

Article

Design and Simulation of a Multi-Channel Biomass Hot Air Furnace with an Intelligent Temperature Control System

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Abstract: Timely and effective drying of agricultural products is crucial for ensuring the quality and yield of grains. Biomass drying enhances energy utilization and reduces energy pressure. To this end, a novel multi-channel circulating biomass hot air furnace was designed to provide precise control of the heat source for grain drying, thereby improving the efficiency and quality of the drying process. The combustion process utilizes a multi-channel combined air supply to ensure complete combustion of biomass pellet fuel. During the heat exchange process, heat exchange plates isolate hot and cold areas, discharging combustion exhaust, while ensuring a pure air output. Using rapeseed as the drying subject, a temperature controller based on adaptive fuzzy PID was designed, targeting the biomass hot air furnace's heat exchange system for modeling and verifying the model with the step response method. Model simulations were conducted in Matlab's Simulink module using both adaptive fuzzy PID and traditional PID controllers, for a given signal. The settling times for the conventional PID and fuzzy PID were 445 s and 364 s, respectively, with overshoots of 20.1% and 6.3%, showing that the fuzzy PID controller performed better in terms of control performance. The validation tests showed that both control methods could maintain the temperature within ± 5 °C. Compared to traditional PID control, the adaptive fuzzy PID control achieved a precision of ± 3 °C. At the target temperature of 90 °C, the error was reduced to 3.7%, with a stabilization time of 1014 s. The use of fuzzy PID control exhibited better dynamic response characteristics, meeting the drying needs of rapeseed. This study provides a theoretical basis for the structural design and control system design of biomass hot air furnaces.

Keywords: biomass hot air furnace; adaptive fuzzy PID; temperature control; simulink simulation



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1. Introduction

In the context of “carbon peaking and carbon neutrality”, biomass pellet fuel as a drying heat source holds great potential for development [1–3]. Drying agricultural products is a crucial step in agricultural production and an important component of the entire mechanization process of grain production [4]. Conventional hot air drying uses coal as the heat source, but biomass fuel, as an important sustainable energy source [5], offers a viable alternative. Using biomass combustion to exchange heat for drying agricultural products is easy to operate and cost-effective. However, the temperature control process in these systems involves a large capacity, significant time delays, and non-linearity [6], making it challenging for traditional PID control systems with a single set of PID parameters to meet the requirements of dynamic adjustment and steady-state output during the drying process.

Jun Huang designed a small-scale domestic biomass pellet burner, conducting a thorough analysis of its structure and combustion characteristics. Using the fluent module in CFD 2024 software, the airflow and temperature fields post-combustion were simulated. The assembled prototype achieved a combustion efficiency of over 95%, with a fuel

utilization rate reaching 85%, meeting the requirements for efficient fuel use [7]. Lei Yu introduced structural and key combustion technologies for biomass molded fuel stoves, conducting combustion tests with corn straw molded fuel. By adjusting the ratio of secondary air volume, air intake position, and inflation angle, a comparative analysis of the combustion effect was carried out, resulting in satisfactory combustion performance [8]. Bin Liu and others [9] designed a fuzzy PID control algorithm for a rapeseed hot air drying control system based on a hot air furnace. The research conducted a detailed study on the combustion conditions of biomass burners, yet there is room for improvement in research on precise temperature control.

Research on hot air furnaces began early in Western countries. Joseph D. Smith utilized computer-aided engineering design, combining effective optimization algorithms with existing CFD models. Through performance simulation, he sought the optimal operating conditions for biomass combustion furnaces and proposed optimization and improvement plans, thereby systematically enhancing the comprehensive performance of the device [10]. Pereira Júnior, Modesto, and others designed a fuzzy multivariable controller for rotary dryers, applying it to fertilizer drying to achieve reliable temperature control. This controller also reduced biomass consumption by 9% [11]. Lukas Böhler and his team proposed a small-scale grate fuzzy model predictive controller based on a biomass combustion model, selecting several local linear controllers as operating points and using gap metrics. The local predictive controllers combined with membership functions formed a global nonlinear fuzzy control structure. Comparisons between the fuzzy model predictive controller, linear model predictive controller, and PI control algorithm in closed-loop simulations showed that the fuzzy model predictive controller performed better [12].

Currently, biomass combustion equipment still faces challenges such as the difficulty of stable combustion, high pollution emissions, and inadequate temperature control capabilities [13–15]. During the drying process, temperature control faces numerous challenges, including achieving higher precision and stability, balancing energy efficiency with effective control, system response delays, and the design of the drying equipment. By making biomass a more efficient and manageable source of energy, biomass can drying contribute to the integration of renewable energy sources into the energy mix. This can help to reduce reliance on fossil fuels, thereby reducing the overall energy pressure and contributing to energy security. Biomass drying can also contribute to waste management by converting agricultural, forestry, and urban waste into energy. This not only reduces the waste that would otherwise end up in landfills but also turns it into a valuable resource. Improving the structure and operating conditions of biomass hot air furnaces through simulation, optimizing combustion efficiency, and applying advanced control theories to the temperature control of drying processes, thereby enhancing industrial performance, may become trends in future research.

This article presents the designing of a multi-channel auxiliary combustion biomass hot air furnace, which uses a multi-channel combined air supply to ensure complete combustion of biomass pellets. A plate-type heat exchanger isolates high-temperature combustion gases and the air requiring heating, maintaining the purity of the air at the outlet. By considering factors such as the inlet environmental temperature, fuel input, and fan speed that affect outlet temperature, a mathematical model of the furnace's combustion and heat exchange system was constructed. With the goal of controlling the outlet temperature of the hot air furnace, an adaptive fuzzy PID-based temperature control system was designed. Taking the drying requirements of rapeseed as an example, experiments compared the performance of traditional PID controllers and adaptive fuzzy PID controllers in temperature control, thereby improving the quality of biomass hot air furnaces in grain drying.

2. Structure and Working Principle of the Biomass Hot Air Furnace

2.1. Structure of the Biomass Hot Air Furnace

As shown in Figure 1, the biomass hot air furnace is composed of a feed motor, hopper, furnace, heat exchange chamber, heat exchange plates, blower, induced draft fan, auxiliary combustion fan, and other components. The feed motor has a power of 250 W and uses

single-phase AC stepless speed control. The auxiliary combustion fan has a rated power of 100 W and a rated speed of 2800 r/min. The induced draft fan has a power of 250 W, a rated speed of 2800 r/min, and a rated air volume of 860 m³/h. The blower has a rated power of 250 W, a rated speed of 1450 r/min, and a rated air volume of 3200 m³/h. Both the induced draft fan and blower are controlled by frequency converters.

