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Research Article

A New Precise High Flow Oxygen Therapy System Based on Sliding Mode Control Strategy

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In recent years, precise high flow oxygen therapy as a new type of oxygen therapy machine has gradually attracted people's attention and has been widely used in hospital emergency and clinical treatment of respiratory diseases; especially in recent years, severe coronavirus disease (COVID-19) has played an important role in the treatment of patients. This paper presents a new type of precise high flow oxygen therapy machine with electromagnetic pneumatic flow valve as the core control element. A sliding mode control strategy based on the system is proposed to realize the accurate control of oxygen concentration and output flow of oxygen therapy mixture. The physical equipment of the precision high flow system is established, and its working performance is verified through the test platform. The optimization design goal of the precision high flow equipment is achieved.

1. Introduction

As a kind of medical equipment to help patients increase lung ventilation and improve respiratory function, under the current medical demand for new coronavirus and a variety of respiratory diseases, oxygen therapy machine is widely used in hospital emergency and clinical treatment of respiratory diseases [1]. Among various clinical oxygen therapy methods, high flow nasal oxygen therapy, as a new type of oxygen therapy, is widely accepted and applied because of its unique treatment characteristics. This method has obvious advantages: firstly, it can provide higher and more stable concentration of inhaled oxygen; secondly, it can provide high flow of mixed gas, which can effectively reduce the nasal cavity and dissect the dead area of pharynx; then, this method can generate positive airway pressure and increase lung volume at the end of exhalation; finally, it can reduce the airway resistance of upper respiratory tract and improve the respiratory efficiency of patients [2]. Especially in the recent treatment of severe patients with coronavirus disease (COVID-19) in 2019, nasal high flow oxygen therapy has a good therapeutic application in the treatment of adult respiratory diseases. Because patients with coronavirus disease (COVID-19) are acute respiratory type, reasonable and effective respiratory support is the most important organ support method for these patients [3]. Therefore, high flow nasal oxygen therapy has greater therapeutic advantages than other noninvasive respiratory support methods. At the same time, high flow nasal oxygen therapy has more advantages in maintaining the oxygenation characteristics and comfort of patients with hypoxemia than conventional oxygen therapy and other types of noninvasive positive pressure ventilation [4]. Precise high flow oxygen therapy is the preferred oxygen therapy for patients with mild to moderate respiratory failure [5].

For the current research field of high flow oxygen therapy [6], the main research direction is to solve the problems of single medical adaptability of traditional oxygen therapy equipment, serious oxygen waste, unstable oxygen concentration of mixed gas, poor actual control effect, and so on [7].

Through the research and summary of the frontier research results of high flow oxygen therapy machine at home and abroad, we can find that its research direction mainly focuses on the system design and control strategy [8]. The improvement direction of the system design is usually through the hardware design and optimization in the high flow oxygen therapy system [9]. In the current research field of high flow oxygen therapy machine [10], the overall design and control strategy of the system are also included in the research scope. In the research of control strategy, the control methods usually only aim at a single control quantity, which is difficult to adapt to the complex needs of practical medical applications. The combination of intelligent control technology and precise high flow oxygen therapy system is still in its infancy [11]. The realization of intelligent control method needs a large number of actual treatment data as the data base, which still needs a long time to realize.

Therefore, this paper presents a new type of precise high flow oxygen therapy machine with electromagnetic pneumatic flow valve as the key control element [12]. Through in-depth research and optimization design of electromagnetic pneumatic flow valve, a high flow oxygen therapy system based on valve is designed. At the same time, in order to solve the control disadvantage of PID method to nonlinear system, a sliding mode control method based on high flow oxygen therapy system is proposed. The physical equipment of the high flow oxygen therapy system is established by precisely controlling the concentration and the output flow [13], and its working performance is verified by the experimental platform. The optimization design goal of the high flow oxygen therapy equipment is achieved, and the design and improvement of the high flow oxygen therapy system are realized [14].

2. Introduction of System Working Principle and Establishment of Mathematical Model

As shown in Figure 1, the working structure of the new precision high flow oxygen therapy machine is mainly composed of the following parts: electromagnetic pneumatic flow valve, air filter, oxygen concentration sensor, flow sensor, pressure relief value, pressure gauge, and turbine fan. Among them, the electromagnetic pneumatic flow valve and turbine fan are the key control components of the system [15]. Firstly, the electromagnetic pneumatic flow valve can control the output flow of the high pressure and high concentration oxygen source in the oxygen circuit. The output flow and oxygen concentration of the oxygen circuit are measured by the gas flow sensor and the oxygen concentration sensor, and it is transmitted to the controller. Then, the turbine fan provides positive pressure for the mixed gas circuit of the system to mix the filtered air and oxygen and deliver them to the container for storage. The flow rate and oxygen concentration of the mixed gas are measured by the gas flow sensor and oxygen concentration sensor and transmitted to the controller. The system is a positive pressure system with gas flow sensor and oxygen concentration sensor as the main detection elements and single chip microcomputer as the control element. Its working principle is that after the system starts, the controller provides control signals to the pneumatic flow valve and the turbine fan to open the oxygen circuit and the mixture circuit, At the same time, the flow of oxygen and mixture is detected by gas flow sensor and oxygen concentration sensor, and the measured data is sent to the controller.

According to the error value, the controller further controls the output flow of the pneumatic flow valve and the speed of the turbine fan and then controls the oxygen concentration and flow of the mixed gas, so as to achieve the accuracy of various control quantities of the oxygen concentration and output flow.

2.1. Mathematical Model of Electromagnet Type Pneumatic Flow Valve. According to the working principle and composition of the new precise high flow oxygen therapy machine, its mathematical model is established, and the feasibility of the system is demonstrated. The main components of the mathematical model are electromagnetic pneumatic flow valve and turbine fan, and the mathematical model of other components such as pipelines and containers is simplified [16].

