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An intelligent control method for a large multi-parameter environmental simulation cabin

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Abstract The structure and characteristics of a large multi-parameter environmental simulation cabin are introduced. Due to the difficulties of control methods and the easily damaged characteristics, control systems for the large multi-parameter environmental simulation cabin are difficult to be controlled quickly and accurately with a classical PID algorithm. Considering the dynamic state characteristics of the environmental simulation test chamber, a lumped parameter model of the control system is established to accurately control the multiple parameters of the environmental chamber and a fuzzy control algorithm combined with expert-PID decision is introduced into the temperature, pressure, and rotation speed control systems. Both simulations and experimental results have shown that compared with classical PID control, this fuzzy-expert control method can decrease overshoot as well as enhance the capacity of anti-dynamic disturbance with robustness. It can also resolve the contradiction between rapidity and small overshoot, and is suitable for application in a large multi-parameter environmental simulation cabin control system.

1. Introduction

High-altitude environment is a major factor impacting performance of aircraft environmental control systems and comprehensive environmental quality of a cockpit. Cockpit environmental quality plays not only a decisive role in flight safety as well as occupant's health and comfort, but also an important role in energy efficiency and environmental protection. High-altitude simulation cabins can simulate flying environment (e.g., height, temperature) for aircrafts and transport planes. Thus, simulation cabins play an important role in the development of feeder aircrafts.

The temperature change in a high-altitude environmental simulation cabin comprises a cooling stage, a constant temperature stage, and a heating stage.[1] The requirements can be found in the national military standards[2] in terms of temperature control precision in environmental simulation cabins, especially systems without self-balance ability, to prevent the occurrence of an overshoot phenomenon. Presently, in the field of environmental simulation control, researchers have developed many methods. For example, Li's research group introduced a PID controller to control the temperature of thermal control systems.[3–7] Dong et al. utilized a double-PID controller to control the temperature of an environmental

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chamber.[8] However, both simulation and experimental results showed that, due to the complexity of factors influencing the cabin temperature and the inertia link caused by the large volumes of most cabins, it is difficult to increase the cooling rate and prevent the overshoot simultaneously with the classic PID control method. Therefore, it is difficult to control the temperature. When an environmental cabin simulates multiple parameters such as temperature and pressure, there has been coupling and interference between these parameters. This limits the ability to simulate temperature and pressure quickly and accurately. Because of the constant increments of the air-operated valve, it is easy to have lower pressure than the target pressure. Thus, it is difficult to control the pressure without an overshoot using the classic PID control method.

To overcome the above difficulties of multi-parameter cabin control systems and ensure that a refrigeration turbine can be put into use safely and as soon as possible, we propose that the processes of automatically powering on and off the refrigeration turbine and decreasing the temperature can be automatically controlled by combining the fuzzy control strategy with an expert PID judgment and thus, the lumped parameter model of cabin temperature and pressure change, established on the basis of the dynamic-state characteristics of the environmental simulation cabin, is valid. A fuzzy controller was used to control the heater of the central air conditioning system.[9,10] The introduction of expert judgments can be used to decrease the temperature, reduce the fluctuation of turbine revolution speed, and lead the refrigeration system into a steady state as soon as possible, therefore improving experimental efficiency. The fuzzy method is a kind of simple and flexible method with the advantages of less computational efforts, strong practicability, rapidity, strong stability, and high robustness.[11] This enables the achievement of higher control accuracy. Appropriate use of this method solves the problems of revolution speed control of the air refrigeration turbine and temperature control, ensuring normal operation of experiments.

2. Control scheme

A large multi-parameter environmental simulation cabin is shown in Fig. 1. The cabin's system includes four parts: refrigeration system, vacuum system, environmental cabin, and measurement control system. The refrigeration system adopts a positive compressor reflux refrigeration air cycle and includes compressor turbine components, a reflux refrigeration device, air-operated adjusting valves, and the environmental cabin. The vacuum system can create a low atmospheric pressure environment and conduct experiments at low pressure and low or high temperature via an environmental cabin pumping system.

By means of adjusting the output power of the electric heater placed in the wind tunnel, the high temperature of the environmental cabin can be controlled. Furthermore, according to the temperature requirements in the cabin, the opening of the air-operated valve QF1 at the turbine entrance shown in Fig. 1 can not only change the pressure at the refrigeration turbine entrance and corresponding refrigeration turbine expansion ratio (and therefore adjust the temperature decrease of the turbine), but also change the refrigeration turbine flow, resulting in effective adjustment of its refrigeration capacity and control of the temperature in the cabin. Because the temperature decreases and the flow changes simultaneously in the same direction, the refrigeration capacity changes rapidly and sensibly. However, the valve QF1 opening is restricted to change only within a certain range by the revolution speed of the refrigeration turbine and the compressor surge, so it is only used to make coarse adjustments. By adjusting the opening of the air-operated valve QF2, which is set at the exit of the turbine and near the cold air entrance pipe in the back of