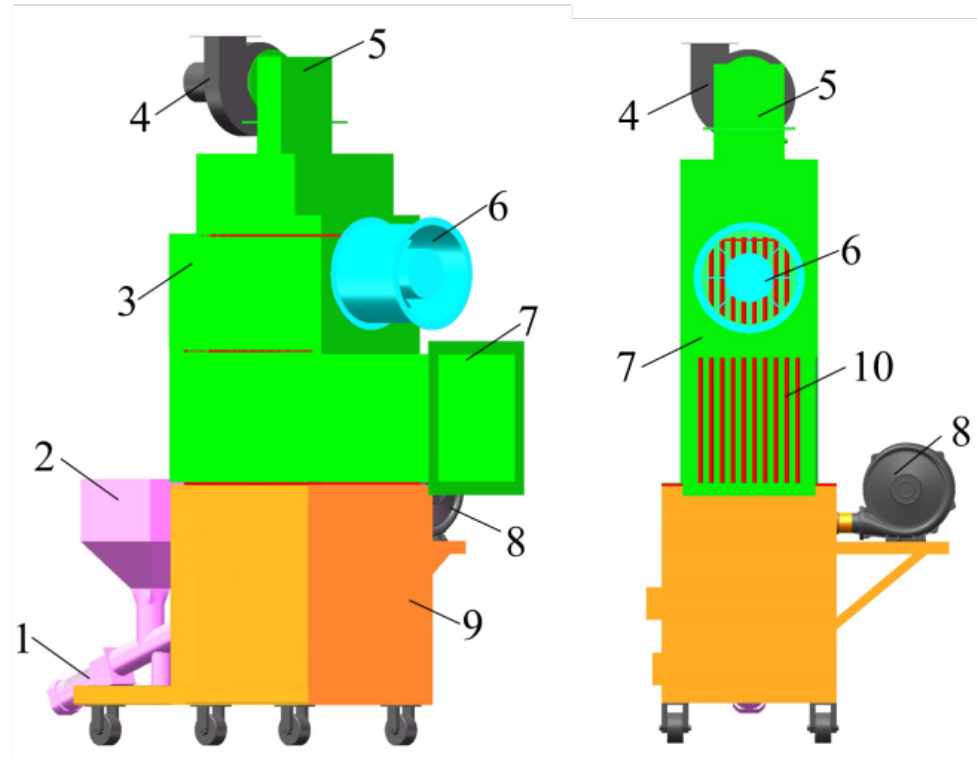


Figure 1. Three-dimensional diagram of the hot air furnace. 1. feed motor; 2. hopper; 3. combustion chamber; 4. auxiliary combustion fan; 5. outlet; 6. blower (inlet); 7. heat exchange chamber; 8. induced draft fan; 9. outlet; 10. plate heat exchanger.

2.2. Working Principle of the Biomass Hot Air Furnace

The biomass hot air furnace operates using an inclined feeding method, where biomass pellet fuel is manually poured into the hopper. As the feeding motor starts, the auger conveys the biomass pellet fuel into the furnace chamber below, accumulating above the grate. The biomass pellets are ignited using a high-temperature, wind-resistant flame gun. Once ignited, the pellets burn inside the furnace chamber. The top-mounted induced draft fan is then activated to expel the combustion exhaust gases and some residues through the top exhaust outlet. During the combustion process, the hot gases exchange heat with ambient air in the heat exchange chamber of the hot air furnace. When the actual temperature is below the set temperature, the supply of biomass pellet fuel will be increased, along with an increase in the frequency of the combustion air fan, blowing in more air to accelerate the combustion process, thereby achieving a rapid increase in temperature. As the temperature approaches the set point, the entire process will slow down. This is a dynamic process. After the heat exchange has been completed, the heated air is expelled from the lower outlet, which is then used for the subsequent grain drying processes. To shut down the furnace, the screw feeder is stopped first. The furnace is fully turned off, including all fans, once the flames inside the chamber are extinguished and the temperature drops to 200 °C [16]. The flow of materials and gases inside the biomass hot air furnace is illustrated in Figure 2.

