Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.cbiore.id

Research Article

Automatic control of constant temperature and humidity in building air conditioning systems based on frequency domain analysis

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Abstract. How to solve their automatic control of constant temperature and humidity gradually becomes a research hotspot as the continuous upgrading of air conditioning systems. This study aims to optimize the traditional proportional-integral-differential controller for improvement to solve the time-delay instability phenomenon in temperature and humidity control. The objective of this study is to optimize existing proportional-integral-differential controllers to improve the time-delay instability problem that is common in temperature and humidity control. Firstly, it treats the controlled object as a first-order and second-order system with time-delay characteristics. Next, the Smith predictor controller is generalized equivalent to ensure that the equivalent system does not contain time-delay. Finally, an analysis of the first-order and second-order closed-loop control system is conducted by combining Smith predictive controller and proportional-integral-differential controller. The system achieves the goal of automatic control of constant temperature and humidity by adjusting the control parameters. The experiment showcased that the temperature control time of the proposed control scheme under first-order and second-order time-delays was 16 s and 3 s, respectively. Meanwhile, the humidity control time was 14 s and 13 s, respectively. In practical applications, the proposed control scheme achieved good control effects in all four seasons. This indicates that the controller designed in this study possesses good control performance. It also can achieve the goal of constant temperature and humidity control. This can provide technical support for the automation control of air conditioning systems.

Keywords: Frequency domain analysis; Temperature; Predictive controller; Automation; Humidity; PID

Received: 3rd Feb 2024; Revised: 28th March 2024; Accepted: 15th April 2024; Available online: 2nd May 2024

1. Introduction

With the continuous improvement of quality of life, Air Conditioning (AC) has become one of the essential household electrical equipment (Zhang *et al.* 2023). How to use relevant technologies to automate temperature and humidity control in AC systems on the ground of environmental changes is currently a hot topic in computer research (Bandewad *et al.* 2023). The AC temperature system is extremely susceptible to changes in the internal and external environment, whose structure is relatively complex. Whether it is the cooling capacity delivery of the water system or the air supply output of the air system, the AC system may suffer from time-delay characteristics (Hermawan *et al.* 2023). Building an AC system has been a key technology to maintain indoor temperature and humidity within a comfortable range. The automatic control effect of the AC system also affects people's living and working environment (He *et al.* 2023). The energy efficiency and intelligent control of AC systems become the focus of building technology research with the increase of global climate change and energy efficiency requirements. The design of modern buildings is increasingly focused on achieving environmental sustainability and improving occupant comfort. The design requires AC systems that not only meet basic temperature and humidity regulation needs, but also have a high degree of energy efficiency and intelligent responsiveness (Hussain T 2023). In addition, the integration of AC systems and the interoperability of intelligent building management systems have also become a key direction to improve the overall performance of the system with the application of Internet of Things technology (Sah *et al.* 2021). These technologies have brought about a reevaluation of traditional AC control strategies, especially in terms of how to effectively manage the dynamic response and environmental adaptability of AC systems. However, the control of AC systems still faces several challenges despite technological advances, especially how to effectively reduce energy consumption while maintaining environmental quality in dynamic environments. Although the traditional Proportional-Integral-Differential (PID) control method is widely used in industrial and commercial AC systems, it has obvious limitations when dealing with complex dynamic and nonlinear problems. The limitations include slow response time-delay and difficult to adapt to rapidly changing environmental conditions (Al-Manthria *et al.* 2021). In addition, traditional control methods are often difficult to achieve accurate and personalized control for large buildings or places with different temperature and humidity requirements in different areas. This limits the overall efficiency and effect of the system (Rajeshwaran *et al.* 2023).

The temperature and humidity control of the AC system mainly depends on the PID controller (Korupu *et al.* 2022). However, this traditional control method is difficult to meet the

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https://doi.org/10.61435/ijred.2024.60102

needs of high efficiency and high precision due to the complexity of AC system and the variability of environmental conditions (Zhang *et al.* 2021). PID control often leads to reduced control performance, especially when dealing with AC systems with significant time-delay (Shruti *et al.* 2021). In addition, most of the existing researches focus on improving PID parameter adjustment. However, there are relatively little research on how to use advanced control theory and technology to overcome the time-delay and improve system stability and response speed (Perez *et al.* 2021). The traditional PID control strategy is faced with the slow response speed and low control accuracy in practical applications, especially when the performance is not ideal when dealing with system delay and external disturbance (Laifa *et al.* 2022). Therefore, how to optimize the control strategy to improve the control performance of the AC system and ensure the stability and comfort of the indoor environment becomes an urgent problem to be solved (Deniz 2022). Based on this background, this study applies generalized equivalence to the Smith predictor controller to ensure that the equivalent system does not contain time-delay. The closed-loop Transfer Function (TFU) of the system meets the standard First-Order (FO) and second-order system forms by combining Smith and PID control. Therefore, the instability and poor performance of the controller can be improved in traditional AC temperature control methods.

The main contribution of this paper is to propose a control strategy combining a Smith predictive controller and a PID controller to improve the automatic control performance of constant temperature and humidity in building an AC system. The Smith predictive controller is combined with Frequency Domain Analysis (FDA) for the first time to study the time-delay problem in the AC system. The effectiveness of the proposed control strategy is verified by simulation and practical application. In addition, the design of control strategy is discussed in detail, including the establishment of system model, the optimization of control parameters, and the evaluation of control effect. The main purpose of this study is to develop a new control strategy combining a Smith predictive controller and a PID controller to optimize the automatic control of constant temperature and humidity in building the AC system through FDA. This paper attempts to combine the Smith predictive control technique with PID to solve the shortcomings of traditional methods in time-delay and precision control. The potential of this control strategy in improving system response speed, increasing control precision, and reducing energy consumption is demonstrated through detailed system modeling and simulation analysis. In addition, this study also discusses the feasibility and practicability of the control strategy. Meanwhile, the effectiveness of the proposed control strategy is verified through practical application cases. This provides a new theoretical and practical basis for the control of AC system in the future intelligent building environment.

2. Related works

FDA, as a fundamental concept in the signal processing, often refers to the signals analysis in terms of frequency to study and process the frequency components of signals (Nagarsheth *et al.* 2020). Currently, many experts have conducted research in electronic engineering, communication engineering, seismology, and many other fields by combining the concept of FDA. Zheng *et al.* (2021) presented a Fractional Complex Order (FCO) controller for speed control of DC motors as an extension of traditional fractional order controllers. Therefore, the possibility of simultaneous changes in phase angle and gain in the motor system due to external interference were addressed. The proposed FCO controller added additional parameters, allowing the system to exhibit strong robustness. In addition, the parameters of the FCO controller were adjusted by integrating gain cross frequency, cutoff frequency, phase margin, and amplitude margin based on FDA. Finally, optimization algorithms were used for solving the optimal solution of a series of constraints. The relevant outcomes showcased that the presented complex fractional order control possessed more excellent dynamic robustness (Zheng *et al.* 2021). Jiang *et al.* proposed an AC coordinated control strategy based on FDA to address the challenges of system Frequency Regulation (FR) brought about by the increase in renewable energy in 2020. In the strategy, the inverter AC unit was used for primary FR, and the fixed frequency AC unit was used for secondary FR. In the primary FR, the set point of the inverter AC unit was adjusted to provide adjustable power. Meanwhile, the random number generation method was used to trigger the inverter AC unit based on the frequency deviation. In the secondary FR, the constant equivalent duty cycle method was used to stabilize the power regulation. Meanwhile, the switching state of the fixed frequency AC unit was determined by changing the time interval method. The simulation results showed that this strategy effectively reduced power rebound, improved FR effect, and had low communication requirements (Jiang *et al.* 2020). Zhang *et al.* (2022) proposed a solution for optimizing heating, ventilation, and AC load scheduling, aiming at balancing user comfort and FR performance. The article adopted an asynchronous model and utilized grid frequency measurement equipment for primary FR based on FDA. This strategy provided the optimal combination of frequency deviation threshold and monitoring period, taking into account maximum frequency deviation and temperature deviation. Finally, the optimal solution of the multi-objective optimization problem was obtained. The simulation results showed that the AC load system can achieve optimal scheduling when the frequency deviation threshold was 0.2Hz and the monitoring period was 5.5 seconds (Zhang *et al.* 2022).