2.1.1. According to the Working Principle of the Valve, the Pressure Equation Can Be Described as Follows.

$$\frac{dP_c}{dt} = \frac{mR}{V_c}\frac{dT_c}{dt} + \frac{RT_c}{V_c}G_c - \frac{P_c S_c}{V_c}\dot{X}^{\#}, \quad (1)$$

where P_C is the working chamber pressure, R is the gas constant, T_C is the temperature, S_c is the effective area of the diaphragm, V_C is the working chamber volume, and X is the spool displacement.

2.1.2. The Flow Equation Can Be Described as Follows.

$$G = S_e P_s \frac{\varphi}{\sqrt{T_s}}. \quad (2)$$

When $P_2/P_1 \leq 0.5283, \varphi = \sqrt{k/R(2/k+1)^{k+1/k-1}}$;

when $P_2/P_1 > 0.5283, \varphi = \sqrt{2k/(k-1)1/R[(P_2/P_1)^{2/k} - (P_2/P_1)^{k+1/k}}$;

where P_1 is the upstream pressure, P_2 is the downstream pressure, and se is the effective cross-sectional area. In this model, P_s is the air source pressure, which can be the upstream air pressure in this formula. And K is the specific heat of air.

2.1.3. The Motion Equation of Valve Core Can Be Described as Follows.

$$m\ddot{X} = (P_c - P_o)S_c - KX - r\dot{X} - mg - F_e, \quad (3)$$

where P_o is the pressure under the diaphragm, that is, the outlet pressure, S_C is the effective area of valve core, K is the spring coefficient of the slide valve, r is the damping coefficient, and F_e is the electromagnetic force of electromagnet.

2.2. Turbine Fan. According to the working principle of three-phase brushless DC motor, the corresponding mathematical model is established.

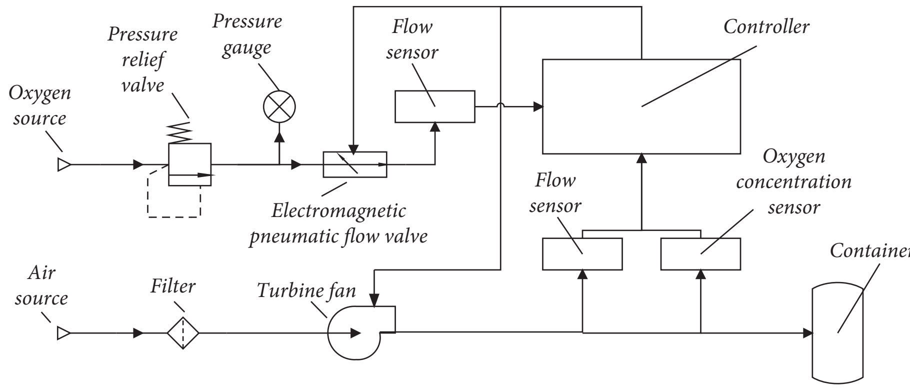

Figure 1: New structure of high flow nasal oxygen therapy system.

By decoupling the three-phase electromagnetic physical quantities of the motor, the mathematical model can be simplified, and the subsequent control signal can be input to control the fan speed.

(1) Voltage balance equation

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} l_d & 0 \\ 0 & l_q \end{bmatrix} p \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega \begin{bmatrix} 0 & -l_q \\ l_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega \Psi_f \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \tag{4}$$

where R_S is the phase resistance, Ψ_f is the phase flux linkage, u is the phase voltage, i is the phase current, p is the differential operator, the subscript q is the torque axis, and the subscript d is the excitation axis. Therefore, u_d is the excitation shaft phase voltage, u_q is the torque shaft phase voltage, l_d is the winding self-inductance of the excitation shaft, l_q is the winding self-inductance of the torque shaft, i_d is the excitation shaft phase current, i_q is the torque shaft phase current, and ω is the mechanical angular speed of the rotor.

(2) Electromagnetic torque equation

$$T_{em} = p_n\left(\Psi_d i_q - \Psi_q i_d\right). \tag{5}$$

(3) Mechanical motion equation

$$T_{em} - T_l = \frac{J}{p_n} p\omega + \frac{B}{p_n}\omega, \tag{6}$$

where T_{em} represents the load torque, J represents the moment of inertia, B represents the rotor viscous friction coefficient, and the starting torque T can be approximately ignored.

Combined with the above equations, the basic mathematical model of the new high flow oxygen therapy machine can be established.

2.3. Sliding Mode Control Strategy. The high flow nasal oxygen therapy system in this paper is an organic combination of pneumatic control technology and medical oxygen therapy. Its pneumatic system characteristics and actual working scene lead to many nonlinear links and uncertain working parameters in the system. These working factors will have a great impact on the control effect of the system. At this stage, COVID-19, as a major global public health safety problem, has caused millions of deaths in the world. It poses a severe and complex challenge to the oxygen therapy treatment mode of inhalation system in China. Due to the requirements of high flow, rapidity, and reliability of pneumatic valve in nasal high flow oxygen therapy system, in order to solve the problems caused by the nonlinear characteristics of the pneumatic valve and the uncertainty caused by the patient as the system object on the design of the system controller, this paper selects the discrete adaptive sliding mode control as the control strategy of the high flow nasal oxygen therapy system [17]. This method can be used as the control strategy of the control system whose parameters are difficult to determine or have time-varying parameters, Aiming at the problem of parameter uncertainty and external disturbance uncertainty in the nonlinear system, the sliding mode control can effectively control the system [18], which can be applied to the system uncertainty and unknown external disturbance caused by the complex actual medical environment and patients in different physiological states in the control of high flow nasal oxygen therapy system in this paper.

Considering that both the controller and the sensor in the actual experiment use discrete signals, the discrete sliding mode control based on discrete exponential control law is adopted. For the convenience of calculation, the system is simplified as a second-order discrete system, and its corresponding mathematical model is as follows [19].

(1) For second-order discrete-time systems

$$x(k+1) = Ax(k) + Bu(k), \tag{7}$$

where x(k) = [x1(k), x2(k)].

