u is PB)

Control surface of the fuzzy controller. Utilizing the fuzzy toolbox in Matlab set the reasoning process of the fuzzy controller. The rule antecedent and implication adopted the "minimizing" rule. The area centroid method was applied to the defuzzifierion rule. Fig.3 was the simulation wave of the pressure fuzzy controller under the step input. And Fig.4was the simulation wave of the fuzzy controller with random interference under the step input. From figures, note that without interference the system response time was shorter, its overshoot was severely small and the system could rapidly trace the given signal and adjusted the velocity value to reach the stability within the regulated time. In addition, the system pressure output could also achieve stability promptly after the certain interference was added. Hence the controller effectively improved the reliability, stability and robustness for the overall system.

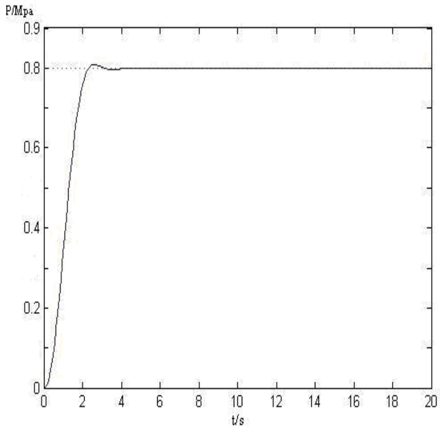

Figure 3 Fuzzy Controller under Step Input

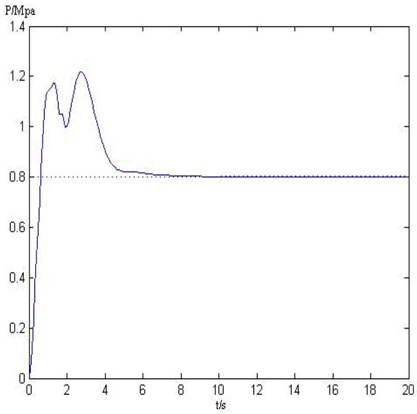

Figure 4 Fuzzy Controller with Random Interference under Step Input

4. Design of Fuzzy Pid Controller

4.1. PID Controller Features

The controller including adjustment modes of proportion, differentiation and integration is called the PID controller [6], which is an industrial controller of wide application. It is depicted mathematically as follows:

$$u(t) = K_p\left[e(t) + \frac{1}{T_1}\int_0^t e(\tau)\tau + T_d\frac{de(t)}{dt}\right] \tag{4}$$

Where K_p, T_i, T_d are the proportional coefficient, integral coefficient and differential coefficient respectively.

The PID control is a kind of control strategy based on the classical control theory. In the PID algorithm, three segments of proportion, differentiation and integration each service with specific function [4].

1) In the proportional segment, the proportional coefficient K_p is applied to accelerating the system response speed and enhancing the system response amplitude. When it reaches to a certain value, the system tends to be unstable. Whereas, assignment of K_p is so minor that adjustment accuracy decreases and regulating time is protracted. As a result, the system dynamic property is made inferior.

2) In the integral segment, the integral time Ti has an effect on the overshoot. This segment function, whose outcome depends on the Ti amplitude, mainly eliminates the steady-state error. Ti expanding, the system overshoot diminishes. Meanwhile, the system response also becomes slow.

3) In the differential segment, its role primarily ameliorates the system dynamic characteristics. The differential time constant Td, whose function restrains the error from altering towards any direction, expanding, the response speed is expedited. Besides, the regulating time is extended and the response amplitude is downsized. Consequently, the system ant-interference performance declines.

The PID controller possesses the following features: 1) the theory is simple. PID parameters are regulated in time according to dynamic characteristics during the system process; 2) the adaptability is powerful. Controllers operating on the basis of the PID control law have been commercialized. The application scope of PID control is fairly wide. Some nonlinear or time-varying procedures are transformed into the basic linear and non-time-varying system through proper simplification and then PID control can put into use; 3) Robustness is faint. For traditional PID control there are many deficiencies: 1) PID parameters can't be regulated self-adaptively. Tuned parameters can adjust to a kind of working condition; 2) the traditional PID controller can just satisfy one aspect in the controlled object during the production process per parameter tuning. Designing the control system, we focus on "tracking characteristic of specified value" and "anti-jamming feature". The traditional PID control can just fulfill one aspect through tuning a collection of PID parameters. Therefore, the obtained control effect is not best as the compromise approach is utilized to tune controller parameters; 4) most of current industrial process possesses characteristics such as high order, nonlinearity, large delay and time-varying. Nevertheless, the traditional control approach is based on the accurate mathematical model.

The application of traditional PID control in the complicated process with nonlinearity, time-varying and indefinite parameters and structure is not satisfactory [7,8,9].