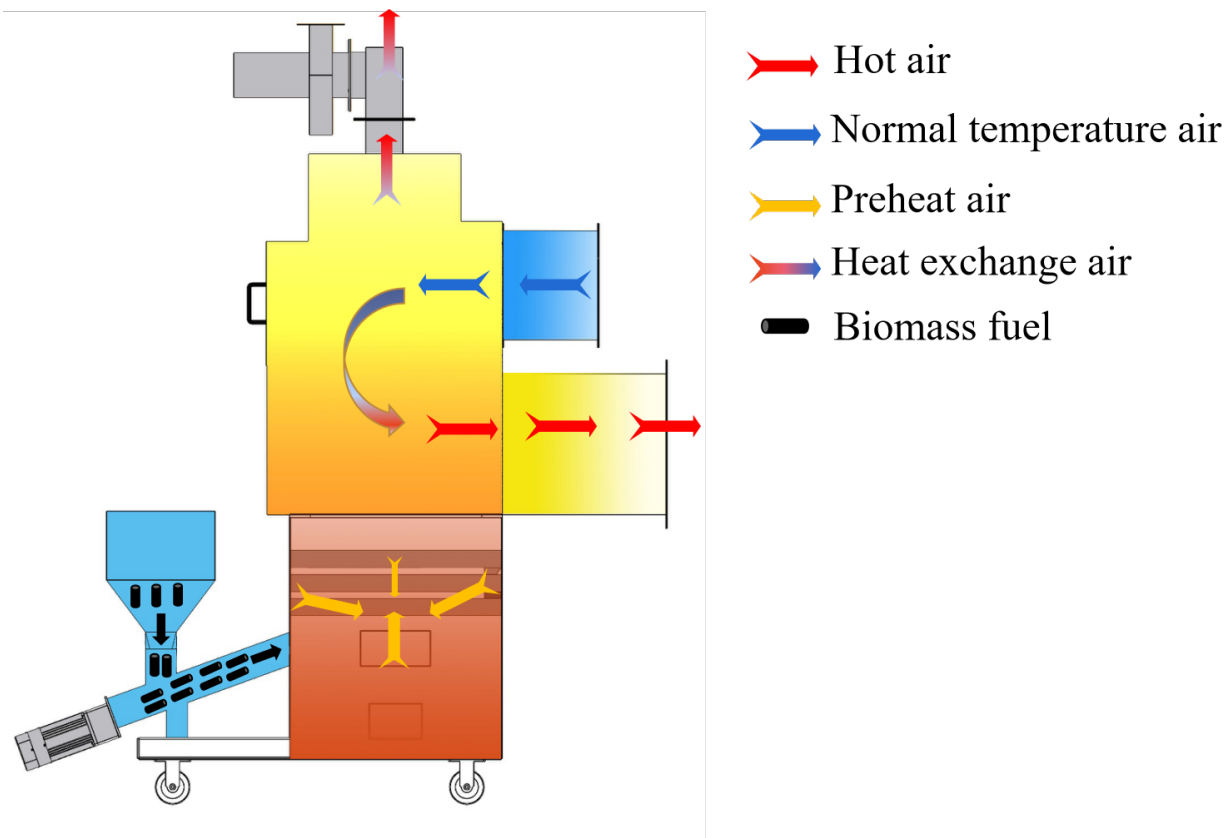


Figure 2. Working principle diagram of the biomass hot air furnace.

3. Key Component Design

3.1. Multi-Channel Combustion Air Duct

In response to the high volatile content of biomass pellet fuel, the biomass hot air furnace adopts a multi-stage air distribution approach. The combustion air duct is shown in Figure 3. One air passage is arranged above the grate, entering the combustion chamber along with the biomass pellet fuel via the feed motor. This part of the air flow is relatively small. The other air passage involves air drawn by the auxiliary combustion fan, which circulates within the furnace wall for heating. The heated air then enters the combustion chamber through the inner wall pipe outlets, forming a spiral airflow field that promotes complete combustion in the chamber and reduces harmful gas emissions.

A surrounding air duct is located on the inner wall of the combustion chamber. The auxiliary combustion fan introduces air from the top, layer by layer downwards, with four rectangular outlets, each with a side length of 5 cm, at the bottom for air input. The arrangement of the surrounding air duct serves several purposes:

1. providing sufficient air volume to ensure complete fuel combustion when the air in the furnace chamber is insufficient for fuel combustion;
2. the inner wall pipe carrying ambient air acts to cool and protect the furnace walls;
3. the four outlets simultaneously create a spiral airflow at the bottom, promoting combustion and reducing black smoke and volatiles;
4. the ambient air heats up as it passes through the pipes, reducing heat loss.

Taking rapeseed drying as an example, let us consider a drying requirement of 200 kg/h with a moisture content of 9%. Assume the initial moisture content of the rapeseed is 25%, the drying inlet temperature is 25 °C, and the outlet temperature is 50 °C.

$$Q_z = Q_s + Q_y - Q_r \quad (1)$$

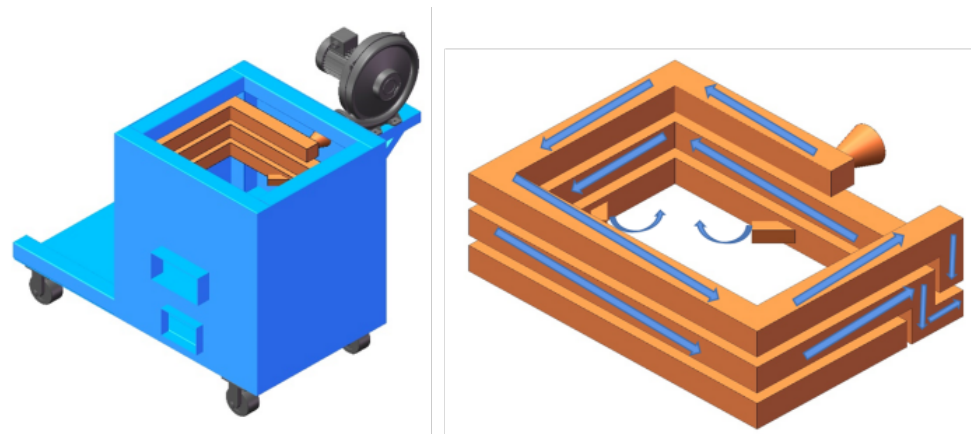


Figure 3. (A) Embedded combustion-supporting air duct, (B) wind direction diagram of the inner wall pipe of the hot air furnace.

Here, Q_z represents the total heat required for drying, Q_s is the heat consumed for evaporating moisture, Q_y is the heat consumed for heating the grains, and Q_r is the heat loss from the hot air furnace's pipes and walls.

$$\begin{cases} Q_s = m_1 \nu \\ Q_y = m_2 c \Delta t \end{cases} \quad (2)$$

where m_1 is the mass of water to be dried, and ν is the latent heat of vaporization for the grains. m_2 is the mass of the dried grains, c is the specific heat capacity of the grains (rapeseed), and Δt is the temperature difference.

From these calculations, the heat consumed for evaporating moisture is 36,018 kcal, the heat consumed for heating the grains is 2150 kcal, and the reference value for heat loss from the hot air furnace's pipes and walls is 408 kcal. Thus, the total heat required for drying is 37,760 kcal.

After calculating the heat required for drying, the required mass of biomass pellets can be determined.

$$m_3 = \frac{Q'_z}{H_L \times \eta} \quad (3)$$

where m_3 is the required mass of biomass pellets; H_L is the lower heating value of the fuel; η is the combustion efficiency, here taken as 0.75. The required mass of biomass pellet fuel is 14.38 kg.

Theoretically, the amount of air needed for the combustion of each kilogram of fuel is [17],

$$\begin{cases} V_L = \frac{O_t}{0.21} \\ V_{ZT} = m_3 \times \frac{V_L}{10\%} \end{cases} \quad (4)$$

In practice, the airflow provided by the inner wall pipes of the hot air furnace is

$$V_{ST} = S v \quad (5)$$

V_L is the theoretical air volume required for combustion, O_t is the oxygen volume required per kilogram of fuel for combustion, V_{ZT} is the total theoretical air volume required for combustion, and V_{ST} is the total air volume provided for actual combustion. The calculations show V_L as 4.1843 Nm³/kg, V_{ZT} as 601 m³/h, and V_{ST} as 720 m³/h.

In practical engineering applications, considering losses and calculation errors, the actual required air volume should be greater than the total theoretical air volume needed for combustion. Therefore, the surrounding air duct in the combustion chamber can effectively promote combustion, providing sufficient oxygen for the combustion of biomass pellet fuel and reducing pollution due to incomplete combustion of the fuel pellets.