Now, the spool displacement X of the pneumatic valve is defined as the system state variable x(k); then the matrices A and B can be defined as

$$A = \begin{bmatrix} 0 & 1 \\ K_a & r \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -K_e \end{bmatrix}; \tag{8}$$

K_a is determined by the valve port diameter, working chamber diameter, and other structural parameters of the valve, and K_e is determined by the electromagnet parameters of the valve.

Set target command as $r(k)$, set rate of change as $dr(k)$, and $R = [r(k), dr(k)]$, $R1 = [r(k+1), dr(k+1)]$.

It used linear extrapolation to forecast r(k+1) and dr(k+1).

$$\begin{aligned} r(k+1) &= 2r(k) - r(k-1) \\ dr(k+1) &= 2dr(k) - dr(k-1) \end{aligned}. \quad (9)$$

(2) the discrete sliding surface is as follows:

$$s(k) = C * E, \quad (10)$$

where $C = [c, 1]$, $E = (R - x(k))$.

(3) Discrete exponential reaching law:

$$s(k+1) = s(k) + T(-\varepsilon \operatorname{sgn}(s(k)) - qs(k)). \quad (11)$$

(4) Discrete control law based on exponential control law

$$\begin{aligned} u(k) = (CB)^{-1} [CR_1 - CAx(k) \\ - s(k) - T(-\varepsilon \operatorname{sgn}(s(k)) - qs(k))]. \end{aligned} \quad (12)$$

The main adjustment parameters are approaching velocity parameter q, sliding surface parameter C, and sign function gain ε. Through the analysis, it can be seen that the approaching speed parameter q mainly affects the speed of the system state point reaching the switching surface, the sliding surface parameter C has a great influence on the response speed and regulation time of the system, and the sign function gain is small ε. It is the main parameter for the system to overcome perturbation and external disturbance [20].

(5) The stability of sliding mode control

Define Lyapunov function:

$$\begin{aligned} V(k) &= \frac{1}{2} s^2(k) \\ \Delta s(k+1) &= s(k+1) - s(k) = -CBF_D E(k) \end{aligned}, \quad (13)$$

where $F_D = [f_1, f_2, \ldots\ldots f_n]$ is the gain of a state variable of the system.

$$f_i = \begin{cases} f_0, & -CBs(k)E_i(k) < -\delta_i \\ 0, & -\delta_i \le -CBs(k)E_i(k) \le \delta_i \\ -f_0, & -CBs(k)E_i(k) > \delta_i \end{cases}. \quad (14)$$

$$\delta_i = \frac{1}{2} f_0 (CB)^2 |e_i(k)| \sum_{i=1}^{n} |e_i(k)|$$

Therefore,

$$\begin{aligned} s(k)\Delta s(k+1) &< -\sum_{i=1}^{n} \delta_i |f_i| \le -\frac{1}{2}(CB)^2 \left(\sum_{i=1}^{n} |f_i| |e_i(k)| \right)^2 \\ &\le -\frac{1}{2}(\Delta s(k+1))^2. \end{aligned} \quad (15)$$

Finally,

$$V(k+1) - V(k) = \frac{1}{2}(\Delta s(k+1))^2 + s(k)\Delta s(k+1) < 0. \quad (16)$$

It can be seen that the controller meets the stability requirements [21].

3. Physical Experiment of Ventilator and Selection of Related Components

Through the establishment of the basic mathematical model of the new precision high flow oxygen therapy machine and the simulation, the feasibility of the system is basically verified. According to the physical design requirements and experimental conditions, the physical components of high flow oxygen therapy equipment are selected and assembled, and then the oxygen therapy machine is tested to test the precise control of various control quantities of oxygen concentration and output flow.

3.1. Selection of Physical Components of Ventilato. According to the actual use requirements of the new high flow oxygen therapy machine, on the premise of ensuring the performance and production cost, the relevant physical components can be selected. The specific selection is shown in Table 1.

3.2. Design of Physical Experiment Circuit for Oxygen Therapy Machine. After determining the selection and assembly of the relevant components of the new high flow oxygen therapy machine, a physical experiment circuit can be designed to test the accurate control effect of the oxygen concentration of the mixed gas output and the output flow, so as to ensure the accuracy of the experiment. On this premise, we can build the relevant experimental circuit in the laboratory.

As shown in Figures 2 and 3, it is the schematic diagram of the actual experimental circuit of the oxygen therapy machine. It can be seen that, in the loop, the high pressure oxygen source and the atmospheric gas source are the gas sources of the system. The outlet pressure of high pressure oxygen source is regulated by pneumatic flow valve to provide accurate and stable gas source conditions for high flow oxygen therapy equipment. The pneumatic on-off valve can control the opening and closing of the gas source and control the beginning and end of the experiment. The experimental loop with throttle valve and vessel as simulated

Table 1: Component selection of a new type of high flow nasal oxygen therapy equipment.

Element	Model
Oxygen concentration/flow sensor	Ultrasonic oxygen sensor OCS-3F
Brushless DC fan	7054ZWF-1-250a-24.0
Pressure sensor	Gas pressure sensor SDNA010BGB
Gas flow sensor	Digital differential pressure sensor datasheet SDP800-Digital

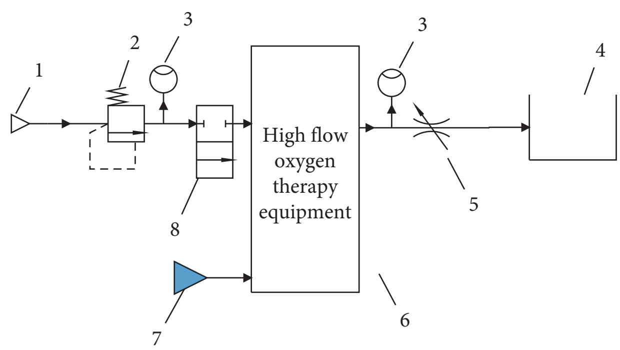

Figure 2: Physical experimental circuit of oxygen therapy machine. 1. High pressure oxygen source; 2. Pneumatic proportional pressure valve; 3. Flow sensor; 4. Container; 5. Throttle valve; 6. High flow oxygen therapy equipment; 7. Normal pressure air source; 8. Pneumatic on-off valve.