The automatic control of constant temperature and humidity in building AC systems is a technology that ensures the stability of the internal environment within the set ranges. Currently, many experts have conducted research on a series of issues in AC systems, such as temperature control, humidity control, and air quality control. Bushnag proposed a technology for automated management of indoor temperature, humidity, and air quality to address ventilation issues in indoor environments caused by fast-paced lifestyles in 2023. The system used an Arduino microcontroller combined with fuzzy logic for control. The research results indicated that the new system performed excellently in controlling and monitoring air quality, temperature, and humidity compared to previous management techniques (Bushnag 2023). Liu H *et al.* proposed an optimal control strategy for heating, ventilation, and AC systems in commercial buildings in 2021. Then the comfort of residents was ensured while participating in FR. The article considered the nonlinear relationship between temperature set points and fan power, aiming at the scheduling optimization based on the difference between indoor temperature and temperature set points. The simulation results showcased that the proposed optimal strategy improved frequency quality, reduced the regulation of traditional generators, and fairly ensured the comfort of residents (Liu *et al.* 2021). Rumalutur *et al.* (2021) designed an AC automatic control system on the ground of the Arduino UNO controller. The system used DHT11 sensors to measure indoor temperature and humidity. Meanwhile, relays were driven through pulse width modulation signals to achieve precise control of AC. The relevant outcomes showcased that the controller possessed the more excellent control performance (Rumalutur *et al.* 2021). Wibawa I MS *et al.* designed a temperature and humidity measurement instrument on the ground of Arduino ATmega 328P in 2022. The instrument utilized an ATmega 328P microcontroller to process temperature and humidity data from DHT22 sensors. Meanwhile, the measurement results were displayed on an LCD keyboard screen. The experiment showed that the accuracy of the controller in air temperature measurement was 97.97%, and the accuracy in air humidity measurement was 99.35% (Wibawa *et al.* 2022).

In summary, existing research has made certain progress in the control of AC temperature, humidity, and air quality. However, there are still shortcomings in dealing with time-delay characteristics and improving energy management efficiency. The current research mainly focuses on the PID control, fuzzy logic control, and FDA to optimize the temperature and humidity control of an AC system. These studies provide valuable solutions for the automatic control of AC systems both theoretically and practically. However, most schemes still have limitations in dealing with system delay and improving control accuracy. The method proposed in this paper shows innovation in the following aspects compared with the existing works. Firstly, this research provides a new solution for accurate control of time-delay characteristics in AC system by combining a Smith predictive controller with a PID controller. Secondly, the dynamic characteristics of the control system are deeply discussed by using FDA, which makes the control strategy more accurate and stable. Finally, the proposed method is not only innovative in theory, but also proved to be effective and superior in practical application through extensive simulation and practical application tests. These characteristics make this research not only provide an efficient solution strategy for the automatic control of constant temperature and humidity of an AC system, but also provide a new research idea and method for similar automatic control problems.

3. Design of automatic control for AC systems

AC accounts for almost half of the total energy consumption of various buildings. This study combines FDA methods, Smith predictive controllers, and PID controllers to design a new temperature and humidity control scheme for AC systems to save sources and reduce costs.

3.1 Smith predictive control method

The continuous innovation of automation technology has gradually made the automatic adjustment of AC equipment simpler (Hou *et al.* 2022). However, there are some problems such as the high complexity of the internal structure of AC and the susceptibility of temperature and humidity systems to external factors. Therefore, the constant temperature and humidity control technology in the systems still needs to be improved. There are many influencing factors, such as external and internal environmental temperature, humidity, fresh air system, seasonal factors, etc. All of these factors can cause significant changes in the AC temperature and humidity system. The complex internal structure also makes the AC system have strong time-delay characteristics (Hao *et al.* 2021). Smith predictive controller is a control strategy used to solve problems in control systems with significant time-delays. The core idea of the AC system is to predict the future behavior through an internal model to offset the impact of time-delays. In Smith predictive control system, a model with the same delay as the actual process is used to estimate future process outputs (Gallardo *et al.* 2021). Then the controller uses this predicted value instead of the actual process output to calculate the control action. In this way, the controller can respond in advance, effectively overcoming the adverse effects caused by time-delay and achieving more precise and stable control (Wu *et al.* 2023). This study first introduces a Smith predictive controller to improve the time-delay of temperature and humidity control in AC systems.

The controlled object often has pure hysteresis characteristics in the temperature and humidity adjustment in AC systems (Morelli *et al.* 2020). This characteristic will reduce the stability of the temperature and humidity system, deteriorate its dynamic performance, and cause system overshoot and oscillation. The introduction of Smith predictive controller can effectively compensate for the pure lag characteristics of delayed objects, thereby improving the overall performance (Waworundeng *et al.* 2020). The working principle of Smith predictive controller is to add a compensator to the branch of the controlled object as lag compensation. Therefore, the characteristic equation of the added closed-loop TFU does not contain a delay link. This can improve the performance of

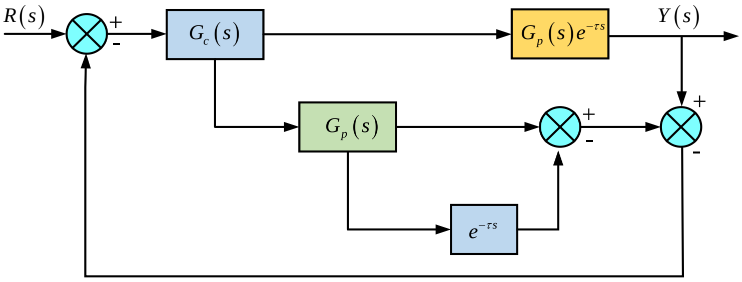


Fig 1 Control block diagram of Smith

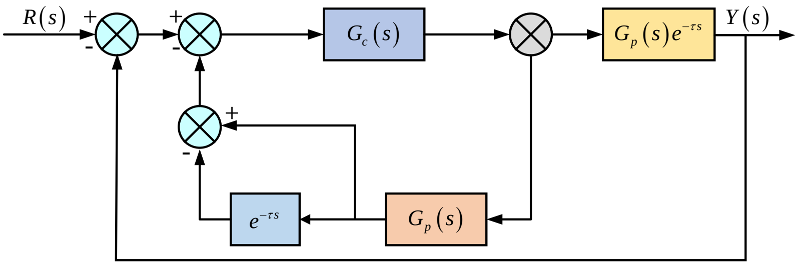


Fig 2 Block diagram of Smith control under anticipatory control

the original controller and increase the stability. The structure of the traditional Smith controller is shown in Figure 1.

In Figure 1, $G_c(s)$ serves as the main controller and $G_p(s)$ serves as the estimation process. The TFU of the manipulated object is represented by $G_p(s)e^{-\tau s}$. The time-delay of the controlled object is represented by $e^{-\tau s}$. $R(s)$ and $Y(s)$ represent the input and output of the system. The Smith estimated control equivalent diagram shown in Figure 2 is obtained by introducing the estimated compensation into the control block diagram shown in Figure 1.

In Figure 2, the traditional Smith controller introduces the estimated compensation. The output of the main controller in Figure 2 is fed into two channels compared to Figure 1. One way is to directly enter $G_p(s)e^{-\tau s}$ to obtain the output value, and the other way is to enter $G_p(s)$. Therefore, the delay effect is reduced by adding an adjustment link to correct the output of the main control path. The TFU of the system will change due to the addition of predictive control on top of Figure 1 and Figure 2. The mathematical model of the TFU under predictive control is shown in equation (1) (Qiao *et al.* 2023).

$$⍰(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-\tau s}}{1+G_c(s)G_p(s)} \quad (1)$$

In equation (1), ⍰(s) represents the TFU of the Closed-Loop System (CLS) after introducing the estimated compensation. $R(s)$ represents the system input that has not received estimated compensation, and $Y(s)$ represents the system output after receiving estimated compensation. In the TFU, the closed-loop characteristic equation determines the stability of the entire system. The stability of the system has been improved compared to systems with time-delay elements because of the absence of time-delay elements in the characteristic function equation of the CLS.