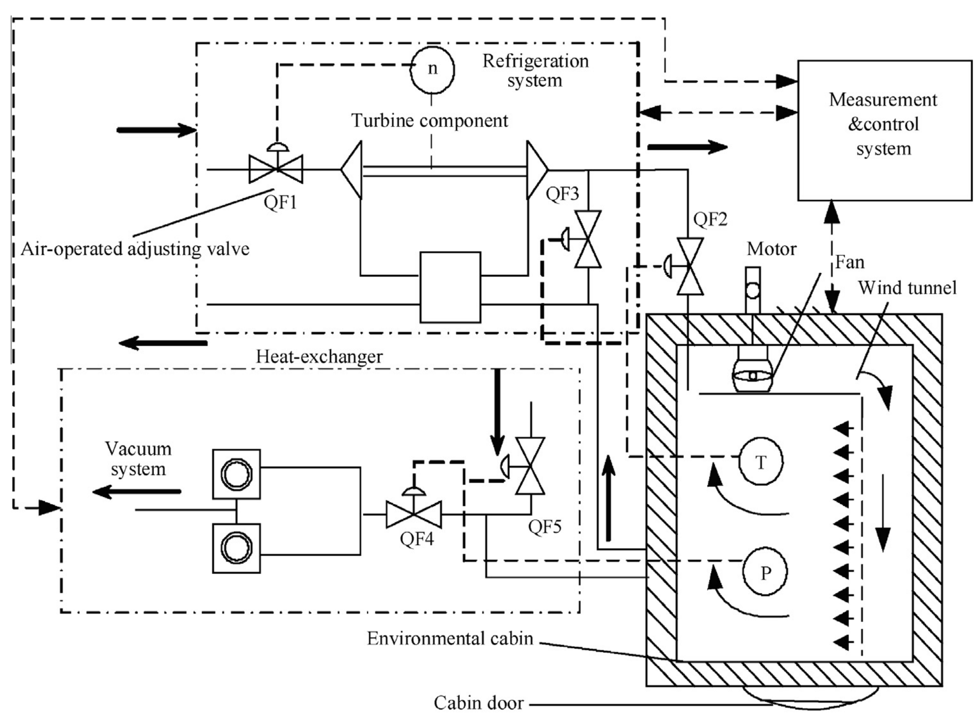

Fig. 1 Flow chart of a large multi-parameter environmental simulation cabin.

the environmental cabin, the cold air flow entering the environmental cabin can be changed, and the cabin temperature can be controlled. Therefore, temperature control in the environmental cabin is essentially accomplished by valve QF2.

The low pressure environment simulation of the cabin is accomplished by means of controlling the pumping valve QF4 and the air supply valve QF5 when the vacuum pumps are working. This method can control the cabin pressure corresponding to rapid altitude changes. In practice, to overcome the coupling effect between temperature and pressure in environmental cabin simulations, the temperature parameter is set first, followed by the pressure parameter.

The automatic control process of the entire low temperature experiment can be divided into the following four steps:

(1) Process of automatic turbine turning-on.

The opening of the air-operated valve QF1 at the turbine entrance is controlled so that it opens slowly. This limitation is necessary to ensure that the turbine revolution speed remains within the permissible maximum.

(2) Process of automatic temperature decreasing.

The revolution speed is controlled in the setting range. After the cabin temperature slowly decreases to the setting range, the insulation process begins.

(3) Process of automatic insulation control.

This is the process of maintaining constant cabin temperature. The control error of the cabin temperature should conform to government standard or the military standard.

(4) Process of automatic turbine turning-off.

The opening of the valve QF1 at the turbine entrance should be controlled so that it closes slowly. During this process, valve QF2 is also opened, but should be closed after the turbine stops.

Based on the above control processes, the controller can be designed with a fuzzy controller, an expert PID controller, and a mode-selective switch, as shown in Fig. 2. In the figure, $E(s)$ is the input value transfer function of control parameters, $V(s)$ is the output value transfer function of revolution speed control parameters. The processes of automatic turning-on and temperature decreasing of the turbine can be carried out by the fuzzy controller and the expert PID controller. During the insulation process, temperature control in the cabin is realized mainly by the expert PID controller. Higher control accuracy can be achieved as a result of the introduction of an integration item.[12]

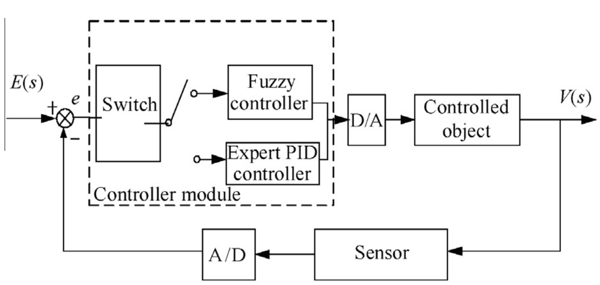

Fig. 2 Control configuration for the turbine refrigeration system.

When revolution speed is being controlled, its deviation e and deviation rate of change ec, applied as the control inputs, can be obtained by comparing the revolution speed v (measured by a revolution speed sensor) with the setting revolution speed v_0. The choice between the expert PID control and the fuzzy control is made based on the setting value; that is, fuzzy control is adopted when e is greater than the setting value, otherwise, expert PID control is used.

3. Models of control system

3.1. The model of temperature

The temperature model can be divided into high and low temperature controls because they have different control objects and methods.[13,14]

There is a close relationship between the heat source of the cabin and the temperature level of the surrounding environment. According to the conservation of energy theorem, the following lumped parameter model can be established to describe the change law of the high temperature cabin:

$$\sum_{i=1}^{n} M_i C_i \frac{\mathrm{d}T}{\mathrm{d}t} = \sum_{i=1}^{m} P_{wi} - \frac{(T - T_0)A_0}{R_{th}} \tag{1}$$

where T, T_0, A_0, and R_{th} represent the cabin air temperature, the outside air temperature, the total area of heat dissipation, and thermal resistance of the bulkhead, respectively; the variables n and m represent the number of endothermic and exothermic links, respectively; M_i and C_i represent the quality and specific heat capacity of endothermic links, respectively; P_{wi} is the quantity of exothermic links. P_{wi} would be equal to the output power of the exothermic device based on the hypothesis that all output power of the exothermic device could transform to heat.