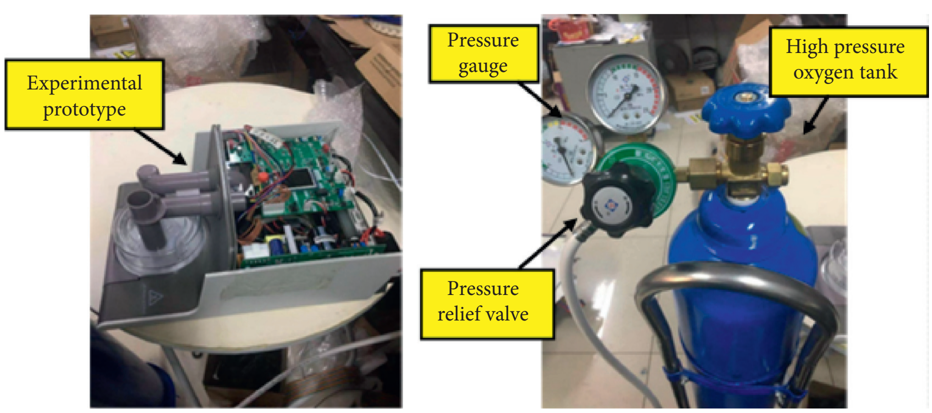

Figure 3: Schematic diagram of prototype experiment.

load provides proportional and adjustable load conditions for oxygen therapy equipment.

Based on the design and mathematical derivation of adaptive sliding mode controller based on discrete reaching law, the adaptive sliding mode control law can be obtained, which can be realized in C language in the test prototype of high flow nasal oxygen therapy system. The pseudocode implementation of adaptive discrete sliding mode controller is shown in Figure 4.

4. Experimental Data Analysis

According to relevant information, in the oxygen supply system of the hospital, the oxygen pressure in the operating room is 0.3 MPa, the typical flow rate is 6–10 L/min, and the design flow rate is 100L/min, while the oxygen pressure in the general ward is 0.3 MPa, the typical flow rate is 6L/min, and the design flow rate is 10L/min. The performance parameters of the system are as follows: 1. The working pressure of oxygen source is 0.3 MPa; 2. The range of mixed gas flow is 0–45L/min; 3. The adjustment range of oxygen concentration of mixed gas is 21%–95%. Based on the use scenarios and performance parameters of the system, the feasibility of the system and control strategy is verified.

4.1. Mixed Gas Total Flow Regulation Experiment. In order to test the total flow control effect of the precise high flow oxygen therapy system, the target value of the total flow of the mixed gas is adjusted. The actual total flow output value of the system under the sliding mode control strategy and PID control strategy is measured, and the data is compared and analyzed. For the other adjustable variables of the system, the oxygen source pressure is set to 0.3 MPa, and the oxygen concentration of the mixed gas is 31%.

As shown in Figure 5, the target value of total flow of mixed gas is adjusted from 10L/min to 20L/min, and the actual flow output value is recorded by the gas flow sensor in

Pseudo code: adaptive discrete sliding mode controller

Parameter definition: Sampling time T; Synovial surface parameter c; Approach speed parameter q; Measured quantity $x = [x1, x2]$; System count value K; Target quantity $r = [rt1, rt2]$;

Input value: Measured value xc; Target value xa;

Output value: Control quantity $u(k)$;

```
For k=0 ← K do
    time ← k*T;
    r(k) ← xa;
    Ce ← [c,1];
    dr(k) ← [r(k)-rt1]/T;
    dr_1 ← [rt1-rt2]/T;
    r1(k) ← 2r(k)-rt1;
    dr1(k) ← 2dr(k)-dr_1;
    R ← [r(k), dr(k)];
    R1 ← [r1(k), dr1(k)];
    E ← R-x;
    e(k) ← E (1);
    de(k) ← E (2);
    s(k) ← Ce*E;
    ds(k) ← -q*Ts(k)-0.5sgn(s(k))T*sat(s(k));
    u(k) ← (Ce*B)^-1(CeR1-CeAx-s(k)-ds(k));
    x1 ← xc;
    x2 ← x1;
    rt2 ← rt1;
    rt1 ← r(k);
return u(k)
```

Figure 4: Pseudocode implementation of adaptive discrete sliding mode controller.

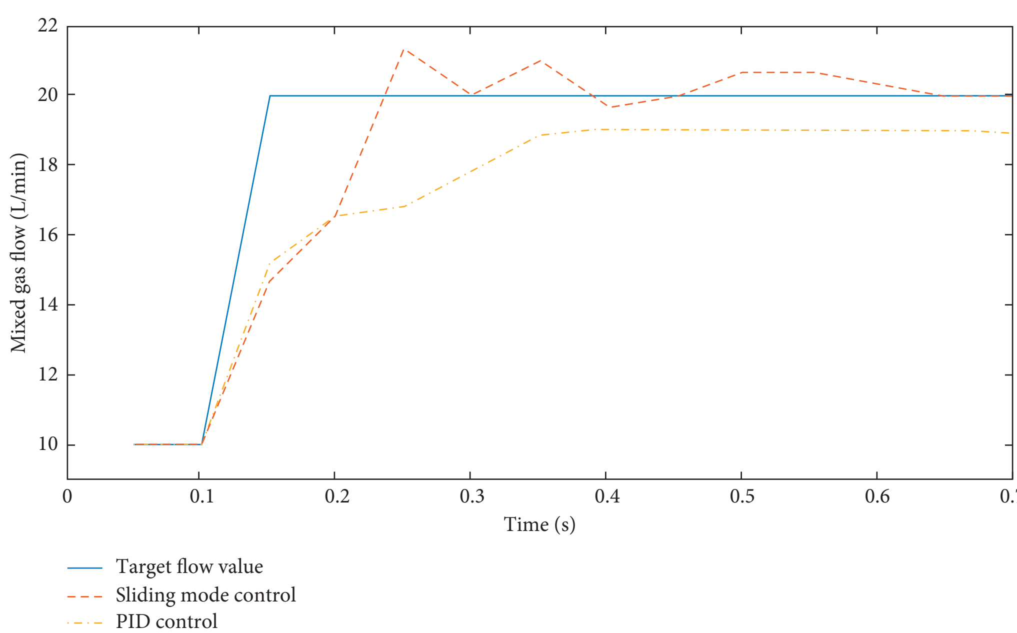

Figure 5: Comparison of actual flow output under the total flow regulation range of 10–20 L/min.