3.2. Anti-Pollution Plate Heat Exchanger

The heat exchange process uses a plate heat exchanger with hot and cold isolation. In this process, high-temperature gases produced by combustion pass through the interior of the heat exchanger plates. The plates heat up between their walls, conducting heat outward and exchanging heat with the air supplied by the blower outside the walls, thus completing the heat exchange process. The Plate heat exchanger cutaway view is shown in Figure 4.

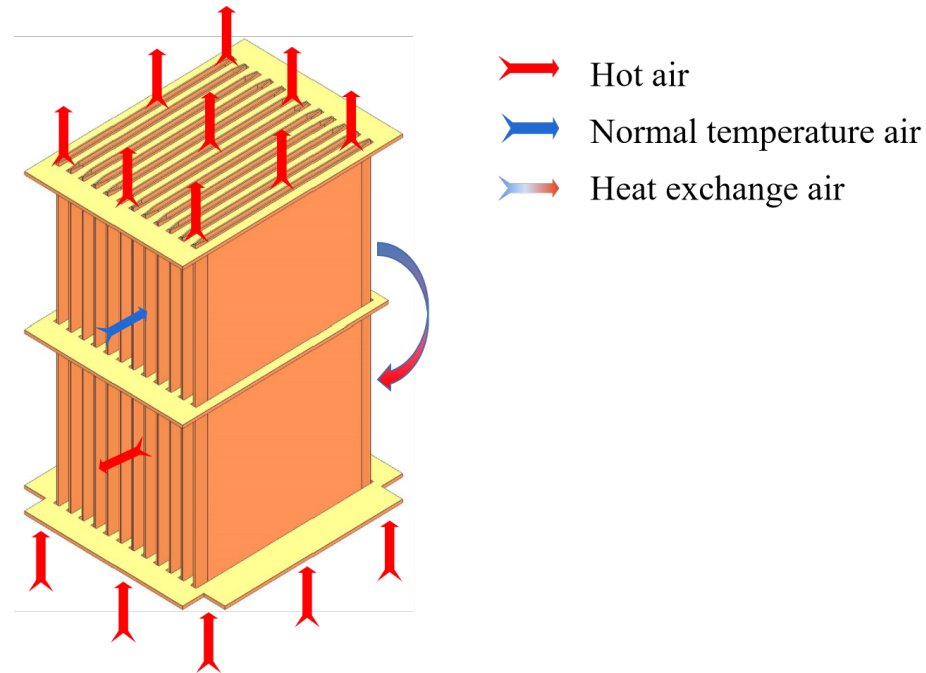


Figure 4. Plate heat exchanger cutaway view.

The hot air furnace adopts a cross-flow heat exchange method, and the logarithmic mean temperature difference is calculated using the following formula:

$$\Delta t = \frac{\Delta t' - \Delta t''}{\ln\left(\frac{\Delta t'}{\Delta t''}\right)} \quad (6)$$

where $\Delta t'$ is the temperature difference between the hot and cold fluids at the inlet, $\Delta t' = 800 - 200 = 600$ °C; $\Delta t''$ is the temperature difference between the hot and cold fluids at the outlet, $\Delta t'' = 100 - 25 = 75$ °C. The logarithmic mean temperature difference is 252 °C.

The total heat exchange area of the heat exchanger can be calculated as

$$F = \frac{Q_z}{P \Delta t} \quad (7)$$

where P is the heat transfer coefficient and, in this paper, the air-to-air heat transfer coefficient of 16 is used. Based on the above formula, the total heat exchange area of the heat exchanger should be 9.36 m². Due to the limited volume of the furnace chamber, multiple plate heat exchangers are arranged inside it. In this device, 12 plates are used.

4. Temperature Model of the Biomass Hot Air Furnace

4.1. Derivation of the Biomass Hot Air Furnace Model

The biomass hot air furnace is considered as a whole system, assuming that the internal air is uniformly mixed [18]. The temperature at the outlet depends on the lower heating value of the biomass fuel and the feed rate, the heat exchange between the furnace body and the external environment, and the heat carried by the inlet air. According to the temperature set, if the actual outlet temperature is lower than the set temperature, the

fuel delivery speed is increased to increase the input heat, and the inlet air quantity is appropriately reduced. Conversely, if higher, the fuel delivery speed is decreased, and the inlet air quantity is increased, to balance the outlet temperature with the set temperature. Let Q_1 be the heat generated by the combustion of biomass pellets per unit time, Q_2 be the heat of the air supplied by the blower, Q_3 be the heat of the air discharged from the outlet, Q_4 be the heat loss through the furnace walls, and Q_5 be the heat carried by the exhaust gases. The heat distribution of the hot air furnace is shown in Figure 5. The equation based on the dynamic heat balance model is as follows:

$$Q_1 + Q_2 = Q_3 + Q_4 + Q_5 \quad (8)$$

The rate of change of temperature at the outlet can be expressed as

$$\frac{RC}{RL\rho c_0 t_1 - \beta} \frac{dt_1}{d\tau} + t_1 = \frac{RL\rho c_0 t_0 + RQ_1}{RL\rho c_0 t_1 - \beta} - \frac{\beta}{RL\rho c_0 t_1 - \beta} t_z \quad (9)$$

where L is the volume of air; ρ is the density of the air; C_0 is the specific heat of air; t_0 is the return air temperature (inlet temperature); t_1 is the outlet temperature; t_z is the ambient air temperature; β is the heat transfer attenuation coefficient of the shell; R is the thermal resistance. Assuming T as the time constant $RC/(RL\rho c_0 t_1 - \beta)$, K as the gain $RL\rho c_0/(RL\rho c_0 t_0 - \beta)$, and t_f as the time delay $(RQ_1 - \beta t_z)/(RL\rho c_0)$, Equation (9) can be expressed as

$$T \frac{dt_1}{dt_z} + t_1 = K(t_0 + t_f) \quad (10)$$

Assuming initial conditions as zero and applying the Laplace transform, this equation becomes

$$G(s) = \frac{K}{Ts + 1} e^{-\tau s} \quad (11)$$

where K is the gain, indicating the ratio of the change in output to the change in input when the controlled system reaches a new equilibrium state. This is a constant not varying with time. The larger the K of a system under the same input conditions, the greater the output, meaning the input has a more significant impact on the output, and the stability of the controlled system is poorer. Conversely, the smaller the K , the better the stability of the system.