Thus, considering the environmental cabin with an electric heater and an air sample being heated in the cabin, it follows that:

$$\sum_{i=1}^{m} P_{wi} = P_{wfan} + P_{wlamp} + P_{wheat} \tag{2}$$

where P_{wfan}, P_{wlamp}, and P_{wheat} represent the output power of the fan, the lighting lamp, and the electric heater, respectively.

$$\sum_{i=1}^{n} M_i C_i = M_{nb} C_{nb} + M_{sj} C_{sj} + M_{kq} C_{kq} + M_{kb} C_{kb} \tag{3}$$

where M_{nb}, M_{sj}, M_{kq}, and M_{kb} represent the quality of the inner wall of the cabin, the air sample being heated in the cabin, and the orifice plate of the cabin, respectively; C_{nb}, C_{sj}, C_{kq}, and C_{kb} are the specific heat capacity of each endothermic link.

Low temperature control in the environmental cabin is actually carried out by controlling the opening of the cold-air valve QF2 to change the cold-air flow entering the cabin. According to the conservation of energy theorem, the following lumped parameter model can be established to describe the change law of the low temperature cabin:

$$\sum_{i=1}^{n} M_i C_i \frac{\mathrm{d}T}{\mathrm{d}t} = Q_{in} - Q_{out} - Q_x - Q_w - Q_e \tag{4}$$

where Q_{in} and Q_{out} are the cold-air quantities entering and leaving the cabin, respectively; Q_x is the air heat leakage power; Q_w and Q_e are the cold quantities absorbed by the bulkhead and samples, respectively.

Assuming Q_x to be directly proportional to the difference between the inside and outside temperatures, Q_x can be expressed as follows:

$$Q_x = k_h(T_c - T_0) \tag{5}$$

where k_h is the heat leakage coefficient, T_c the inside temperature.

Q_w denotes the power corresponding to the heat that the bulkhead transfers to the indoor air by way of convective heat transfer, whose formulation is as follows in accordance with the heat transfer equation[3]:

$$Q_w = (W_{in}C)(T_w - T_c)\left[\exp\left(-\frac{(hA)_w}{W_{in}C}\right) - 1\right] \tag{6}$$

where W_{in} is the cold-air mass flow entering the cabin, $(hA)_w$ the product of the bulkhead heat transfer coefficient and the area, T_w the bulkhead temperature, and C the constant pressure specific heat coefficient.

Q_e denotes the temperature decrease transferred to the sample air space by way of air convection in the cabin, which can be formulated as follows:

$$Q_e = (hA)_e(T_e - T_c) \tag{7}$$

where $(hA)_e$ is the product of the sample heat transfer coefficient and the area, and T_e the sample temperature.

Q_{out}, the cold air leaving the cabin, expressed in terms of temperature difference, has the following formulation:

$$Q_{out} = \frac{W_{out}C(T_o - T_c)}{3600} \tag{8}$$

where T_o is the temperature of environment which is outside of cabin, W_{out} the cold-air mass flow entering the cabin which can be calculated by the following expression in accordance with the resistance equation:

$$W_{out} = \sqrt{\frac{2(P_c - P_o)}{f\rho}} \tag{9}$$

Thus, it follows that:

$$Q_{out} = \sqrt{\frac{2(P_c - P_o)}{f\rho}}\frac{C(T_1 - T_c)}{3600} \tag{10}$$

where P_c and P_o are the pressure of the cabin and the pressure of environment which is outside of cabin, f and ρ the resistance coefficient and air density, respectively; T_1 is the cold-air temperature.

Q_{in}, the cold air entering the cabin, has the following formulation:

$$Q_{in} = \frac{W_{in}C(T_1 - T_c)}{3600}. \tag{11}$$

3.2. The model of pressure

The cabin pressure depends on the air capacity. According to the conservation of mass theorem, it follows that:

$$\frac{dW_g}{dt} = W_{in} + W_x - W_{out} \tag{12}$$

where W_g and W_x are the air mass flow inside the cabin and the air leakage mass flow of the cabin.Substituting the ideal gas law ($PV = RT_0$) into the above equation, it follows that:

$$\frac{dP_c}{dt} = \frac{RT_c}{V}(W_{in} + W_x - W_{out}) \tag{13}$$

where V is the volume of the cabin, R the constant of air quality.

As Fig. 1 shows, the low pressure simulation of the cabin is accomplished by means of controlling the pumping valve QF4 and the air supply valve QF5. Hypothesizing that the vacuum system capacity is sufficient to maintain and control the low pressure environment of the cabin, the method relies on controlling the air supply air flow from QF5. The lumped parameter equation is:

$$\frac{dP_c}{dt} = \frac{RT_c}{V}(W_x - W_{out}) \tag{14}$$

The air flow equation is defined as follows:

$$W_{out} + W_1 = W_2 \tag{15}$$

The incremental air flow of the vacuum system, represented by ΔW_2, is calculated as follows:

$$\Delta W_2 = k_2(\Delta P_1 - \Delta P_2) \tag{16}$$

$$W_2 = W_{20} + k_2(\Delta P_1 - \Delta P_2) \tag{17}$$

$$k_2 = \frac{\partial W_2}{\partial P_1} = -\frac{\partial W_2}{\partial P_2} \tag{18}$$

The air supply flow, W_1, has the following formulation[15]:

$$W_1 = gA^*\sqrt{\frac{2K}{K-1}P_0\rho_0}\cdot f\left(\frac{P_1}{P_0}\right) \tag{19}$$

where A^*, g, and K are the flow sectional area, the acceleration of gravity, and the adiabatic compression index, respectively; P_0 is the outside pressure.