4.2. Fuzzy PID Controller

The tuning of three parameters for the conventional PID affects the control effect. Three parameters of the conventional PID control can not automatically vary with the system working condition. According to structure, fuzzy PID controllers are classified as two categories: the first is PID fuzzy controllers which are two-dimensional. They integrate the two-dimensional controller with integral algorithm. The organization possesses PID performance, which is indicated as Fig.5. Even though similar to the conventional PID controller, the controller structure has no tangible adjustable parameters like the conventional controller, such as proportional coefficient, integral coefficient and differential coefficient. And it employs some fuzzy inference rules based on operator experience and expert regulation experience knowledge. The fuzzy controller is labeled as the two-dimensional PI fuzzy control system, two-dimensional PD fuzzy control system and two-dimensional PID fuzzy control system in accordance with the import pattern of fuzzy integration. The second is controllers combining conventional PID controllers and fuzzy controllers. The controller accomplishes complementarity and improves its entire control property. The fuzzy-parameter self-tuning PID controller pertains to the category.

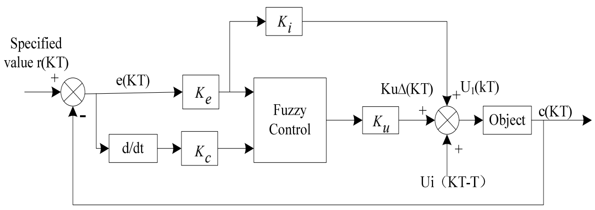

Figure 5 Fuzzy PID control system

In this paper, combining a kind of fuzzy rule with the PID parameter turning is proposed to make parameters adapt automatically. Not only does the control system avoid the overshoot, but also the response time is speeded up. Furthermore, the system dynamic performance is improved. The control principle is shown as Fig.6 [10, 11].

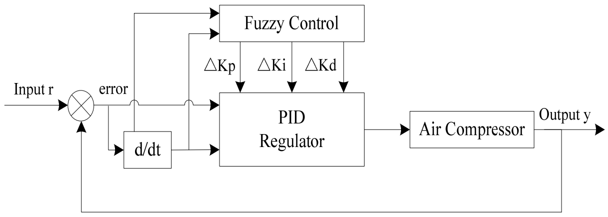

Figure 6 Fuzzy self-adaptive PID control principle

4.3. Design of Fuzzy PID Controller

The multi-variable-two-dimensional fuzzy controller is chosen for the controller structure since there are three output variables in the fuzzy PID controller.

a) Ascertain input and output Variables. The deviation e and variation ratio of deviation ec are interpreted as input variables. And three output parameters which are defined as Kp, Ki and Kd respectively are calculated through the fuzzy rule-based reasoning.

b) Confirm domain and membership function of input and output variables. Input variables: the primary domains of the deviation e and the variation ratio of deviation ec are $\{-0.7,+0.7\}$ and $\{-0.4,+0.4\}$ respectively according to the compressor operating characteristics and manipulator experience. Output variables: primary domains of the proportional coefficient $\triangle K_p$, integral coefficient $\triangle K_i$ and differential coefficient $\triangle K_d$ are $\{-0.2,+0.2\}$, $\{-0.1,+0.1\}$ and $\{-0.1,+0.1\}$ respectively. Primary domains of the input and output are converted into the fuzzy control domain. Seven linguistic variables which are labeled as both the input and output are respectively: negative big, negative medium, negative small, zero, positive small, positive medium and positive big, which were abbreviated to NB, NM, NS, ZO, PS, PM and PB, respectively. During picking the input and output membership function shapes, both endpoint values of variables adopt a lower-resolution Gaussian-shaped membership function while other values select a higher-resolution triangle-shaped membership function.

c) Formulate fuzzy control rules. When formulating fuzzy control rules, take not only overshoot reduction and the system response speed enhancement but also the system stability boost into account. Based on the appointed function of three parameters in the previous PID controller as well as engineer manipulating experience and expert

knowledge, fuzzy control rules of $\triangle K_p$, $\triangle K_i$, $\triangle K_d$ are constituted [5], which are depicted as follows:

1.If (e is NB) and (ec is NB) then ($\triangle K_p$ is PB)($\triangle K_i$ is NB)($\triangle K_d$is PS)

2.If (e is NB) and (ec is NM) then ($\triangle K_p$ is PB)($\triangle K_i$ is NB)($\triangle K_d$ is NS)

3.If (e is NB) and (ec is NS) then ($\triangle K_p$ is PM)($\triangle K_i$ is NM)($\triangle K_d$ is NB)

4.If (e is NB) and (ec is ZO) then ($\triangle K_p$ is PM)($\triangle K_i$ is NM)($\triangle K_d$ is NB)

5.If (e is NB) and (ec is PS) then ($\triangle K_p$ is PS)($\triangle K_i$ is NS)($\triangle K_d$ is NB)

6.If (e is NB) and (ec is PM) then ($\triangle K_p$ is ZO)($\triangle K_i$is ZO)($\triangle K_d$ is NM)

...