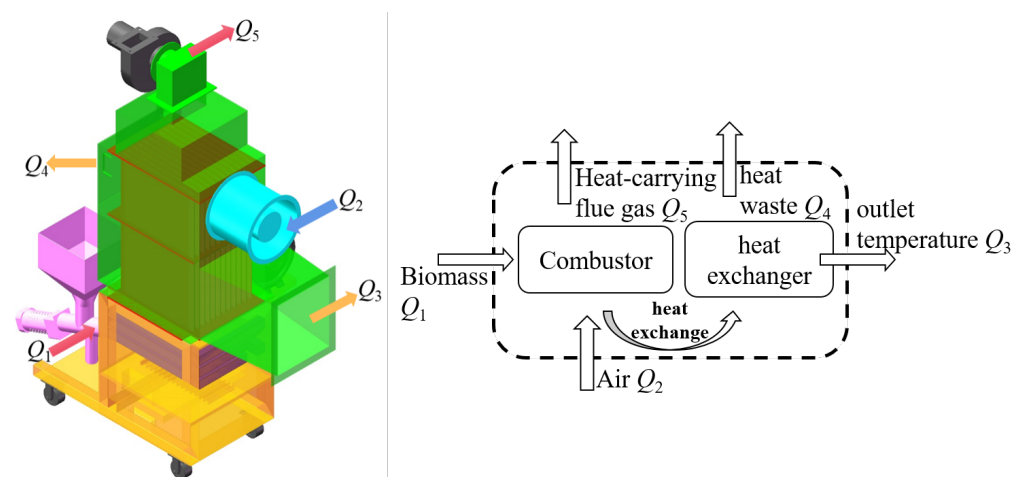


Figure 5. Heat Distribution diagram of the hot air furnace.

T is the time constant, indicating the speed at which the output reaches a new steady state after being subjected to an input, reflecting the rate of change over time in the entire dynamic process, a dynamic characteristic parameter of the controlled system.

τ is the time delay, reflecting the time taken for the controlled system to respond to an input and undergo change [19]. In this system, this is mainly determined by the volume of the hot air furnace and its heat exchange efficiency.

4.2. Establishment of the Biomass Hot Air Furnace Model

Through calculation and derivation, the temperature control system of the hot air furnace was identified as a first-order nonlinear system with a delay. To identify its parameters, the most commonly used experimental identification methods are the response curve method, correlation statistics method, and least squares method [13]. In this paper, the step response method from the response curve method was used to identify the relevant parameters.

First, the hot air furnace was maintained in a steady state at room temperature, and the input to the inverter was controlled to produce a step change [20]. The speed of the auxiliary combustion fan was increased to promote the combustion of biomass pellet fuel in the furnace, raising the temperature at the outlet until it reached a new steady state. During this period, a temperature sensor was used to record the temperature variation over time with a sampling period of 60 s; where t is the output, i.e., the outlet temperature, f_0 is the frequency of the inverter under initial conditions, and f is the step change applied. The temperature variation curve over time is shown in Figure 6.

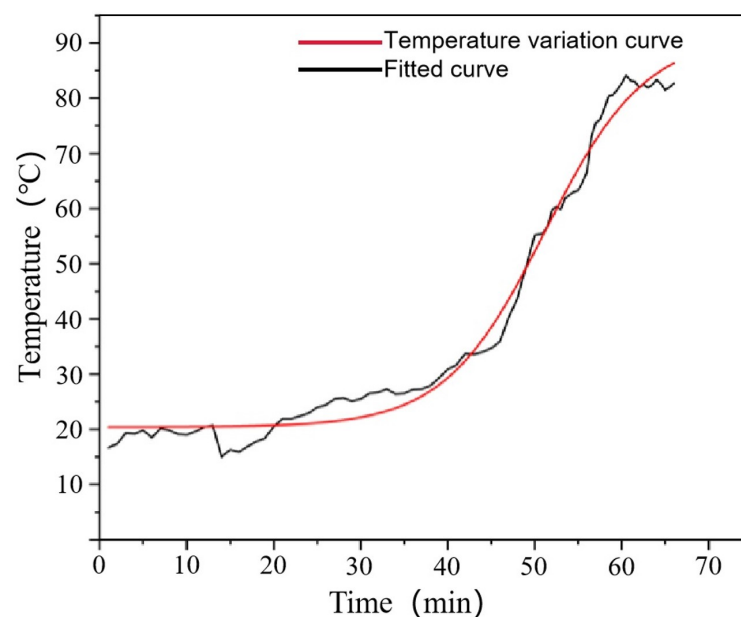


Figure 6. Temperature variation curve of the biomass hot air furnace.

Using Origin's curve fitting function, a polyline graph was fitted into a smoother step response curve that was easier to calculate, as shown in Figure 7. By analyzing the step response curve, the system parameters K , T , and τ were calculated. Consequently, the transfer function of the biomass hot air furnace's temperature control system was determined based on these calculations.

$$G(s) = \frac{3.08}{889s + 1} e^{-50s} \quad (12)$$

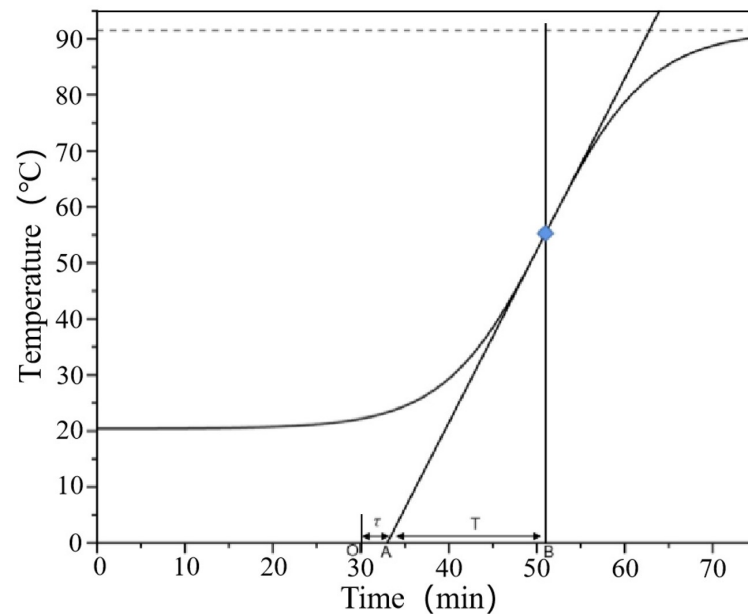


Figure 7. Step response curve of the open-loop temperature control system.