3.2 Construction of automatic adjustment model for first and second-order systems

PID controller is a widely used feedback controller, named after its three main components, namely Proportional, Integral, and Differential (Zhang *et al.* 2023). Proportional is a response to the difference between a set point and a measured value. Integral is a response to the accumulation of errors, aimed at eliminating long-term steady-state errors. The role of Differential is to predict the future behavior of the system and control it by observing the rate of error change. The structure of the PID controller is shown in Figure 3.

In Figure 3, the closed-loop structure of PID control is shown. $r(t)$ and $y(t)$ serve as the input and output quantities of PID control. $e(t)$ and $u(t)$ represent the deviation and control quantities, respectively. There are four common types of PID controllers, namely proportional controller, proportional integral controller, proportional differential controller, and PID controller. The mathematical model of the proportional controller is shown in equation (2).

$$u(t) = K_p e(t) \quad (2)$$

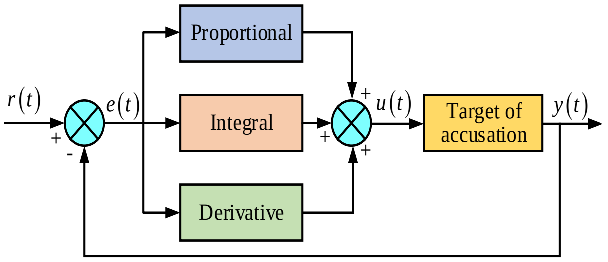


Fig 3 Control block diagram of PID

In equation (2), K_p represents the proportional gain, which determines the strength of the controller's output response to the current error. The mathematical model of the proportional integral controller is shown in equation (3).

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \quad (3)$$

In equation (3), K_i represents the integral gain, which mainly adjusts the sensitivity of the controller to accumulated errors in the past. $\int_0^t e(t)dt$ represents the integral of the deviation from the beginning to the current time point. The mathematical model of the proportional differential controller is shown in equation (4).

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} \quad (4)$$

In equation (4), K_d is the differential gain, which determines the strength of the controller's response to the rate of error change. $\frac{de(t)}{dt}$ represents the rate of change of the deviation. According to equations (2) to (4), the mathematical model of the PID controller is obtained as shown in equation (5) (Lu *et al.* 2022).

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (5)$$

Equation (5) indicates that the design of the PID controller aims to adjust the system's output by integrating these three functions. Therefore, it can quickly and steadily reach and maintain the set point. This study considers that temperature and humidity control in building AC systems may have different time-delay instability situations at different stages, and the structure of the AC system is relatively complicated. Therefore, this study treats the controlled object as an FO and second-order system with time-delay characteristics to simplify the computational complexity. Meanwhile, mathematical models for each FO and second-order system are built to optimize its time-delay. When the temperature and humidity control object of the indoor AC system is an FO time-delay model, the calculation formula for the FO time-delay link model is shown in equation (6) (Chen *et al.* 2023).

$$G_1(s) = \frac{0.92}{1+TS} e^{-30s} \quad (6)$$

In equation (6), $G_1(s)$ represents the FO Time-Delay Model (TCM). It draws on relevant parameter values from relevant literature and combines them with actual situations. Therefore, T represents the inertia link, with a value of 144. S represents the control delay duration, with a value of 30. The gain coefficient takes a value of 0.92. It sets the input signal as a step signal and optimizes the PID control parameters of the FO TCM through the response curve method. The simulation structure of the standard PID tuned by the response curve method under disturbance is shown in Figure 4.

In Figure 4, Step represents a step input used to simulate system startup or changes in set points. Gain represents that the gain of the model can be used to adjust the amplitude of the step input, and three gain types are used: Gain17, Gain18, and Gain19. Derivative5 and Integrator6 represent the differentiation and integration stages in PID controllers, respectively. Transfer Fcn8 represents the TFU, representing the dynamic behavior model of the system. Transport Delay9 represents transmission delay, used to simulate the time-delay present in the system. Product6 represents the product part, which is mainly achieved by multiplying with the input signal to achieve the proportional part in PID control. Scope8 is used to observe and analyze the waveform output by the system (Kang *et al.* 2024).

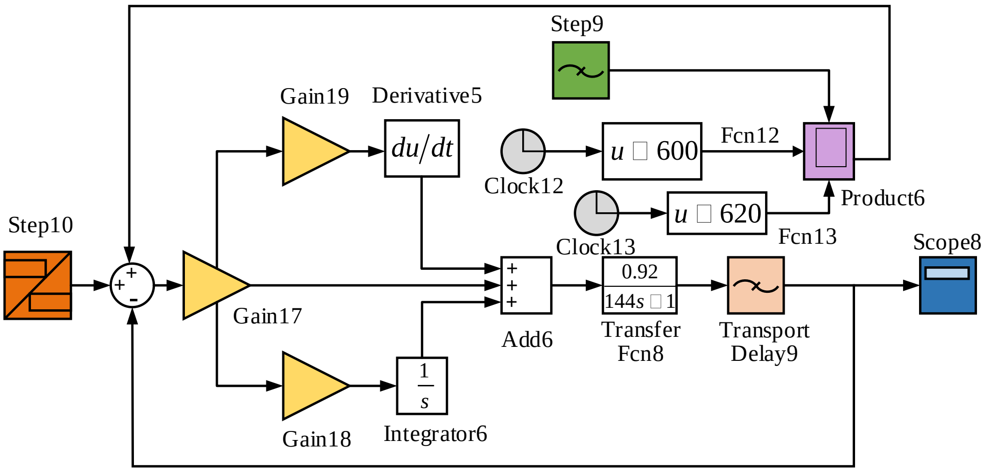


Fig 4 Simulation structure of standard PID under perturbation

The operating temperature of the FO and second-order TCM is set to a common indoor temperature of 25 ℃ and a relative humidity of 45%. Smith predictive compensator and PID controller are combined for control. Smith-PID is used to simultaneously add a 20-second external step disturbance signal during system stability for simulation. When the controlled object is an FO system model, the expression of its optimized TFU is further obtained as shown in equation (7) (Kim *et al.* 2022).

$$G_p(s)=\frac{K_1}{1+TS} \quad (7)$$

In equation (7), K_1 represents the FO control parameter. A proportional integral controller is required to simplify its TFU to second-order standard form, and its TFU is shown in equation (8).

$$G_p(s)=K_p+\frac{K_i}{s} \quad (8)$$

In equation (8), $\frac{1}{s}$ represents the integration operation in Laplace transform. The TFU of the CLS in its second-order form can be further obtained from equation (8), as shown in equation (9).

$$\square(s)=\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \quad (9)$$

The characteristic equation of the controlled object as an FO system can be obtained from equation (9), as shown in equation (10).

$$D(s)=s^2+\left(\frac{K_1K_p+1}{T}\right)S+\frac{K_1K_i}{T} \quad (10)$$

Smith is combined to tune the PID parameters in FO and second-order control systems and establish corresponding control models (Wu *et al.* 2020). Meanwhile, the FDA method is used to optimize the model. Firstly, the estimated controller and the controlled object are generalized equivalent. The final structure is optimized based on Figure 1 to obtain the generalized equivalent diagram of Smith-PID's estimated control, as shown in Figure 5.