the system. After setting the target flow value each time, wait for the actual output flow to stabilize again, then change the target flow value, and wait for the actual output flow to stabilize, and end the data recording. By analyzing the experimental data, it can be seen that, for the system with sliding mode control, the delay time TD is 0.06 s, the regulation time Ts is 0.20 s, and the steady-state error is 3.33%. For the PID control system, the delay time TD is 0.05s, the regulation time Ts is 0.35s, and the steady-state error is 4.72%. After comparing the two groups of data under different control strategies, it can be seen that when the total flow of mixed gas is small, the response of the system with sliding mode control in the initial state is slow, and its delay time is larger than that of PID control. But with the increase of gas flow value, the response speed of sliding mode control is faster, its regulating time is smaller than PID control, and the steady-state error of sliding mode control is smaller, so the final control effect is better.

As shown in Figure 6, the target value of total flow of mixed gas is adjusted from 30L/min to 40L/min, and the actual flow output value is recorded by the gas flow sensor in the system. After setting the target flow value each time, wait

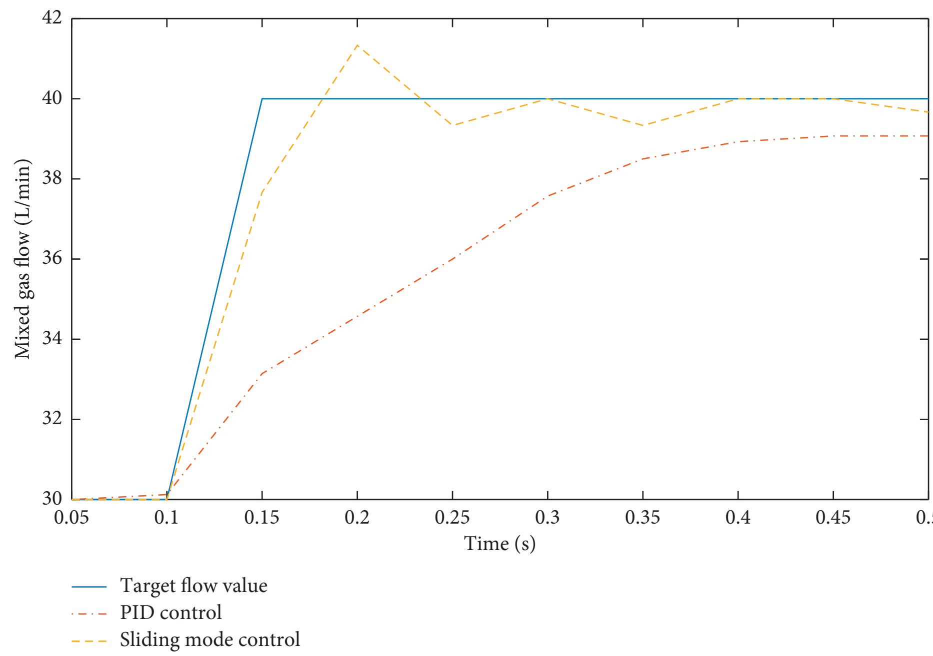

Figure 6: Comparison of actual flow output under the total flow regulation range of 30–40L/min.

for the actual output flow to stabilize again, then change the target flow value, and wait for the actual output flow to stabilize, and end the data recording. Through the analysis of the experimental data, it can be seen that, for the system with sliding mode control, the delay time TD is 0.04s, the regulation time Ts is 0.15s, and the steady-state error is 1.67%. For the PID control system, the delay time TD is 0.15s, the regulation time Ts is 0.25s, and the steady-state error is 2.32%. After comparing the two groups of data under different control strategies, it can be seen that when the total flow of mixed gas is large, the response of the system with sliding mode control is faster in the initial state, its delay time is smaller than that of PID control, and the adjustment time of sliding mode control is smaller than that of PID control. At the same time, the steady-state error of sliding mode control is small, and the final control effect is better. By comparing the data of the system in the two working states of small and large total flow of mixed gas, it can be seen that the control effect of sliding mode control and PID control is similar in the case of small total flow of mixed gas, but in the working state of large total flow of mixed gas, the working performance of the system under sliding mode control is better.

4.2. Mixed Gas Oxygen Concentration Regulation Experiment. In order to test the control effect of mixed gas oxygen concentration of precision high flow oxygen therapy system, the target value of mixed gas oxygen concentration is adjusted, the actual gas oxygen concentration output value of the system under sliding mode control strategy and PID control strategy is measured, and the data is compared and analyzed. For the other adjustable variables of the system, the oxygen source pressure is set to 0.3 MPa, and the total flow of mixed gas is set to 30L/min.