5. System Simulation of the Biomass Hot Air Furnace

5.1. Selection of the Simulation Controller

The traditional PID controller consists of three control units: proportional, integral, and derivative. The calculation formula is as follows:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (13)$$

K_p is the proportional coefficient, determining the sensitivity and stability of the control system. A higher K_p value means smaller integral and derivative coefficients, enabling a quicker response to feedback. However, this may also lead to poor noise resistance, larger errors, and greater overshoot.

K_I is the proportional-integral coefficient, which can improve the system's tracking response performance, enhance noise resistance, and reduce output error. A smaller K_I coefficient significantly enhances the system's tracking performance but reduces its stability.

K_D is the integral coefficient, suppressing errors and accelerating the response time. This constant is mainly used to improve a system's dynamic quality, such as disturbance resistance and response speed, and can also enhance the ability to suppress errors [21].

Traditional PID control methods offer good adjustability and applicability. However, the temperature adjustment requirements for drying systems are high. Under different initial conditions, different hot air drying methods, and varying moisture content conditions, the temperature requirements for hot air drying vary as shown in Table 1 [22]. A high precision and extensive range adjustments are needed. Traditional PID controllers struggle to meet the temperature requirements under different conditions, leading to large overshoots, long adjustment times, and consequently poor control effects and drying results falling short of expectations.

Table 1. Temperature requirements of hot air drying under different moisture content conditions.

Initial Water Content of Rapeseed	Mixed-Flow Drying	Drum Drying	Fluid Bed Drying
$\geq 18\%$	90	110	90
12–18%	110	130	120
$\leq 12\%$	130	150	140

Fuzzy logic theory, however, can effectively solve these problems. Fuzzy logic control methods are based on a large amount of process data, primarily relying on human-like fuzzy "if-then" rules. These rules are expressed in simple language and combined with traditional non-fuzzy processing. The results of all individual rules are then averaged into a defuzzified signal, guiding the controller's actions [23]. It adjusts its control parameters automatically in real time based on the process's current state and performance. This adaptability is crucial for dealing with the nonlinear and time-varying behaviors of many systems, ensuring optimal performance under varying operating conditions. By integrating fuzzy logic with PID control, the system can handle uncertainty and imprecision more effectively than traditional PID controllers. By optimizing the combustion process and maintaining precise temperature control, this system can improve the overall energy efficiency of a biomass hot air furnace.

5.2. Basic Principles of the Fuzzy PID Controller

A fuzzy controller primarily consists of three modules: fuzzification, fuzzy inference, and defuzzification.

Fuzzification: This involves establishing the domain of fuzzy sets and determining the range of variation for input and output variables in practical work. Inputs and outputs are quantified by multiplying them with a quantification factor in their respective domains, converting them to a common domain. Membership functions are then defined for each fuzzy subset that requires fuzzification, ultimately achieving fuzzification of the controller variables [24].

Fuzzy inference: When the system operates in different states, the input value deviation e and the rate of change of the input value deviation e_c are calculated based on the measured actual values. The values of e and e_c vary within a certain range, which is divided into seven parts, represented as $PB, PM, PS, ZO, NS, NM, NB$ and corresponding to "positive big, positive medium, positive small, zero, negative small, negative medium, negative big", respectively. The output increments $\Delta K_p, \Delta K_I, \Delta K_D$ also undergo the same fuzzification process as e and e_c [25]. Based on past control experience and the quantification of inputs and outputs, the system's state and trend are determined. The rules for $\Delta K_p, \Delta K_I, \Delta K_D$ in adaptive fuzzy PID control are established based on different combinations of variables e and e_c .

Defuzzification: This process converts the fuzzy quantities in fuzzy inference into clear quantities used for control. First, the fuzzy control quantities are transformed into clear quantities in the domain. Then, these clear quantities within the domain range are converted into control quantities [26].

5.3. Design of the Fuzzy PID Controller

5.3.1. Fuzzification

The temperature control system of the biomass hot air furnace adopts a two-input, three-output structure. The input language of the fuzzy controller is the temperature difference, denoted as e , set within the range of $[-3, 3]$. It is divided according to intervals, with the rate of change of the temperature difference denoted as e_c , and the sampling period T_s set at 60 s, having a domain of $[-3, 3]$. The output languages are $\Delta K_p, \Delta K_I, \Delta K_D$, with the fuzzy domain chosen as $[-3, -2, -1, 0, 1, 2, 3]$. The domain for ΔK_p is $[-0.3, 0.3]$, for ΔK_I it is $[0, 1]$, and for ΔK_D it is $[0, 1]$. The quantification factors for the controller outputs are as follows, with $\Delta K_p, \Delta K_I, \Delta K_D$, all using Z-type membership functions. The membership functions are shown in Figure 8.

5.3.2. Fuzzy Inference

Based on the temperature variation pattern of the biomass hot air furnace's temperature control system and the roles of $\Delta K_p, \Delta K_I$, and ΔK_D in PID control, the following fuzzy control rules were established:

1. During system startup or shutdown, when there is a significant difference between the set temperature and the actual temperature, a larger ΔK_p should be chosen to increase the response speed. To avoid excessive deviation e at the beginning, causing differential saturation and pushing the control beyond permissible limits, a moderate ΔK_D should be chosen. To prevent overshoot and integral saturation at startup, a smaller or elimination of the integral action $\Delta K_I = 0$ is preferable.
2. Once the system is operating normally, with moderate temperature deviation e and rate of temperature deviation change e_c , a smaller ΔK_p should be selected to minimize overshoot. The values of ΔK_I and ΔK_D should be moderate to maintain the system's response speed.
3. When the system's temperature is nearly stable, with a small temperature deviation e , ΔK_p and ΔK_I can be moderately increased to enhance system stability, while ΔK_D should be adjusted to avoid oscillation near the setpoint and to consider the system's disturbance rejection capability. A higher ΔK_D value should be used when e_c is small, and a lower ΔK_D value when e_c is large [27].