If $\frac{P_1}{P_0} > 0.582$,

$$f\left(\frac{P_1}{P_0}\right) = \sqrt{\left(\frac{P_1}{P_0}\right)^{\frac{2}{K}} - \left(\frac{P_1}{P_0}\right)^{\frac{K+1}{K}}} \tag{20}$$

If $\frac{P_1}{P_0} \leqslant 0.582$,

$$f\left(\frac{P_1}{P_0}\right) = \sqrt{\left(\frac{K-1}{K+1}\right)\left(\frac{2}{K+1}\right)^{\frac{1}{K-1}}} \tag{21}$$

When l, the displacement of the valve core, P_0, and P_1 change, the incremental air flow has the following formulation:

$$\Delta W_1 = k_i\Delta l + k_0\Delta P_0 + k_1\Delta P_1 \tag{22}$$

We consider the change of P_0 to be negligible, giving the following formulation:

$$\Delta W_1 = k_l\Delta l_0 + k_1\Delta P_1 \tag{23}$$

$$W_1 = W_{10} + k_l\Delta l_0 + k_1\Delta P_1 \tag{24}$$

$$k_l = \frac{\partial W_1}{\partial l} = \sqrt{\frac{2Kg}{R(K-1)}} \cdot \frac{A^*(l)}{\sqrt{T_0}} \cdot \frac{\mathrm{d}f(P_1)}{\mathrm{d}P_1} \tag{25}$$

$$k_1 = \frac{\partial W_1}{\partial P_1} = \sqrt{\frac{2Kg}{R(K-1)}} \cdot \frac{A^*(l)P_0}{\sqrt{T_0}} \frac{\partial f\left(\frac{P_1}{P_0}\right)}{\partial \frac{P_1}{P_0}} \frac{1}{P_0} \tag{26}$$

When the environmental cabin is working at low pressure, there is a pressure difference between the inner air of the cabin and the outside air. The infiltration quantity is also dependent on the pressure difference, so the model has the following formulation:

$$\Delta W_x = \frac{\Delta P_0 - \Delta P_1}{f_x} \tag{27}$$

$$W_x = W_{x0} + \frac{\Delta P_0 - \Delta P_1}{f_x} \tag{28}$$

where f_x is the coefficient of resistance force.

3.3. The model of actuator

3.3.1. The model of the air-operated adjusting valve

The relationship between W_{in} and the control variable l, i.e., the valve opening and the flow, can be obtained from the flow characteristics of the adjusting valve as follows:

$$\frac{W_{in}}{W_{max}} = f\left(\frac{l}{l_{max}}\right) \tag{29}$$

We denote a regulation ratio, $R_l = W_{max}/W_{min}$, as the ratio of flows, in which W_{max} is the maximum of flows and W_{min} is the minimum of flows. l/l_{max} are ratios of flows and trips under valve compression and full opening, respectively. Most valves applied in air-conditioning have logarithmic flow characteristics, also known as percentage flow characteristics. The mathematical expression is shown as follows:

$$\frac{W_{in}}{W_{max}} = R_l^{\frac{l}{l_{max}}} - 1 \tag{30}$$

It can be seen from the above expression that the valve characteristic curve is nonlinear.

3.3.2. The model of the electric heater

Considering the solution for electric heater temperature and applying the conservation of energy theorem, we have the following formulation:

$$MC\frac{\mathrm{d}T_w}{\mathrm{d}t} = Pw - Q_H \tag{31}$$

The heat exchange between air and the electric heater can be calculated according to the following formulation:

$$Q_H = hA_W(T_w - T_1). \tag{32}$$

3.3.3. The model of the refrigeration turbine

The simulation model is carried out in MATLAB-Simulink using the positive compressor turbine air refrigeration program for an environmental chamber. The mathematical model of the turbine expansion system is built so that the control model of the turbine revolution speed can be obtained by the mathematic model of its shaft, and the latter is used to calculate the dynamic change of the revolution speed with different input and output powers. The simulation model belongs to the first-order inertial element, which can be formulated as follows[16,17]:

$$I\frac{\mathrm{d}N}{\mathrm{d}t} = Pw_{in} - Pw_{out} \tag{33}$$

$$Pw_{in} = \frac{W_2 C_p T_1}{\eta_c}\left(\pi_c^{\frac{K-1}{K}} - 1\right) \tag{34}$$

$$Pw_{out} = 0.99\eta_T W_2 C_p T_1 \left(1 - \frac{1}{-}\pi_T^{\frac{K-1}{K}}\right) \tag{35}$$

where I is the moment of inertia, N the revolution speed; Pw_{in} and Pw_{out} are the input work of the compressor and the output work of the turbine, respectively; C_p is the gas specific heat capacity, T_1 the entrance temperature; π_c and π_T are the compression ratio of the compressor and the expansion ratio of the expender, respectively, η_c and η_T the efficiencies of the compressor and the expander, respectively; W_2 is the output flow. Calibration of the simulation model is performed on the basis of the efficiency and flow curves measured in the experiment.