As shown in Figure 7, the target value of mixed gas oxygen concentration is adjusted from 33% to 43%, and the actual oxygen concentration output value is recorded by the gas oxygen concentration sensor in the system. After setting the target oxygen concentration value each time, wait for the actual oxygen concentration to stabilize again, then change the target oxygen concentration value, and wait for the actual oxygen concentration to stabilize, and end the data recording. By analyzing the experimental data, it can be seen that, for the system with sliding mode control, the delay time TD is 0.25 s, the regulation time Ts is 0.80 s, and the steady-state error is 1.16%. For the PID control system, the delay time TD is 0.30s, the regulation time Ts is 0.75s, and the steady-state error is 1.86%. After comparing the two groups of data under different control strategies, it can be seen that when the oxygen concentration of the mixed gas is small, the response of the system with sliding mode control is faster in the initial state, and its delay time is smaller than that of PID control. But the sliding mode control will quickly enter the steady-state regulation state, so its regulation time is smaller than that of PID control. At the same time, the steady-state error of sliding mode control is smaller, and the final control effect is better.

As shown in Figure 8, the target value of mixed gas oxygen concentration is adjusted from 43% to 53%, and the actual oxygen concentration output value is recorded by the gas oxygen concentration sensor in the system. After setting the target oxygen concentration value each time, wait for the actual oxygen concentration to stabilize again, then change the target oxygen concentration value, and wait for the actual oxygen concentration to stabilize, and end the data recording. By analyzing the experimental data, it can be seen

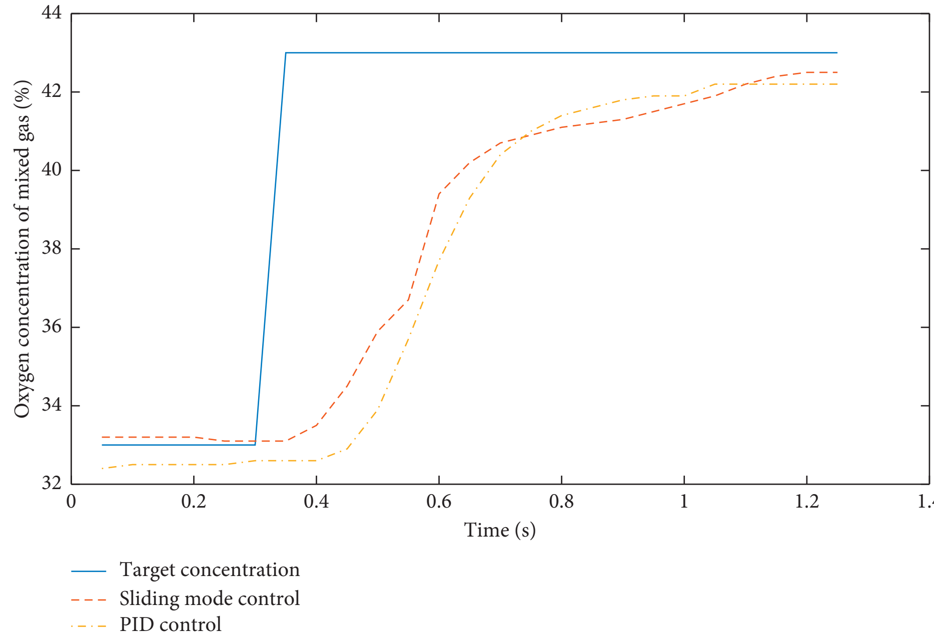

Figure 7: Comparison of actual gas oxygen concentration in the range of 33–43%.

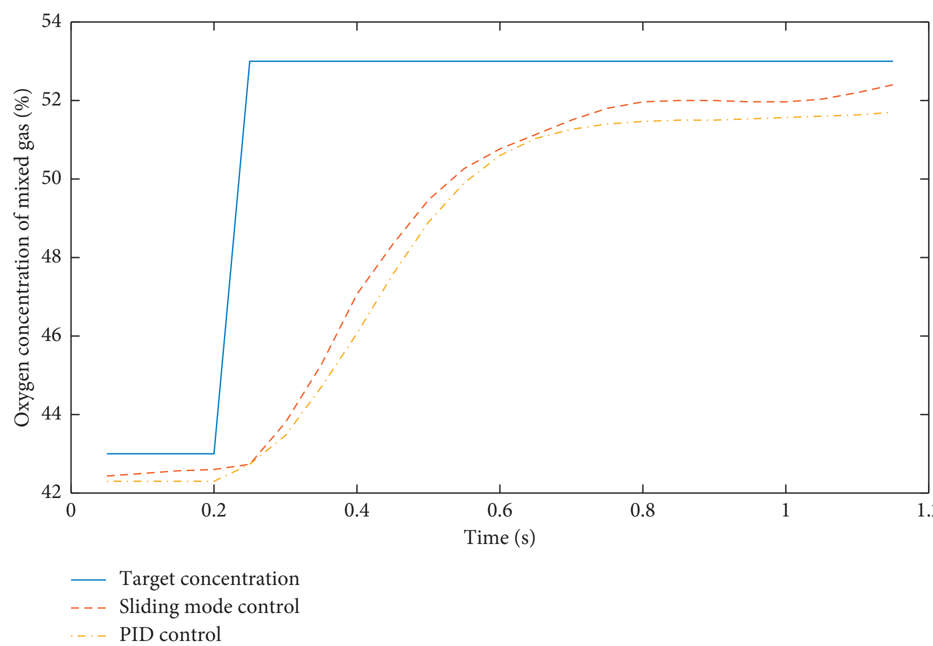

Figure 8: Comparison of actual gas oxygen concentration under 43–53% oxygen concentration adjustment range of mixed gas.

that, for the system with sliding mode control, the delay time TD is 0.25 s, the regulation time Ts is 0.60 s, and the steady-state error is 1.97%. For the PID control system, the delay time TD is 0.30s, the regulation time Ts is 0.85s, and the steady-state error is 2.64%. After comparing the two groups of data under different control strategies, it can be seen that the response speed of sliding mode control and PID control is similar when the oxygen concentration of mixed gas is large. But when the system enters the steady-state regulation state, the steady-state error of sliding mode control is small, and the final control effect is better.