The dashed part in Figure 5 represents the generalized equivalent object, which is generalized equivalent to the controlled object $G_p(s)$ without time-delay. It is further regarded as an FO and second-order system without time-delay, and Smith-PID control is adopted for it. Second-order systems are prone to situations where the damping is not sufficient to prevent vibration from crossing the equilibrium position due to insufficient damping. Therefore, the characteristic equation of the CLS under this condition will have special conjugate complex roots. Using the FDA method to analyze the TFU of its second-order system, its representation is shown in equation (11).

$$G_{xin}(s)=G_p(s)e^{-\tau s}+G_p(s)(1-e^{-\tau s})=G_p(s) \quad (11)$$

In equation (11), $G_{xin}(s)$ represents the expression of the second-order system TFU under the FDA method. When the controlled object becomes a second-order system model, the TFU is shown in equation (12).

$$G_p(s)=K_p+K_is \quad (12)$$

When the selected building AC temperature control model exhibits second-order time-delay phenomenon, the second-order time-delay mathematical model can be obtained from equations (11) to (12) as shown in equation (13).

$$G_2(s)=\frac{10}{1+61s+60_s^2}e^{-30s} \quad (13)$$

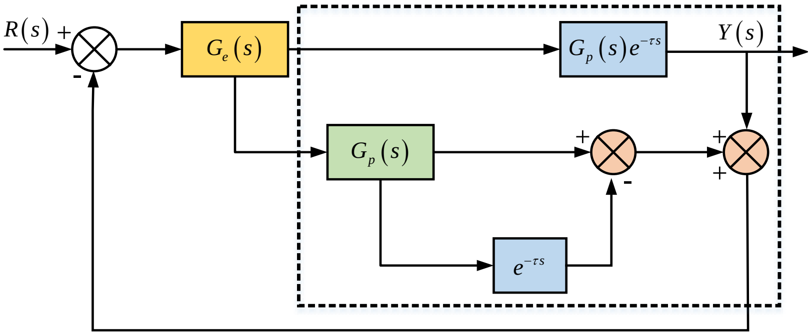


Fig 5 Generalized equivalence diagram for anticipatory control

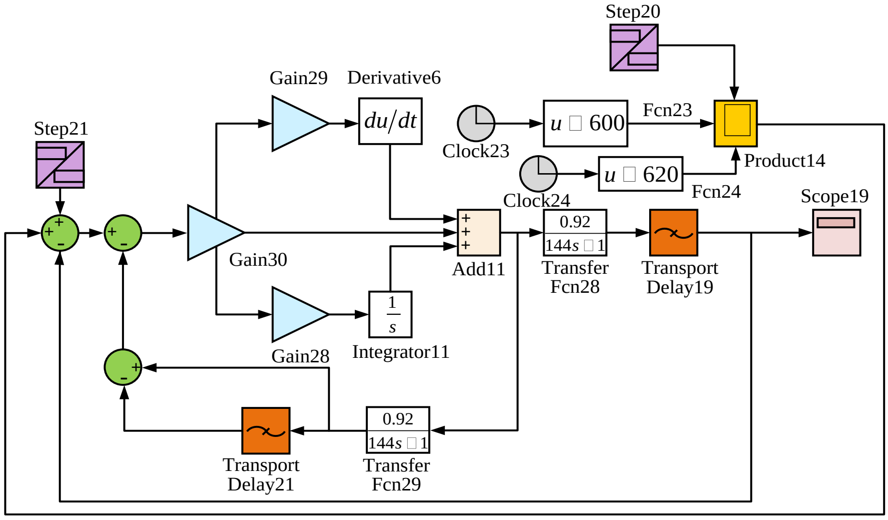


Fig 6 Simulation structure of Smith-PID under predictive compensation for perturbation

In equation (13), $G_2(s)$ represents the second-order TCM. On the ground of the FO and second-order time-delay models, the disturbance simulation structure of the final generalized equivalent Smith-PID control under estimated compensation is shown in Figure 6. Figure 6 shows a Simulink model of a PID control system combined with a Smith predictor controller. The model in Figure 6 includes an additional component, namely the Smith predictive controller compared to the standard PID control system model in Figure 4. Through in-depth analysis of Figure 6, the response speed of the system to external disturbances will be improved after the introduction of Smith predictive controller, while the overshoot will be significantly reduced. This is mainly due to the superior performance of the Smith predictive controller. This effectively reduces the negative impact of latency on system performance by predicting the impact of latency and adjusting the output of the PID controller accordingly. Specifically, the Smith predictive controller can reflect the future behavior of the system in advance of the control action, so that the controller can adjust its output more sensitive and timelier to adapt to changes in the actual process. Therefore, Figure 6 not only proves the feasibility of Smith-PID control strategy in theory, but also shows its important contribution to improving the anti-interference ability and control accuracy of the system in practice.

4. Experimental results of Smith-PID controller

Simulation tests were conducted on the Matlab platform to show the effectiveness of the control scheme. The standard PID control and Fuzzy-PID control (Fuzzy-PID) were chosen as the comparison methods. First, the control effects of different control schemes in FO and second-order problems were tested. Then the advantages of Smith-PID control were further verified in different seasons combined with practical problems.

4.1 Simulation test results of FO and second-order time-delay automation control model

First, the control performance of three different control schemes was tested in an FO and second-order TCM. Simulations were conducted in the same equipment environment to eliminate experimental equipment errors. The experimental environment configuration for this study is shown in Table 1. Table 1 shows the computer configuration for this simulation experiment. Firstly, the tuning effects of three different PID control methods were compared. Meanwhile, the PID tuning response curves of different control methods under temperature and humidity disturbance conditions were obtained as shown in Figure 7.

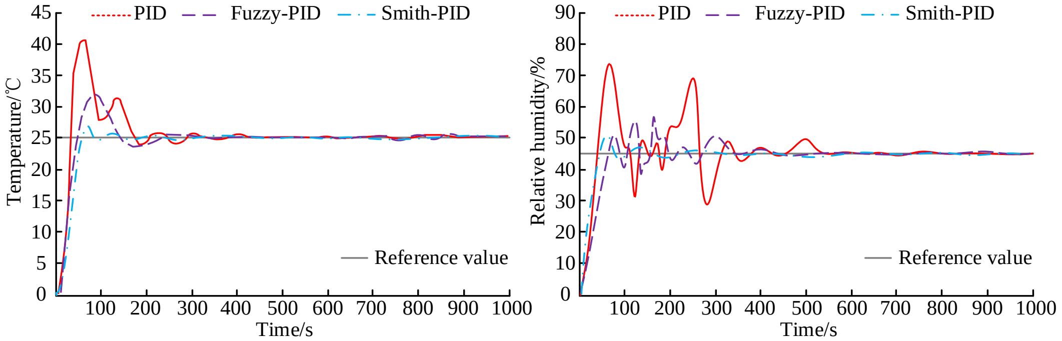
Table 1
Configuration of the experimental environment

Components	Norm
Processor	Intel Core i7-9700K
Memory	16 GB DDR4
Hard drive	512 GB SSD
Graphics card	NVIDIA GeForce GTX 1660
Operating system	Windows 10 Professional
Simulation software	MATLAB R2021a
Simulation tools	Simulink

Figures 7 (a) and 7 (b) show the tuning response curves of PID, Fuzzy-PID, and Smith-PID under temperature and humidity disturbances, respectively. From Figure 7, Smith-PID control strategy was faster than PID and Fuzzy-PID when it reached steady state, which indicated that Smith-PID had faster response speed and higher efficiency. Specifically, Smith-PID was 116 seconds faster than Fuzzy-PID and 259 seconds faster than traditional PID to reach a stable state in the temperature control. In the humidity control, shorter setting times were also shown. This result highlighted the superior performance of Smith predictive controller when dealing with time-lag effects.

Figure 8 shows the effect of three control methods on external temperature and humidity disturbances under an FO time-delay model. For the temperature control, Smith-PID took only 8 seconds to return to the preset 25 °C compared to 15 seconds for Fuzzy-PID and 19 seconds for conventional PID. The results for humidity control were similar, showing that Smith-PID was far more resistant to external disturbances than the other two methods. This ability to react quickly was critical to ensuring the comfort and stability of the indoor environment.