4. Controller

4.1. Expert PID controller

The expert PID control method is based on the classical PID methods.[18] In essence, it intelligently uses knowledge of control objects and control rules to design a controller. Using experts' experience[19,20] to design PID parameters forms the basis of expert PID control.

The no-overshoot expert PID control method improves upon the expert PID control method. In PID control, the integration part is introduced to eliminate static deviations and improve control precision. However, when turning on and off and changing values rapidly, the system output will have large deviations during a short time, resulting in the accumulation of integration. As a result, the controller will have 100% output for long periods, causing large overshoot and even shock. Therefore, it is necessary to design the overshoot suppression coefficient k_f. The no-overshoot expert PID control method can be expressed as follows:

$$u(k) = k_p e(k) + k_f k_i \sum_{j=0}^{k} e(j) T_s + k_d \frac{e(k) - e(k-1)}{T_s} \tag{36}$$

The expert PID controller proposed in this paper is designed according the following cases:

Case 1 $|e(k)| > M_1$

Here, M_1 is the set limit, meaning that the absolute value of deviation is very large. Regardless of the trend of the deviation, the controller output should achieve the maximum (or the minimum) to regulate the deviation rapidly, resulting in the absolute value of deviation decreasing at the maximum rate. In this case of PID control, $k_f = 0$ is used.

Case 2 $e(k)\mathrm{D}e(k) \geqslant 0$.

The absolute value of deviation increases or is constant, where M_2 is the set limit. If $|e(k)| > M_2$, meaning larger deviations, the system is controlled strongly by the controller. If $|e(k)| < M_2$, it means that although the absolute value of deviation changes in the increasing direction, it is not very large. Therefore, it can be controlled generally. In this case, $k_f = 0$.

Case 3 $e(k)\mathbf{D}e(k) < 0$ **and** $\mathbf{D}e(k)\mathbf{D}e(k-1) > 0$ **or** $e(k) = 0$

These conditions mean that the deviation decreases or has achieved balance. k_f can be set in (0, 1).

Case 4 $e(k)\mathbf{D}e(k) < 0$ **and** $\mathbf{D}e(k)\mathbf{D}e(k-1) < 0$

These conditions mean that the deviation is in an extreme state. If $|e(k)| \geqslant M_2$, it can be controlled strongly. k_f can be set in (0, 1).

Case 5 $|e(k)| < \varepsilon$

This means a small deviation. The integration is integrated to reduce the steady-state deviation. Here $k_f = 1$.

Case 6 $e(k) = 0$

This means that the system has been in a balanced state. Thus, the current control values are maintained.

The expert control rules of our improved method are summarized as follows:

(1) Rule: IF $|e(k)| > M_1$, THEN $u(k) = U_{max}$, $k_f = 0$.
(2) Rule: IF $e(k)\mathbf{D}e(k) \geqslant 0$ AND $|e(k)| > M_2$, THEN $u(k) = k_1 k_p\, e(k)$, $k_f = 0$.
(3) Rule: IF $e(k)\mathbf{D}e(k) \geqslant 0$ AND $|e(k)| < M_2$, THEN $u(k) = k_p\, e(k)$, $k_f = 0$.
(4) Rule: IF $e(k)\mathbf{D}e(k) < 0$ AND $\mathbf{D}e(k)\mathbf{D}e(k1) > 0$ OR $\mathbf{D}e(k) = 0$, THEN $u(k) = k_p\, e(k) + k_d \mathbf{D}e(k)$, k_f is set in (0, 1).
(5) Rule: IF $e(k)\mathbf{D}e(k) < 0$ AND $e(k)\mathbf{D}e(k1) < 0$ AND $|e(k)| \geqslant M_2$, THEN $u(k) = U_{max}$, $k_f = 0$.
(6) Rule: IF $e(k)\mathbf{D}e(k) < 0$ AND $e(k)\mathbf{D}e(k1) < 0$ AND $|e(k)| < M_2$, THEN $u(k) = U_{min}$, $k_f = 0$.
(7) Rule: IF $|e(k)| < \varepsilon$, THEN $u(k) = k_p e(k) + k_i \sum_{j=0}^{k} e(j)T + k_d \Delta e(k)$.

In the above rules, k_1 is the ratio coefficient. U_{max} and U_{min} are the maximum and minimum output of the controller, respectively. They can be used as the magnification coefficients when the controller needs stronger control output. To prevent the controller output from exceeding the permissible maximum range, the amplitude of the control quantity should be restricted as follows:

$$u(k) = \begin{cases} U_{max} & u(k) > U_{max} \\ U_{min} & u(k) < U_{min} \end{cases} \tag{37}$$

4.2. Fuzzy controller

The fuzzy controller uses a fuzzy logic system (Mamdani type) with a fuzzy generator and a fuzzy eliminator.[21] It is primarily composed of the following components: input and output linguistic variables, including linguistic values and their membership functions; fuzzy rules; methods of the input fuzzification and the output defuzzification; fuzzy reasoning algorithms. In the following, how to use the fuzzy control to control the turbine revolution speed will be introduced for the control system of the refrigeration turbine revolution speed.

4.2.1. Inputs and outputs

These automatically control the revolution speed deviation $e = n - n_0$ (kr/min) by the introduction of a negative feedback method. Taking into account the maximum turbine revolution speed of 50 kr/min and the setting revolution speed of 40 kr/min, [–10, 40] is the actual universal interval of the deviation e. A more precise deviation range of the revolution speed in the fuzzy control, $-1 \leqslant e \leqslant 4$ (10 kr/min), can be obtained by transforming the above universal interval.