48.If (e is PB) and (ec is PM) then ($\triangle K_p$ is NB)($\triangle K_i$ is PB)($\triangle K_d$ is PS

49.If (e is PB) and (ec is PB) then ($\triangle K_p$ is PB)($\triangle K_i$ is PB)($\triangle K_d$ is PB)

5. Simulation of Fuzzy Self-Tuning PID Control

From membership grades of fuzzy subset of E, EC and $\triangle K_p$,$\triangle K_i$, $\triangle K_d$, implementing the fuzzy compositional rule of inference devises a fuzzy control matrix table of PID parameters according to the assignment table of respective fuzzy subset membership grades and the fuzzy control model of various parameters. Adjustment-calculation formulas of parameters K_p, K_i and K_d were denoted as following[6]

$$\begin{cases} K_p = K_{p0} = \{e_i, e_{ci}\}_p & .. \\ K_i = K_{i0} = \{e_i, e_{ci}\}_i & .. \\ K_d = K_{d0} = \{e_i, e_{ci}\}_d & .. \end{cases} \tag{5}$$

During the online operation, sample signals were captured and then the controller enforced the disposal, look-up table and calculation on the results of fuzzy control rules formulated to attain a final control command for achieving the online self-tuning of PID parameters of the system. The flow chart was shown in Fig.7.

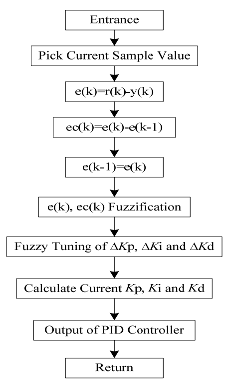

Figure 7 Fuzzy controller self-tuning flow chart

Fig.8 exhibited the comparison of simulation waves between the conventional PID controller and the fuzzy self-tuning PID controller without interference under the step input. Fig.9 illustrated the comparison between the conventional PID and the fuzzy self-tuning PID with real-time interference under the step-signal input.

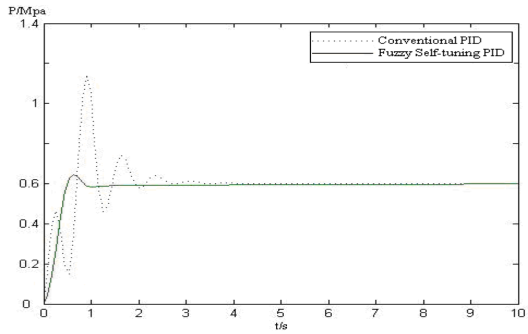

Figure 8 Comparison of step responses in two controls without interference

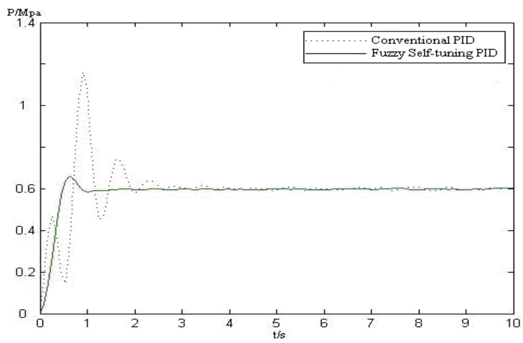

Figure 9 Comparison of step responses in two controls with interference

As seen from two simulation wave figures of Fig.8 and Fig.9, the control effect of the fuzzy self-tuning PID control was better than that of the conventional PID control in the system. The steady time of the system was briefer apparently and the overshoot was also exceedingly minor. So the controlled system performance was ameliorated obviously. It revealed the powerful anti-interference capability that the response curve fluctuation in the fuzzy self-tuning PID control was extremely tiny.

6. Conclusions

The ECS-700 system from the DCS technology is applied to designing the monitoring system of the air compressor system which offered data required for the system controller design. The monitoring system is guaranteed in effective, safe and steady operation since a scientific and reasonable control project is chosen. Aiming at variation of outlet pressure of the air compressor, a pressure fuzzy controller was designed by utilizing the fuzzy control theory. It was calculated and analyzed to obtain the curved surface of the output control and control rule table through applying fuzzy tool in Matlab. So not only did air-supply control at the constant pressure in the air compressor system become more reliable and steady, but also the control efficiency was improved. Aiming at operation characteristics and control requirements in the compressor system, the fuzzy self-tuning PID controller which made the control of constant pressure air supply in the air compressor system reliable and stable, demonstrated the superior robustness and improved the control efficiency of the air compressor system is designed based on combining the fuzzy control theory with the conventional PID control. The simulation results show that self-tuning fuzzy PID control performance was superior, anti-disturbance ability, fast enough to stabilize the output pressure of air compressor. The control effect is much better than traditional PID control. The experimental results of control method designed in this paper show that the control is feasible, provides a theoretical basis for the actual control of compressed air system, and has important reference value.

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