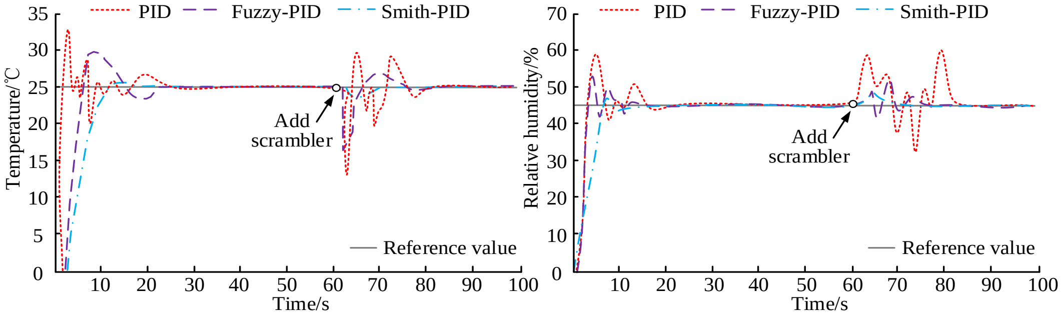
In Figure 9 (a), when a temperature disturbance was applied to the second-order time-delay system from the outside at 60 seconds, the PID, Fuzzy-PID, and Smith-PID control methods fluctuated for 15 seconds, 12 seconds, and 4 seconds, respectively, before the temperature control was restored to stability and reaches the preset 25 ℃. In Figure 9 (b), when a humidity disturbance was utilized for the second-order time-delay system from the outside at 60 seconds, the PID, Fuzzy-PID, and Smith-PID fluctuated for 19 seconds, 18 seconds, and



(a) Integration response curves of different PID control methods under temperature perturbation

(b) Integration response curves of different PID control methods under humidity perturbation

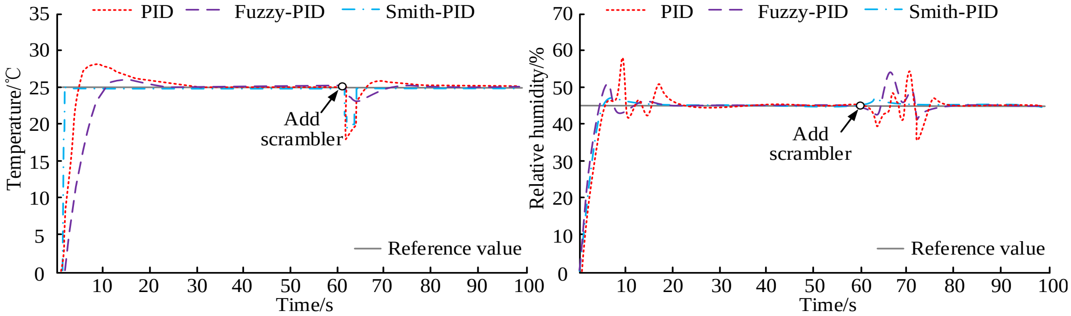
Fig 7 Integration response curves of the three PID control methods under different perturbation conditions



(a) Step response results of different PID controls under temperature perturbation with first order time lag

(b) Step response results of different PID controls under humidity perturbation with first order time lag

Fig 8 Step response results of different controls under FO time lag



(a) Step response results of different PID controls under temperature perturbation with second order time lag

(b) Step response results of different PID controls under humidity perturbation with second order time lag

Fig 9 Step response results for different controls with second-order time lag

3 seconds, respectively to restore stable relative humidity. In Figure 9, the Smith-PID control method still significantly reduced the adjustment time in the face of more complex system dynamics. In particular, in humidity control, Smith-PID's adjustment time of 3 seconds was much faster than Fuzzy-PID's 18 seconds and PID's 19 seconds. This demonstrated its potential advantages in improving system damping and reducing overshoot, which was particularly important in applications where precise control of complex systems was required.

Table 2 presents the parameter comparison of three control methods under FO and second-order time-delays. According to

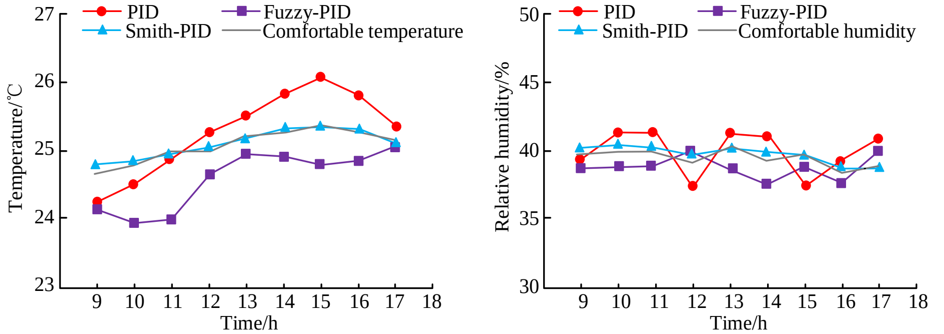
Table 2
Parameter variations of the three PID controls with first and second-order time lags

Delay phase	Comparison parameters	Smith-PID	Fuzzy-PID	PID
FO time delay	Over-adjustment amount	0.01	0.12	0.26
	Temperature adjustment time/s	16	23	31
	Humidity adjustment time/s	14	18	26
Second-order time delay	Over-adjustment	0.18	0.24	0.35
	Temperature adjustment time/s	3	24	29
	Humidity adjustment time/s	13	19	22

Table 2, the overshoot, temperature adjustment time, and humidity adjustment time of Smith-PID were 0.01, 16s, and 14s, respectively, under the FO time-delay. The overshoot, temperature adjustment time, and humidity adjustment time of Fuzzy-PID were 0.12, 23s, and 18s, respectively. The overshoot, temperature adjustment time, and humidity adjustment time of PID were 0.26, 31s, and 26s, respectively. The temperature regulation time, and humidity regulation time of Smith-PID were 0.18, 3, and 13 seconds, respectively, under second-order time-delay, the overshoot. The overshoot, temperature regulation time and humidity regulation time of Fuzzy-PID were 0.24, 24, and 19 seconds, respectively. The overshoot, temperature regulation time, and humidity regulation time of PID were 0.35, 29, and 22 seconds, respectively. In summary, the proposed control method had a smaller overshoot and a shorter system adjustment time when controlling temperature and humidity.

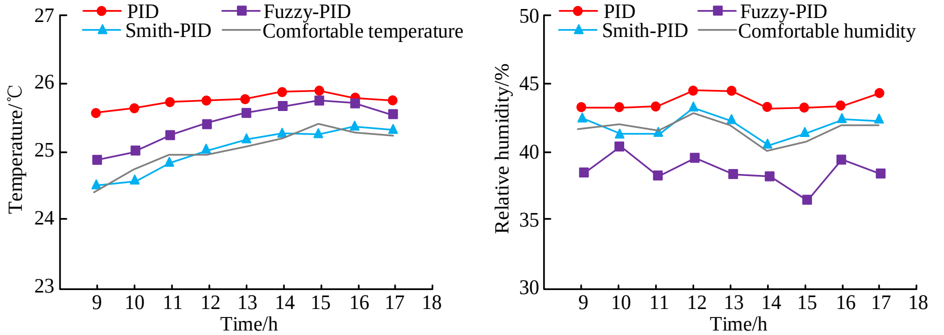
4.2 The application effect of Smith-PID control in actual AC systems

This study selected the AC system of a certain office building as the test object to demonstrate the advantages of Smith-PID controller in automatic temperature and humidity control in actual building AC systems. Then days from four



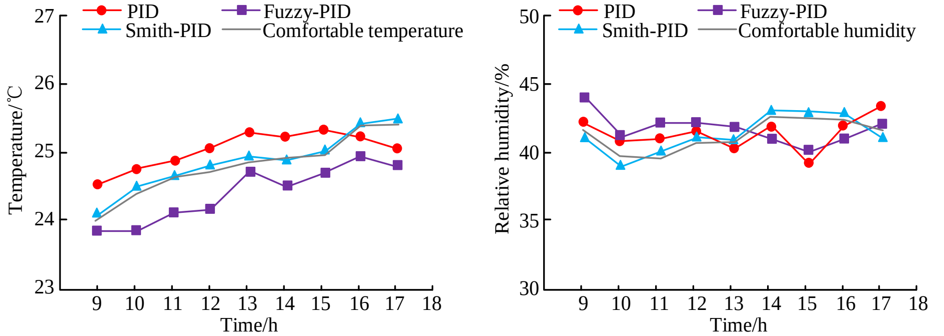
(a) Effectiveness of different methods in automatic spring temperature control