The deviation rate of change of the revolution speed has the following formulation: $ec = \mathrm{d}e/\mathrm{d}t$ (r/s), whose range in fuzzy control is $-1000 \leqslant ec \leqslant 1000$.

In reality, the valve opening l is the output control variable, which can be expressed by the valve stroke ratio l/l_{max}, where l_{max} is the maximum valve opening in a control range of $0 \leqslant u \leqslant 1$, with 0 representing the valve closed and 1 representing the valve at its maximum opening.

4.2.2. Membership function

The fuzzy linguistic set of the revolution speed deviation e is set to be {positive middle (PM), positive small (PS), zero (ZE), negative small (NS), negative middle (NM), negative big (NB)}, representing {a higher speed, a slightly higher speed, a moderate speed, a slightly lower speed, a lower speed, a much lower speed}, respectively. Due to the smoothness and symmetry of the Gaussian function, the membership functions are expressed in the form of Gaussian functions, as shown in Fig. 3.

The fuzzy linguistic set of the revolution speed deviation change rate ec is set to be {positive big (PB), positive small (PS), zero (ZE), negative small (NS), negative big (NB)}, representing {a rapid positive change, a positive change, no change, a negative change, a rapid negative change}, respectively. The membership functions of the revolution speed

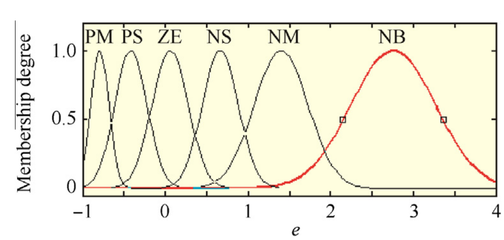

Fig. 3 Membership function curve of e.

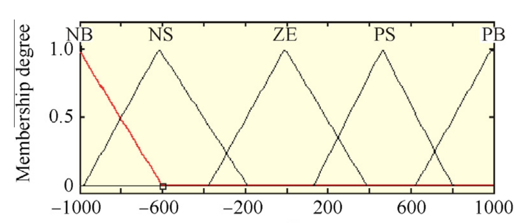

Fig. 4 Membership function curve of ec.

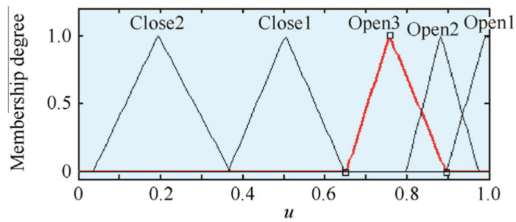

Fig. 5 Membership function curve of the output u.

Table 1 Control rules.

ec	*e*					
	NB	NM	NS	ZE	PS	PM
NB	Open1	Open1	Open2	Open3	Close1	Close2
NS	Open1	Open1	Open2	Open3	Close1	Close2
ZE	Open1	Open1	Open2	Open3	Close1	Close2
PS	Open1	Open1	Open2	Close1	Close2	Close2
PB	Open1	Open2	Open3	Close1	Close2	Close2

deviation change rate *ec* are expressed by the mathematic form of trigonometric functions, as shown in Fig. 4.

The control of the valve opening is represented by the stroke ratio. The fuzzy linguistic set of the control outputs u is set to be {Open1, Open2, Open3, Close1, Close2}, representing the five valve stroke ratios from large opening to close. The fuzzy set membership functions of the control outputs are shown in Fig. 5.

4.2.3. Table of control rules

The fuzzy control rules, described in the form of "IF-THEN", can be transmitted into the following form by experimental analysis and simulation adjustments:

R_{ij}: IF e is A_i and ec is B_j, THEN u is C_{ij}

where $i = 1, 2, \ldots, 6$, $j = 1, 2, \ldots, 5$. Thus, there are 30 controlling rules in total, as shown in Table 1.

5. Simulation

A simulation model is established according to the design scheme of the large multi-parameter environmental simulation cabin. The simulation model of the control system is built on the platform of MATLAB-Simulink according to the principle shown in Fig. 1, wherein the simulation model can be established in accordance with the mathematical model defined by Eqs. (1)–(35).

5.1. High temperature simulation test

The high temperature simulation model can be established in accordance with the mathematical model defined by Eq. (1). A delay is also added considering the pure delay in the cabin and the control system. According to the requirements, the temperature increases from room temperature at 291 K (18 °C) to E0 at 343 K (70 °C), and the fuzzy-expert controller is used to control the electric heater. The results of the fuzzy-expert control method and the classic PID control method are shown in Fig. 6. It can be seen from Fig. 6 that the effect of the fuzzy-expert control strategy is better than that of classic PID control. The fuzzy-expert method can effectively suppress overshoot and improve the heating rate.

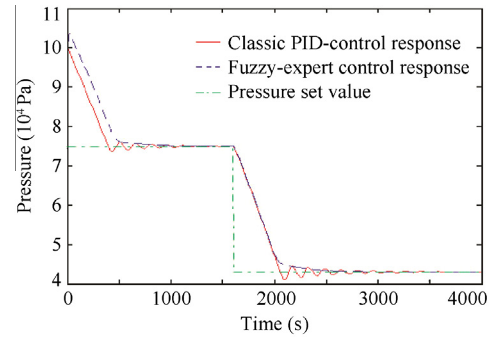

Fig. 6 High temperature simulation comparison.