4.3. Continuous Regulation Experiment of Total Flow Rate and Oxygen Concentration of Mixed Gas. In order to test the continuous control effect of the total flow and oxygen concentration of the mixed gas in the precise high flow oxygen therapy system, the target values of the total flow and oxygen concentration of the mixed gas are continuously adjusted. The actual gas output values of the system under the sliding mode control strategy and PID control strategy are measured, and the data are compared and analyzed. For the remaining adjustable variables of the system, the oxygen source pressure is set to 0.3 MPa.

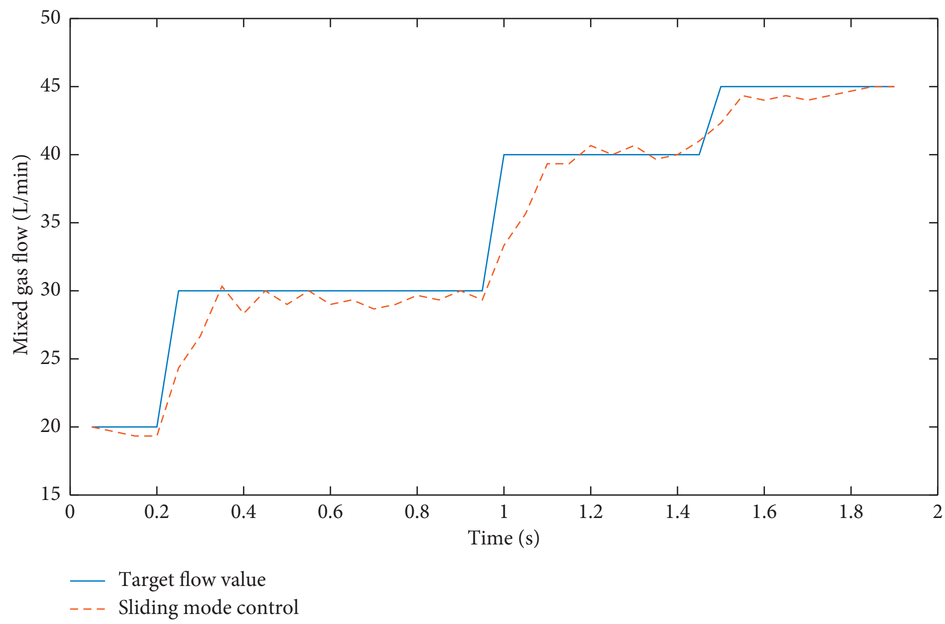

Figure 9: Comparison of continuous adjustment of total flow of mixed gas under sliding mode control.

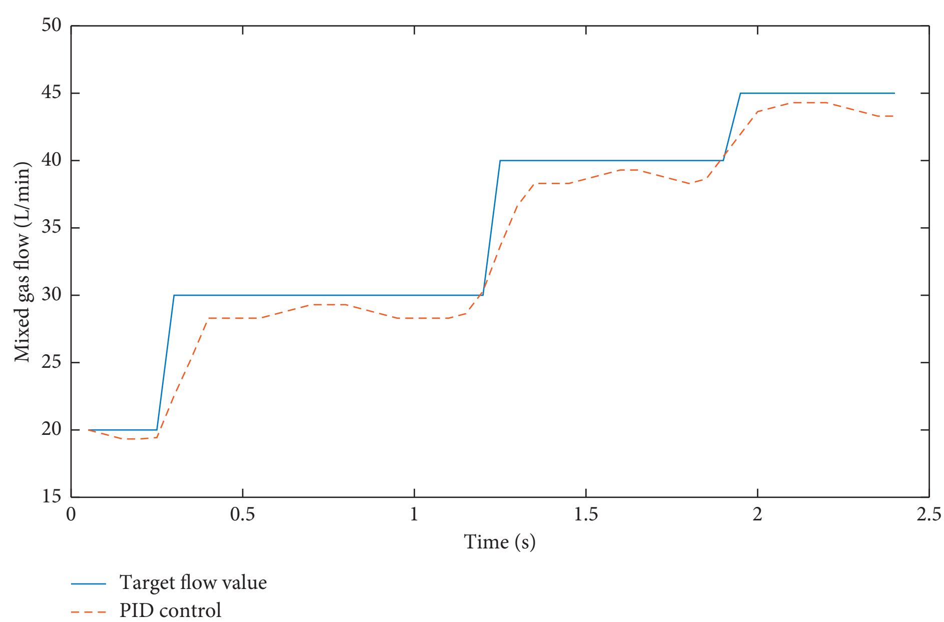

Figure 10: Comparison of total flow of mixed gas continuously regulated by PID control.

As shown in Figures 9 and 10, the oxygen concentration of the system is set to 31%, and the target value of the total flow of mixed gas is continuously adjusted from 20L/min to 45L/min. The actual flow output value is recorded by the gas flow sensor in the system. After setting the target flow value each time, wait for the actual output flow to stabilize again, then change the target flow value, and wait for the actual output flow to stabilize, and end the data recording. Through the analysis of the experimental data, it can be seen that, for the system with sliding mode control, with the increase of the working flow, the steady-state regulation time is shortened, from about 0.50s in the stage of 20L/min to 30L/min to about 0.20 s in the stage of 40 L/min to 45 L/min; compared with the continuous regulation of PID control, the regulation time is shorter. At the same time, the steady-state error of the system with sliding mode control is about 1.6%–4.1%, which is smaller than the continuous regulation of PID control. Through the data analysis, it can be seen that the total flow regulation performance of the sliding mode control system is better, and its working performance is better in the large flow state.