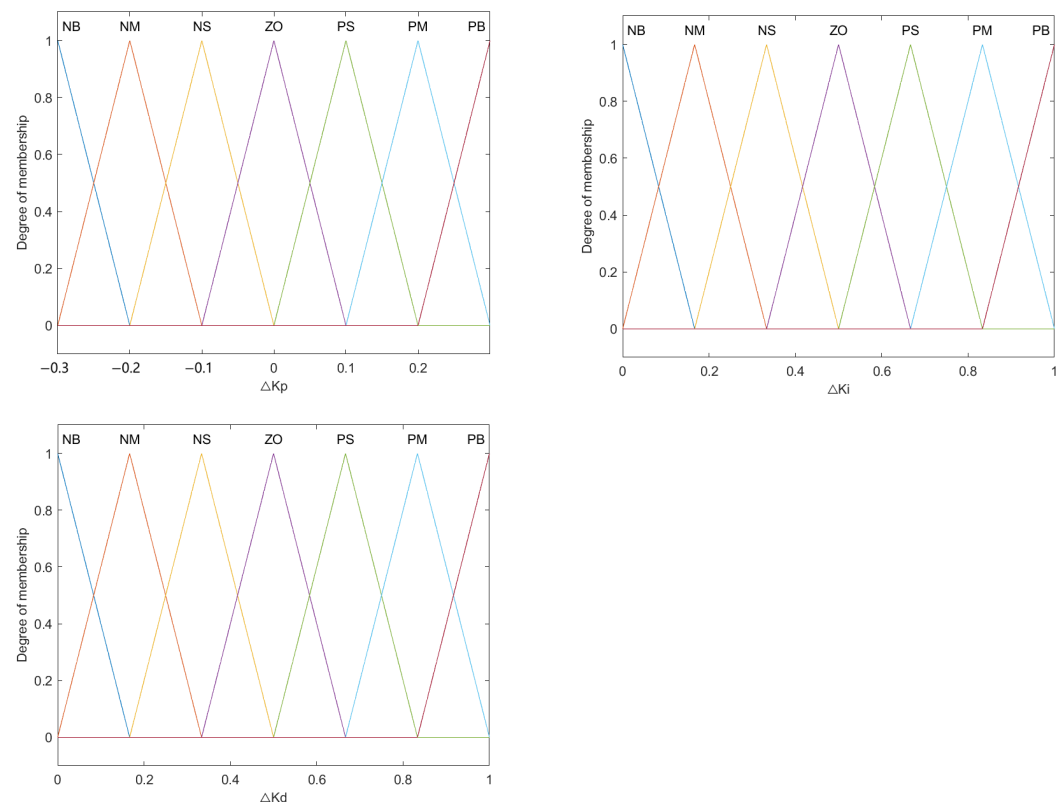


Figure 8. Membership function of ΔK_p , ΔK_I , ΔK_D .

The fuzzy control rules based on these principles are specified in Table 2. The surface of the fuzzy control rules is shown in Figure 9.

Table 2. Table of fuzzy control rules.

$e_c \setminus e$	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/PS	PB/NB/ZO	PM/NM/ZO	PS/NS/ZO	PS/ZO/PB	ZO/ZO/PB
NM	PB/NB/NS	PB/NB/NS	PM/NB/NS	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	ZO/ZO/PM
NS	PM/NM/NB	PM/NM/NB	PM/NS/NM	PS/NS/NS	ZO/ZO/PS	NS/PS/PM	NM/PS/PM
ZO	PM/NM/NB	PS/NS/NM	PS/NS/NS	ZO/ZO/NS	NS/PS/PM	NM/PS/PS	NM/PM/PS
PS	NB/PS/NB	PS/NS/NB	ZO/ZO/NS	PS/NS/PS	NS/NS/PB	NM/PS/PM	NM/PM/PS
PM	ZO/ZO/NM	ZO/ZO/NM	NS/PS/NS	NM/PM/NS	NM/PM/ZO	NM/PB/PS	NB/PB/PS
PB	ZO/ZO/PS	NS/ZO/ZO	NM/PS/ZO	NB/PB/ZO	NB/PB/PB	NB/PB/PS	NB/PB/PS

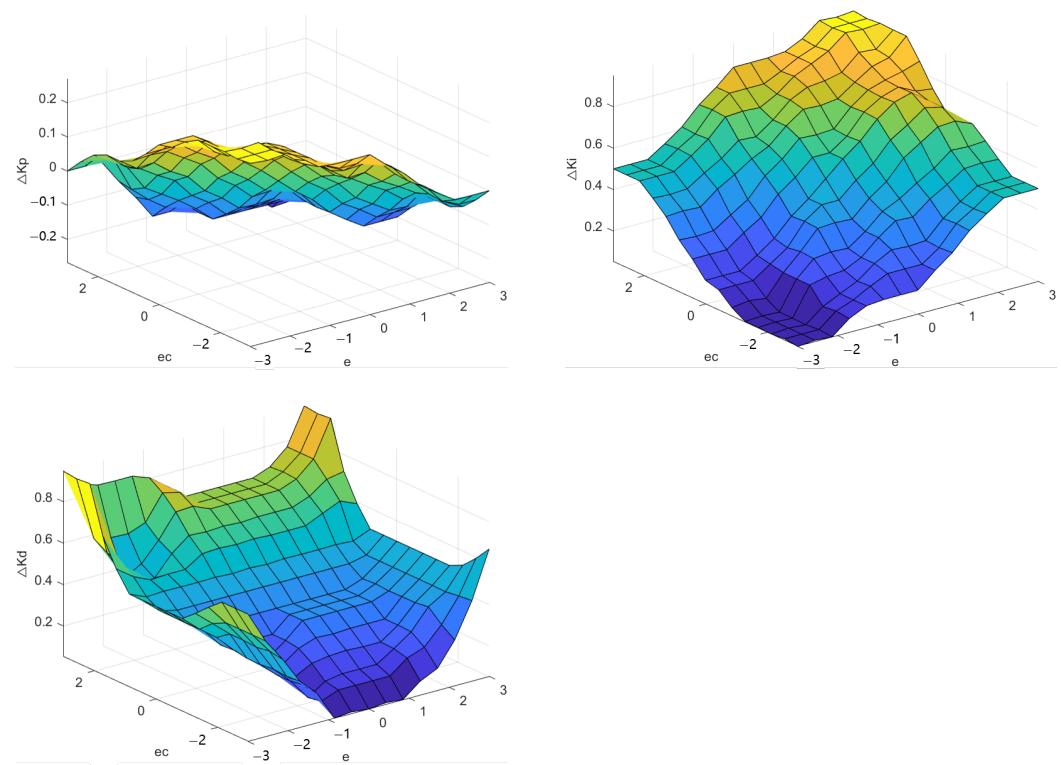


Figure 9. Surface of fuzzy control rules.