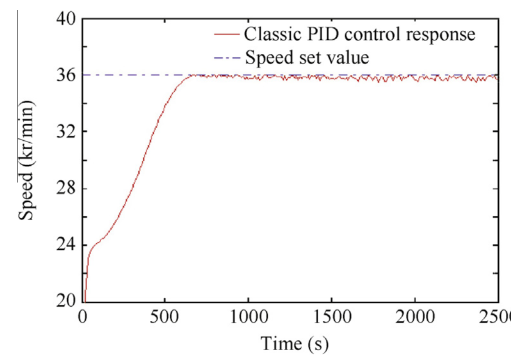

Fig. 7 Turbine speed classic PID control simulation results.

5.2. Low temperature simulation test

The speed of the refrigeration turbine, regarded as the main control parameter, is simulated on the platform of MATLAB, and the fuzzy-expert control method and the classic PID control method are considered separately. The classic PID control simulation results are shown in Fig. 7, and the fuzzy-expert control simulation results are shown in Fig. 8. In the simulation model, the maximum flow through the air refrigeration compressor turbine is 4000 kg/h. The initial conditions include an entrance temperature of 300 K, a standard atmosphere of 101.3 kPa, and a mechanical efficiency of the shaft of 99%. It can be seen from the figure that the fuzzy method has better control in meeting the experimental requirements.

According to the requirements, the temperature decreases from room temperature at 290 K (17 °C) to E0 at 218 K (−55 °C). After coming into the deviation range of ±1 °C, the temperature is fixed for 5 min and then decreases to 193 K (−80 °C). The no-overshoot expert PID control method is adopted. The results of both the no-overshoot expert and classic PID control methods are shown in Fig. 9. It can be seen from Fig. 9 that the effect of the expert PID control strategy is better than that of classic PID Control. The expert control method can effectively suppress overshoot and improve the cooling rate. The transition times of the expert control and classic PID methods are 200 s and 500 s, respectively. Further-

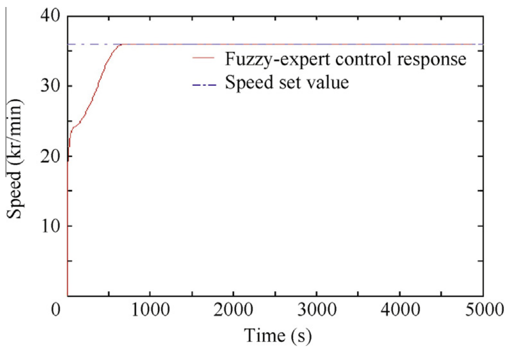

Fig. 8 Turbine speed fuzzy-expert control simulation results.

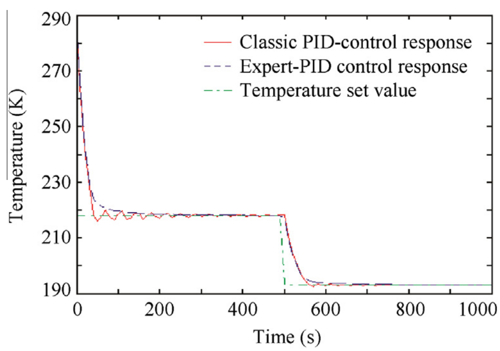

Fig. 9 Low temperature simulation comparison.

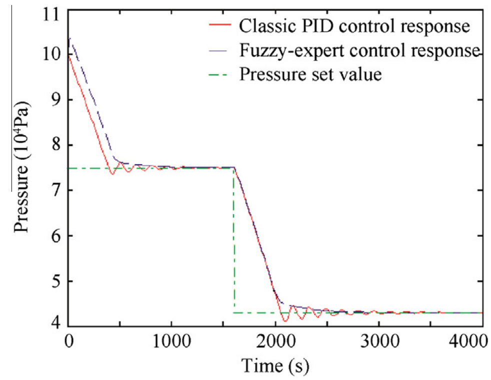

Fig. 10 Low pressure simulation comparison.

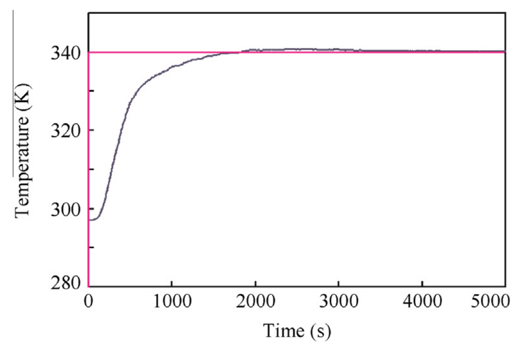

Fig. 11 Fuzzy-expert control in the high temperature experiment.

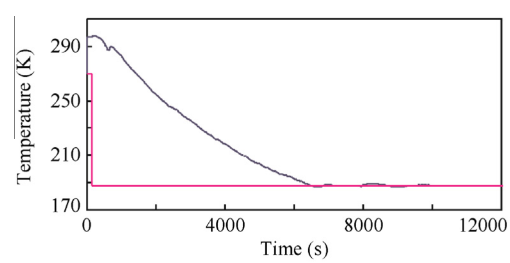

Fig. 12 Fuzzy-expert control in the low temperature experiment.