(b) Effectiveness of different methods in automatic spring humidity control



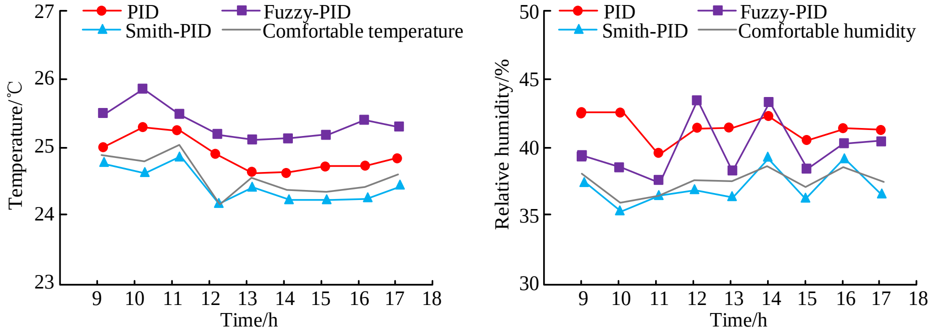
(c) Effectiveness of different methods in automatic summer temperature control

(d) Effectiveness of different methods in automatic summer humidity control



(e) Effectiveness of different methods in automatic fall temperature control

(f) Effectiveness of different methods in automatic fall humidity control



(g) Effectiveness of different methods in automatic winter temperature control

(h) Effectiveness of different methods in automatic winter humidity control

Fig 10 Temperature and humidity control effect of different control systems in different seasons

Table 3
Fluctuation values of control accuracy of different control schemes

Season	Fluctuation of accuracy	Smith-PID	Fuzzy-PID	PID
Spring	Temperature control accuracy (±°C)	0.02	0.12	0.25
	Humidity control accuracy (±%)	0.11	0.36	0.53
Summer	Temperature control accuracy (±°C)	0.03	0.09	0.21
	Humidity control accuracy (±%)	0.08	0.31	0.57
Autumn	Temperature control accuracy (±°C)	0.01	0.07	0.18
	Humidity control accuracy (±%)	0.06	0.42	0.54
Winter	Temperature control accuracy (±°C)	0.02	0.10	0.26
	Humidity control accuracy (±%)	0.13	0.45	0.61

seasons: spring, summer, autumn, and winter were selected for testing. This study recorded the optimal perceived temperature and humidity of the AC system from 9am to 5pm for four days. Then the automatic control effects of PID, Fuzzy-PID, and Smith-PID control schemes in the AC system were compared, as shown in Figure 10.

Figures 10 (a) and 10 (b) show the effects of three control schemes on spring temperature and humidity control, respectively. From Figure s 10 (a) and 10 (b), the highest temperature of three control methods of PID temperature control: Smith-PID, Fuzzy-PID, and PID in the spring was 25.6 ℃, 25.1 ℃, and 26.2 ℃, respectively. The highest humidity value of the humidity control in spring was 40.2%, 41.1%, and 42.1%, respectively. Figures 10 (c) and 10 (d) show the effects of three control schemes on summer temperature and humidity control, respectively. In Figure s 10 (c) and 10 (d), the highest temperature of three control methods of PID temperature control: Smith-PID, Fuzzy-PID, and PID in summer was 25.3 ℃, 25.6 ℃, and 25.8 ℃. The high humidity value of the humidity control in summer was 43.2%, 41.3%, and 44.9%, respectively. Figures 10 (e) and 10 (f) show the effects of three control schemes on autumn temperature and humidity control, respectively. In Figures 10 (e) and 10 (f), the maximum temperature of Smith-PID, Fuzzy-PID, and PID control methods in autumn temperature control was 25.5℃, 24.8℃, and 25.3℃, respectively. Meanwhile, the maximum humidity value in autumn humidity control was 43.4%, 44.8%, and 43.8%, respectively. Figures 10 (g) and 10 (h) show the effects of three control schemes on temperature and humidity control in winter, respectively. From Figures 10 (g) and 10 (h), the highest temperature of three control methods of PID temperature control: Smith-PID, Fuzzy-PID, and PID in winter was 24.8 ℃, 25.8 ℃, and 25.3 ℃. The highest humidity value of the humidity control in winter was 38.1%, 44.2% and 43.0% respectively. In Figure 10, during the four seasons, the temperature and humidity values controlled by the Smith-PID controller were closest to the optimal perceived temperature and humidity between 9:00 and 17:00 every day. The control effects of the three control schemes were Smith-PID>Fuzzy-PID>PID.

To further analyze the advantages of the Smith-PID control scheme, a further comprehensive observation of the data in Figure 10 showed that whether it is spring, summer, fall, or winter, the Smith-PID control scheme could adjust the AC system in a short time to achieve the optimal perceived temperature and humidity, and the fluctuation is minimal. This phenomenon shows that Smith-PID control scheme can effectively adapt to the fluctuation of indoor and outdoor temperature and humidity in the environment of different seasons, and ensure the comfort of indoor environment. In addition, the Smith-PID controller not only had a fast response speed through the in-depth analysis of the four seasons data, but also achieved more accurate temperature and humidity control while ensuring energy efficiency, which was of great significance for improving the energy-saving performance of the AC system.

Table 3 shows the fluctuation values of control accuracy under different control schemes. From Table 3, when the AC system ran in spring, the fluctuation values of temperature control accuracy of Smith-PID, Fuzzy-PID and PID control schemes were 0.02℃, 0.12℃ and 0.25℃, respectively, and the fluctuation values of humidity control accuracy of the three schemes were 0.11%, 0.36%, and 0.53%, respectively. In summer, the accuracy fluctuation value of Smith-PID, Fuzzy-PID, and PID temperature control was 0.03℃, 0.09℃, and 0.21℃, respectively. The humidity control accuracy fluctuation value was 0.08%, 0.31%, and 0.57%. In autumn, the accuracy fluctuation value of Smith-PID, Fuzzy-PID, PID temperature control was 0.01℃, 0.07℃, and 0.18℃, respectively. The humidity control accuracy fluctuation value was 0.06%, 0.42%, and 0.54%. In winter, the accuracy fluctuation value of Smith-PID, Fuzzy-PID, PID temperature control was 0.02℃, 0.10℃, and 0.26℃, respectively. The humidity control accuracy fluctuation values were 0.13%, 0.45%, and 0.61%. In summary, the Smith-PID control scheme had the smallest precision fluctuation value, which showed that the control result under this control scheme was closer to the actual value.

Figure 11 shows the satisfaction evaluation of experts on the control effect of constant temperature and humidity of an AC system under different control strategies. The results showed that the Smith-PID control method achieved the highest satisfaction scores on all indicators, which reflected its superior performance and user acceptance in practical applications. Specifically, Smith-PID showed significant advantages in control accuracy, response speed and system stability compared with traditional PID and Fuzzy-PID controls. To further analyze these results, the study compared the performance of Smith-PID to other advanced control techniques reported in recent literature. Furizal *et al.* (2024) showed that although control strategies using machine learning technology provided good control effects, they were generally inferior to model-based predictive control methods in terms of real-time performance and computational complexity (Shang F *et al.* 2022). At the same time, Smith-PID provided an efficient and low-cost solution due to its structural simplification and optimization of the prediction mechanism, especially its high efficiency and accuracy when dealing with systems with complex time-delay. This was verified by several independent studies as the key to improving system performance (Zaki O M *et al.* 2024).

To sum up, from the satisfaction survey of experts that Smith-PID control strategy has significant advantages in improving the performance of AC systems. Combined with

(a) Satisfaction of PID control system (b) Satisfaction of Fuzzy-PID control system

(c) Satisfaction of Smith-PID control system

Fig 11 Expert satisfaction with different control systems

other research results and practical application feedback results, the combination of Smith predictive control and PID can effectively improve the overall efficiency and user satisfaction of the AC system.