As shown in Figures 11 and 12, the total flow of the system is set at 30L/min, the target value of oxygen

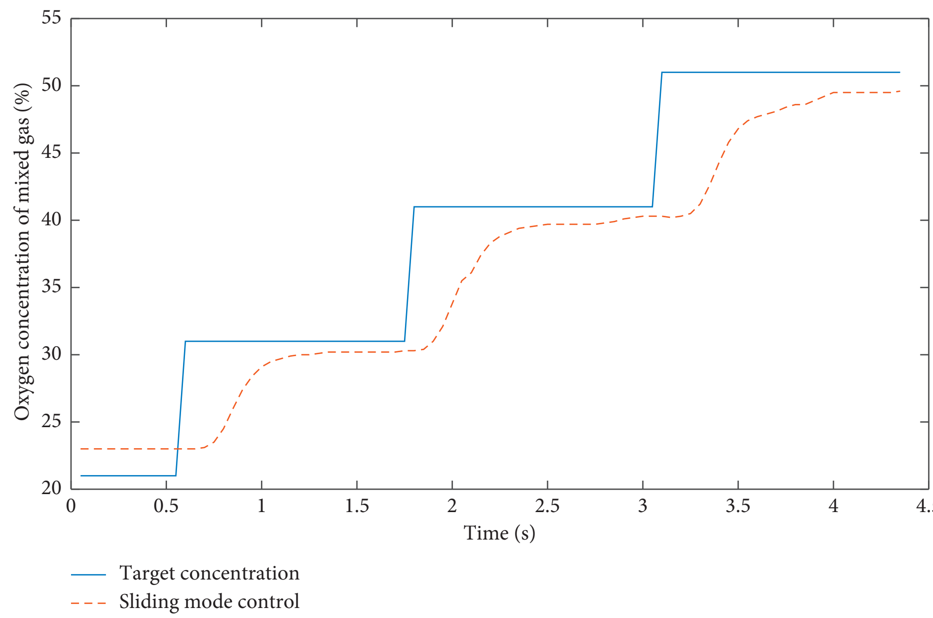

Figure 11: Comparison of mixed gas oxygen concentration under sliding mode control.

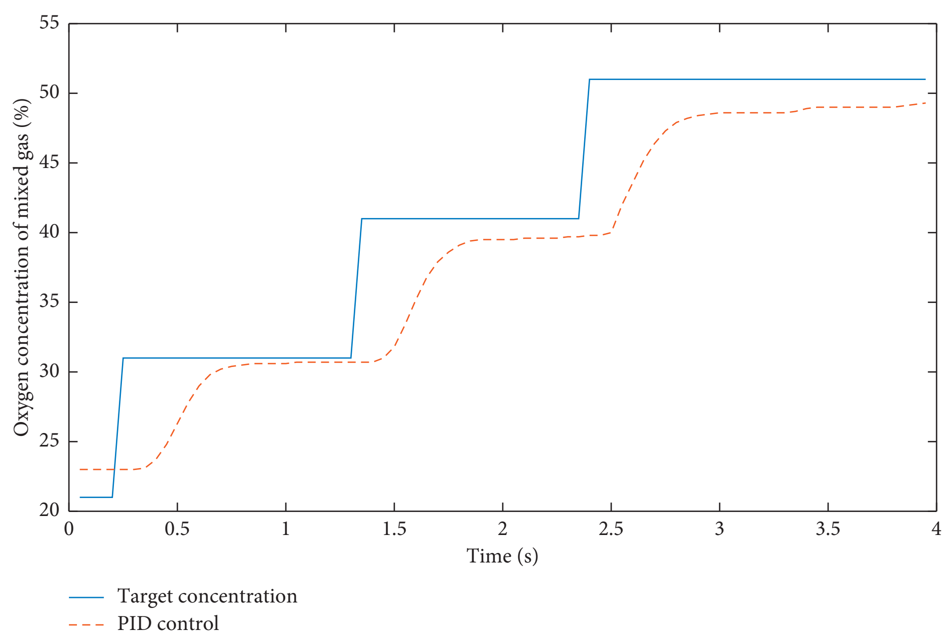

Figure 12: Comparison of mixed gas oxygen concentration under PID control.

concentration is adjusted from 21% to 51%, and the actual oxygen concentration output value is recorded through the gas oxygen concentration sensor in the system. After setting the target oxygen concentration value each time, wait for the actual oxygen concentration to stabilize again, then change the target oxygen concentration value, and wait for the actual oxygen concentration to stabilize, and end the data recording. Through the analysis of the experimental data, it can be seen that, compared with PID control, for the system with sliding mode control, in the continuous control, with the increase of working oxygen concentration, the adjustment time is shorter. At the same time, the steady-state error of the system with sliding mode control is about 1.20%–1.80%, which is smaller than the continuous regulation of PID control. Through the data analysis, it can be seen that the system of sliding mode control has better regulation performance in oxygen concentration, but with the increase of oxygen concentration, its steady-state error increases, but compared with PID control, the error of sliding mode control is still small.

5. Conclusion

This paper presents a new type of precise high flow oxygen therapy machine with pneumatic flow valve as the key control element. Firstly, on the basis of deeply studying and optimizing the working characteristics of the existing electromagnetic pneumatic flow valve, a precise high flow oxygen therapy system is designed, a sliding mode control strategy based on the system is proposed, and the mathematical model of the system is established. Secondly, the physical equipment of the precise high flow oxygen therapy system is established, and its working performance is verified by the experimental platform. Finally, through the design of sliding mode control strategy, the precise control of oxygen concentration and output flow of oxygen therapy mixed flow is realized, which provides a theoretical basis for the design and development of precise high flow oxygen therapy equipment.

(1) The mathematical model of the new precise high flow oxygen therapy system is designed and established, and the sliding mode control strategy based on the system is proposed. Through the experimental verification, it is verified that the oxygen concentration and the output flow of the oxygen therapy mixture are accurately controlled.

(2) Through the practical experiment of a reasonable high flow oxygen therapy system, the precise control effect of the system based on sliding mode control strategy is verified. For the control of the total flow of mixed gas, the control effect of sliding mode control and PID control is similar when the total flow of mixed gas is small, but the system has better performance under sliding mode control when the total flow of mixed gas is large. For the control of oxygen concentration, compared with PID control, the system of sliding mode control has better regulation performance in oxygen concentration, but with the increase of oxygen concentration, its steady-state error increases, but compared with PID control, the error of sliding mode control is still small.

Data Availability

No data will be provided for the time being.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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