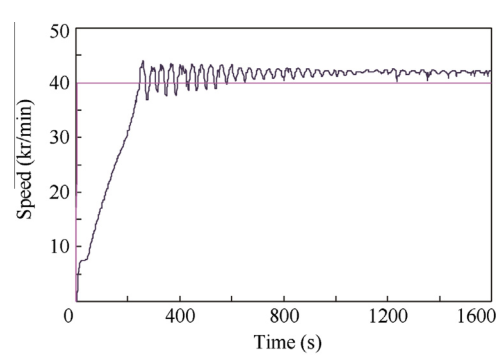

Fig. 13 Turbine speed classic PID control actual experiment results.

more, the expert PID control method can achieve higher temperature control precision. During the simulation process, a normalization method is used to reduce the simulation time and CPU demands.

5.3. Low pressure simulation test

The low pressure simulation model can be established in accordance with the mathematical model defined by Eq. (13). The results of both the fuzzy-expert and classic PID control methods are shown in Fig. 10. It can be seen from Fig. 10 that the effect of the fuzzy-expert control strategy is better than that of classic PID Control. The fuzzy-expert method can effectively suppress overshoot and improve the pumping rate.

6. Experimental results

Regarding the commissioning experiment of the large multi-parameter environment simulation cabin control system, adopting the fuzzy-expert control method, the same result has been reached by both experiment and simulation. The fuzzy-expert control result of the high temperature experiment is shown in Fig. 11. The high temperature set value is 343 K (70 °C) and the maximum error is 0.7. The result shown in Fig. 11 is very similar with the simulation result shown in Fig. 6, which is established in accordance with the mathematical model defined by Eq. (1). Therefore, the accuracy of simulation models has been proved.

The measured experimental data of the refrigeration turbine system are shown in Figs. 12–14. The MW308, produced by

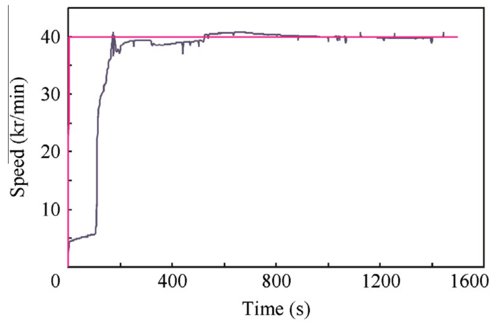

Fig. 14 Turbine speed fuzzy-expert control actual experiment results.

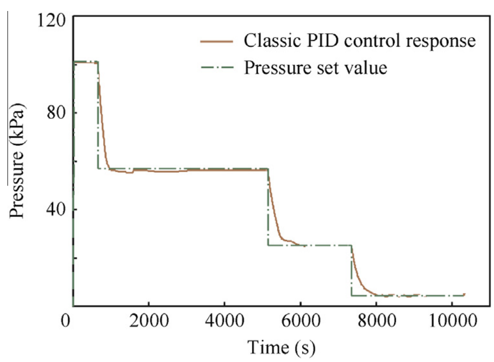

Fig. 15 Low pressure fuzzy-expert control actual experiment results.

Nanjing Engineering Institute of Aircraft System, is used as the turbine refrigeration equipment. Fig. 12 shows that the result of the fuzzy-expert control method for the low temperature 191 K (−82 °C) experiment is similar with the simulation result shown in Fig. 9 established by Eq. (4). The classic PID control speed data for the refrigeration turbine are shown in Fig. 13. The fuzzy-expert control speed data for the refrigeration turbine are shown in Fig. 14. The results shown in Figs. 13 and 14 are also similar with the simulation results shown in Figs. 7 and 8, which are established in accordance with the mathematical model defined by Eq. (33). The low temperature set value is 191 K (−82 °C) and the maximum error is 0.5.

The fuzzy-expert control of low pressure is shown in Fig. 15. It can be seen from the figure that the classical PID control method has a longer adjusting process and that the revolution speed has greater fluctuation and a longer transition time, which is similar with the simulation result shown in Fig. 10 defined by Eq. (13). The control performance will be greatly affected by the change of the system state. On the other hand, the fuzzy control has a rapid adjustment, a shorter transition time, and a smaller steady-state deviation to control the segment change of pressure. Therefore, its control performance is superior to the classical PID control system among multi-parameter environment simulation cabin control adjusting systems.

7. Conclusions

Controlling a large multi-parameter environmental simulation cabin is a great challenge. Based on the multi-parameter control characteristics in the environmental simulation cabin, a fuzzy expert control method is adopted in this paper for the purpose of analyzing the dynamic-state characteristics and modeling the parameter changes. This method can resolve many difficulties such as the problem of high-precision temperature and pressure control, achieving the required cabin warming or cooling rate, and not requiring PID tuning of the revolution speed control of the refrigeration turbine in the environmental simulation system. Additionally, the method can ensure automatic control of the turbines without overspeed, and the turbine revolution speed is maintained within a stable range during the processes of environmental simulation cabin temperature decreasing and insulation. Furthermore, the method can decrease operation of the control valve and prolong the life of the actuator. It can be seen from the simulation and actual experiments that the lumped parameter approach proposed in this paper is correct and that the fuzzy-control method is superior to the classical PID control method. Moreover, the fuzzy-control method has the advantages of no-overshoot, fast response, high steady-state precision, and effective control.

In the future, new control methods including artificial neural networks can be applied in multi-parameter simulation cabin control systems. To improve the PID method, the fuzzy control method can be used in combination, giving PID method parameters automatic self-tuning ability. A decoupling and slope tracking control strategy using a fuzzy strategy combined with an expert strategy may be used to deal with the decoupling problem. Furthermore, the control method can be simulated on a platform with the lumped parameter model given in this article. Finally, it is very useful to apply an intelligent method in the control system of a large multi-parameter simulation cabin.

Acknowledgements

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