5 Discussion

This paper presents a control strategy based on FDA and Smith-PID through the in-depth analysis and research of building air-conditioning system constant temperature and humidity automatic control. First of all, Figure 7 shows the tuning response curves of PID, Fuzzy-PID and Smith-PID under temperature and humidity disturbance. Smith-PID control scheme can achieve stable temperature tuning response curves and humidity tuning response curves, respectively, after 153s and 264s, which takes a shorter time. Second, Smith-PID only needs 8s and 6s to restore a stable temperature and stable relative humidity to the AC system when disturbed from the outside. The realization of parameters of Smith-PID is also better than PID and Fuzzy-PID under the first and second-order delay. Figure 10 clearly demonstrates the advantages of Smith-PID controller compared with traditional PID and Fuzzy-PID control schemes in maintaining the optimal indoor temperature and humidity in spring, summer, autumn, and winter. This result not only demonstrates the efficiency of the Smith-PID control scheme in dealing with time-delay and nonlinear problems, but also highlights its potential to ensure user comfort and energy savings. However, although the method proposed in this study demonstrates superiority in many aspects, there are still some limitations and challenges. First of all, the design and implementation of Smith-PID control strategy is complex, requiring accurate modeling, and in-depth understanding of the system. Secondly, the effect of the control strategy largely depends on the accurate prediction and adjustment of the system parameters, which may encounter difficulties in practical application. In addition, this study mainly focuses on a single building AC system, and fails to consider the mutual interference and optimization problems that may occur when multiple systems work together. This study pays more attention to the development of control strategies rather than single performance evaluation compared with other studies, such as the evaluation of the AC performance under constant outdoor humidity and variable dry bulb temperature described in reference (Setyawan *et al.* 2022). Although the intelligent AC control system based on the Internet of Things in reference (Zhang 2022) improved energy efficiency and comfort, this study achieved faster response time and higher system stability by integrating Smith-PID controller. Although the adaptive backstepping controller proposed in reference (Furizal *et al.* 2024) had advantages in ensuring the global exponential stability of the system state, the Smith-PID control scheme might be easier to implement and adjust in practical applications.

To sum up, this research successfully develops a new type of building AC system constant temperature and humidity automatic control method, and its effectiveness is verified through experiments. Despite some limitations, these findings provide valuable insights and references for further improving and optimizing building AC systems. Future research can overcome these limitations by expanding the application scope of control strategies, simplifying implementation processes, and enhancing system robustness to further improve the performance and user satisfaction of air-conditioning systems.

6. Conclusion

This study proposed a constant temperature and humidity control method for building AC systems on the ground of FDA and Smith-PID to solve the automatic control of constant temperature and humidity in building AC systems. The experiment showed that compared to Fuzzy-PID and PID, the Smith-PID designed in this study had a more stable tuning response curve under temperature and humidity disturbances, reaching a stable state after 153 seconds and 264 seconds, respectively. When temperature and humidity disturbances were applied to the FO TCM at 60 seconds, Smith-PID only needed 8 seconds and 6 seconds to recover the preset temperature and relative humidity under the FO time-delay. Similarly, Smith-PID only took 4 seconds and 3 seconds to recover the preset temperature and relative humidity under second-order time-delay, which took much less time than Fuzzy-PID and PID. In addition, the overshoot, temperature regulation time, and humidity regulation time of Smith-PID under FO time-delay were 0.01, 16s, and 14s, respectively. The overshoot, temperature regulation time, and humidity regulation time under second-order time-delay were 0.18, 3 seconds, and 13 seconds, respectively. All indicators were better than the other two control schemes. In practical application analysis, Smith-PID performed better than Fuzzy-

PID and PID in constant temperature and humidity control during the four seasons. The control effect of Smith-PID was closer to the optimal sensory temperature and humidity, achieving the highest expert satisfaction. In summary, the proposed control scheme had good performance and practical application effects.

Although this study has achieved remarkable results in the automatic control of constant temperature and humidity in building air-conditioning system, there are still some limitations. First of all, when designing Smith-PID control strategy, this study is based on some idealized assumptions, such as the accuracy of system model and the stability of environmental factors. Building AC systems may be affected by a variety of unpredictable factors in practical applications, which may affect the effectiveness of control strategies. Second, the performance of the Smith-PID controller depends heavily on the precise adjustment of the parameters. Finding the optimal parameter configuration can require complex calculations and real-time adjustments in a dynamically changing environment, which increases the difficulty of practical applications. In response to the above challenges, future research can focus on optimizing system models and increasing their adaptability to better cope with uncertainties and dynamic changes in the real environment. More precise and adaptive control strategies can be achieved by introducing more sophisticated machine learning and artificial intelligence algorithms. In addition, an intelligent parameter adjustment mechanism can be developed to monitor system performance and environmental changes in real time and automatically adjust control parameters, which will greatly improve system stability and reduce manual intervention.

References

Al-Manthria, I., Al-Ismailia, A. M., Kotagamab, H., Khanc, M., & Jeewanthad, L. J. (2021). Water, land, and energy use efficiencies and financial evaluation of air conditioner cooled greenhouses based on field experiments. *Journal of Arid Land,* 13(4), 375-387. https://doi.org/10.1007/s40333-021-0060-y

Bushnag, A. (2023). An improved air quality and climate control monitoring system using fuzzy logic for enclosed areas. *Journal of Ambient Intelligence and Humanized Computing,* 14(5), 6339-6347. https://doi.org/10.1007/s12652-022-03814-z

Bandewad, G., Datta, K. P., Gawali, B. W., & Pawar, S. N. (2023). Review on discrimination of hazardous gases by smart sensing technology. *Artificial Intelligence and Applications,* 1(2), 86-97. https://doi.org/10.47852/bonviewAIA3202434

Chen, Y., Zhang, B., Qiu, D., & Xie, F. (2023). A unified frequency domain model of analog and digital PWM DC-DC converter considering PWM delay. *IEEE Transactions on Power Electronics,* 38(12), 15390-15405. https://doi.org/10.1109/TPEL.2023.3312694

Deniz, F. N. (2022). An effective Smith predictor based fractional-order PID controller design methodology for preservation of design optimality and robust control performance in practice. *International Journal of Systems Science,* 53(14), 2948-2966. https://doi.org/10.1080/00207721.2022.2067366

Furizal, F., Sunardi, S., Yudhana, A., & Umar, R. (2024). Energy efficiency with Internet of Things based fuzzy inference system for room temperature and humidity regulation. *International Journal of Engineering,* 37(1), 187-200. https://doi.org/10.5829/IJE.2024.37.01A.17

Gallardo, J. M., Bellone, G., Acevedo, R., & Risk, M. (2021). Ultra-short-term heart rate variability analysis: Comparison between Poincare and frequency domain methods. *IEEE Latin America Transactions,* 20(1), 180-188. https://doi.org/10.1109/TLA.2022.9662187

Hussain, T. (2023). Optimization and comparative performance analysis of conventional and desiccant air conditioning systems regenerated by two different modes for hot and humid climates: Experimental investigation. *Energy and Built Environment,* 4(3), 281-296. https://doi.org/10.1016/j.enbenv.2022.01.003

Hao, J., Dai, X., Yang, L., Liao, R., Gao, J., Du, Y., & Deng, Y. (2021). Physical mechanism analysis of conductivity and relaxation polarization behavior of oil-paper insulation based on broadband frequency domain spectroscopy. *IEEE Transactions on Dielectrics and Electrical Insulation,* 28(5), 1571-1578. https://doi.org/10.1109/TDEI.2021.009618

Hou, C., Liu, G., Tian, Q., Zhou, Z., Hua, L., & Lin, Y. (2022). Multisignal modulation classification using sliding window detection and complex convolutional network in frequency domain. *IEEE Internet of Things Journal,* 9(19), 19438-19449. https://doi.org/10.1109/JIOT.2022.3167107

Hermawan, S., Rahmawati, S., Aditia, Q., Wibowo, B., & Yuswanto, A. (2023). Designing a water temperature control and monitoring system for Vaname shrimp cultivation based on the Internet of Things (IoT). *Komets: Jurnal Komputer dan Elektro Sains,* 1(1), 14-17. https://doi.org/10.58291/komets.v1i1.96

He, X., & Shen, D. (2023). Distributed iterative learning temperature control for large-scale buildings. *International Journal of Robust and Nonlinear Control,* 33(7), 4210-4227. https://doi.org/10.1002/rnc.6259

Jiang, T., Ju, P., Wang, C., & Liu, J. (2020). Coordinated control of air-conditioning loads for system frequency regulation. *IEEE Transactions on Smart Grid,* 12(1), 548-560. https://doi.org/10.1109/TSG.2020.3022010

Kang, G. H., Kim, K. S., Chang, C. Y., & Kim, C. S. (2024). Reliability evaluation of air dryer control printed circuit board for electric multiple unit by accelerated life test. *Journal of Electrical Engineering & Technology,* 19(1), 821-830. https://doi.org/10.1007/s42835-023-01447-6

Kim, D. E., Li, A., Dau, M. N., Kim, H. H., & Chung, W. Y. (2022). Deep learning-based smith predictor design for a remote grasping control system. *Journal of Mechanical Science and Technology,* 36(5), 2533-2545. https://doi.org/10.1007/s12206-022-0435-9

Korupu, V. L., & Muthukumarasamy, M. (2022). A comparative study of various Smith predictor configurations for industrial delay processes. *Chemical Product and Process Modeling,* 17(6), 701-732. https://doi.org/10.1515/cppm-2021-0026

Laifa, S., Boudjehem, B., & Gasmi, H. (2022). Direct synthesis approach to design fractional PID controller for SISO and MIMO systems based on Smith predictor structure applied for time-delay non integer-order models. *International Journal of Dynamics and Control,* 10(3), 760-770. https://doi.org/10.1007/s40435-021-00831-2

Lu, Z., & Jiao, Y. (2022). Efficiently all-digital code tracking for band-limited DSSS systems. *IEEE Communications Letters,* 27(2), 686-690. https://doi.org/10.1109/LCOMM.2022.3222296

Liu, H., Xie, H., Luo, H., Qi, J., Goh, H. H., & Rahman, S. (2021). Optimal strategy for participation of commercial HVAC systems in frequency regulation. *IEEE Internet of Things Journal,* 8(23), 17100-17110. https://doi.org/10.1109/JIOT.2021.3076434

Morelli, E. A., & Grauer, J. A. (2020). Practical aspects of frequency-domain approaches for aircraft system identification. *Journal of Aircraft,* 57(2), 268-291. https://doi.org/10.2514/1.C035599

Nagarsheth, S. H., & Sharma, S. N. (2020). The combined effect of fractional filter and Smith Predictor for enhanced closed-loop performance of integer order time-delay systems: Some investigations. *Archives of Control Sciences,* 30(1), 47-76. https://doi.org/10.24425/acs.2020.132585

Perez, R. R., Batlle, V. F., & Hernandez, J. S. (2021). State feedback temperature control based on a Smith predictor in a precalciner of a cement kiln. *IEEE Latin America Transactions,* 19(1), 138-146. https://doi.org/10.1109/TLA.2021.9423857

Qiao, S., Yang, Q., Wu, J., Zhan, X., & Yan, H. (2023). An approach for the stability of communication constrained networked time-delay control systems. *International Journal of Control, Automation and Systems,* 21(4), 1062-1069. https://doi.org/10.1007/s12555-021-0737-1

Rajeshwaran, S., Kumar, C., & Ganapathy, K. (2023). Hybrid optimization based PID controller design for unstable system. *Intelligent Automation & Soft Computing,* 35(2), 1611-1625. https://doi.org/10.32604/iasc.2023.029299

Rumalutur, S., & Mappa, A. (2019). Temperature and humidity moisture monitoring system with Arduino R3 and DHT 11. *Electro Luceat,* 5(2), 40-47. https://doi.org/10.32531/jelekn.v5i2.154

Shang, F., Ji, Y., & Peng, W. (2022). Adaptive backstepping controller design for the air handling units of the HVAC system. *Numerical Heat Transfer, Part A: Applications,* 83(10), 1095-1110. https://doi.org/10.1080/10407782.2022.2102374

Sah, S. K., Murugesan, K., & Elangovan, R. (2021). Optimization of energy consumption for indoor climate control using Taguchi technique and utility concept. *Science and Technology for the Built Environment,* 27(10), 1473-1491. https://doi.org/10.1080/23744731.2021.1924856

Setyawan, A., Najmudin, H., Badarudin, A., & Sunardi, C. (2022). Evaluation of split-type air conditioner performance under constant outdoor moisture content and varied dry-bulb temperature. *International Journal of Heat & Technology,* 40(5), 1277-1286. https://doi.org/10.18280/ijht.400521

Shruti, P., Praveen, Y. G., Vipin, C. P., & Babu, B. C. (2021). Analytical tuning of 2-DOF smith predictor control scheme for DC-DC boost converter: A process control perspective. *International Journal of Circuit Theory and Applications,* 49(3), 641-655. https://doi.org/10.1002/cta.2966

Waworundeng, J., & Limbong, W. H. (2020). AirQMon: Indoor air quality monitoring system based on microcontroller, android, and IoT. *Cogito Smart Journal,* 6(2), 251-261. https://doi.org/10.31154/cogito.v6i2.213.251-261

Wibawa, I. M. S., & Putra, I. K. (2022). Design of air temperature and humidity measurement based on Arduino ATmega 328P with DHT22 sensor. *International Journal of Physical Sciences and Engineering,* 6(1), 9-17. https://doi.org/10.53730/ijpse.v6n1.3065

Wu, H., & Wong, J. W. C. (2020). Current challenges for shaping the sustainable and mold-free hygienic indoor environment in humid regions. *Letters in Applied Microbiology,* 70(6), 396-406. https://doi.org/10.1111/lam.13291

Wu, Y., Zhang, S., Liu, H., & Cheng, Y. (2023). Thermal sensation and percentage of dissatisfied in thermal environments with positive and negative vertical air temperature differences. *Energy and Built Environment,* 4(6), 629-638. https://doi.org/10.1016/j.enbenv.2022.06.002

Zhang, B. (2022). Research on intelligent control system of air conditioning based on Internet of Things. *International Journal of Advanced Computer Science and Applications,* 13(9), 803-814. https://doi.org/10.14569/IJACSA.2022.0130994

Zaki, O. M., El-Morsi, M., & Abdelaziz, O. (2024). Unlocking energy savings and emissions reduction: A comparative study of fixed-speed and variable-speed room air conditioners in high ambient temperature environments. *Science and Technology for the Built Environment,* 30(2), 153-171. https://doi.org/10.1080/23744731.2023.2291006

Zhang, D., Li, C., Luo, S., Luo, D., Shahidehpour, M., Chen, C., & Zzhou, B. (2022). Multi-objective control of residential HVAC loads for balancing the User's comfort with the frequency regulation performance. *IEEE Transactions on Smart Grid,* 13(5), 3546-3557. https://doi.org/10.1109/TSG.2022.3171847

Zhang, J., Wang, F., Wen, G. (2023). Bipartite consensus for networked Euler–Lagrange systems with cooperative–competitive interactions and time delays. *IET Control Theory & Applications,* 17(9), 1214-1226. https://doi.org/10.1049/cth2.12451

Zhang, X., Kim, D., Bang, J., & Lee, J. (2021). Time delay compensation of a robotic arm based on multiple sensors for indirect teaching. *International Journal of Precision Engineering and Manufacturing,* 22(11), 1841-1851. https://doi.org/10.1007/s12541-021-00542-w

Zhang, Y., Yan, T., Xu, X., Gao, J., & Huang, G. (2023). Room temperature and humidity decoupling control of common variable air volume air-conditioning system based on bilinear characteristics. *Energy and Built Environment,* 4(3), 354-367. https://doi.org/10.1016/j.enbenv.2022.02.005

Zheng, M., Zhang, G., & Huang, T. (2021). Tuning of fractional complex-order direct current motor controller using frequency domain analysis. *Mathematical Methods in the Applied Sciences,* 44(4), 3167-3181. https://doi.org/10.1002/mma.6653