5.3.3. Defuzzification

Defuzzification involves calculating the output value in the domain based on the membership degrees obtained from fuzzy inference and then determining the output using interval mapping relationships. Common methods for defuzzification include the mean of maximum method, the maximal membership principle, and the center of area method [28]. This paper adopted the center of area method, to obtain precise output values, as shown in Equation (15). In the actual control process, the calculated results are stored in the processor as a control decision table. During control, corresponding values are queried to read data, reducing the computation time and improving the response speed.

$$Z_0 = \frac{\sum_{i=0}^n \mu_c(Z_i) Z_i}{\sum_{i=0}^n \mu_c(Z_i)} \quad (14)$$

where Z_0 is the precise value after defuzzification of the fuzzy controller; Z_i are the values within the domain of the fuzzy control quantity; and $\mu_c(Z_i)$ is the membership degree of Z_i .

The traditional Ziegler–Nichols tuning formula, after being modified, appears in various designs of PID controllers. The Cohen–Coon method is one such calculation and similar to Ziegler–Nichols [29]. The calculation method is shown in Table 3.

Table 3. Cohen–Coon tuning method for different controllers.

	K_p	K_i	K_d
P	$\frac{1}{a} \left(1 + \frac{0.35\tau_r}{1-\tau_r} \right)$	/	/
PI	$\frac{0.9}{a} \left(1 + \frac{0.92\tau_r}{1-\tau_r} \right)$	$\frac{3.3-3\tau_r}{L} \left(1 + \frac{1}{1.2\tau_r} \right)$	/
PD	$\frac{1.24}{a} \left(1 + \frac{0.13\tau_r}{1-\tau_r} \right)$	/	$\frac{0.27-0.36\tau_r}{L} \left(1 - \frac{0.87\tau_r}{1-0.87\tau_r} \right)$
PID	$\frac{1.35}{a} \left(1 + \frac{0.18\tau_r}{1-\tau_r} \right)$	$\frac{2.5-2\tau_r}{L} \left(1 - \frac{0.39\tau_r}{1-0.39\tau_r} \right)$	$\frac{0.37-0.37\tau_r}{L} \left(1 - \frac{0.81\tau_r}{1-0.81\tau_r} \right)$

Among them $a = \frac{K\tau}{T}$, $L = \frac{\tau}{T+\tau}$, where ΔK_p , ΔK_I , ΔK_D are the initial values from Table 3, which can be determined using model parameters and Table 2. During the machine's operation, real-time deviations and rates of change in the deviation are collected and calculated. By consulting the fuzzy control rule table, corresponding adjustment values are obtained, thereby adjusting the three parameters of the fuzzy PID controller, and in turn fine-tuning the controller parameters [30,31].

6. Simulation and Testing of Biomass Hot Air Furnace Temperature Control System with Simulated PID

6.1. Simulation Test

To validate the adjustment performance of the adaptive fuzzy PID temperature control system, a simulation model based on Simulink in Matlab was constructed. During the simulation process, the control coefficient was set to 1.0, and a ramp function with a slope of -0.17 was added to simulate the temperature curve changing over time. The performances of conventional PID and fuzzy PID were compared by running simulations and analyzing their behaviors. The structure of the simulation is shown in Figure 10. The simulation results are shown in Table 4.

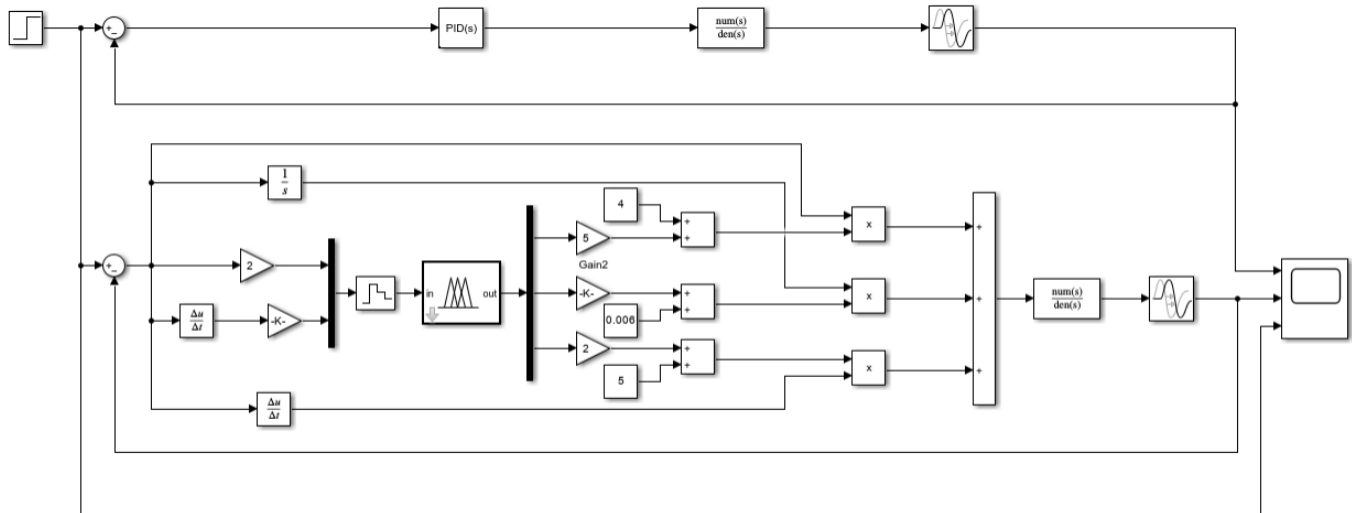


Figure 10. Simulation structure based on Simulink.

Table 4. Performance comparison of different control methods.

Control Mode	Stabilization Time (s)	Steady State Error	Overshoot (%)
PID	445	0.019	20.1
Fuzzy PID	364	0.011	6.3

(1) Figure 11 shows the response of the biomass hot air furnace temperature control system to a set signal of 1.0. The settling times for PID and fuzzy PID were 445 s and 364 s, respectively, with overshoots of 20.1% and 6.3%, respectively. The fuzzy PID temperature control, compared to the conventional PID control, demonstrated a smaller overshoot, shorter adjustment time, and smaller error. It exhibited better dynamic response characteristics and steady-state performance, achieving effective control.

(2) Figure 12 illustrates the temperature control performance of the system set at a temperature of 100 °C. The error with fuzzy PID was smaller, showing a higher fitting with the set temperature and better temperature tracking performance, meeting the design requirements.

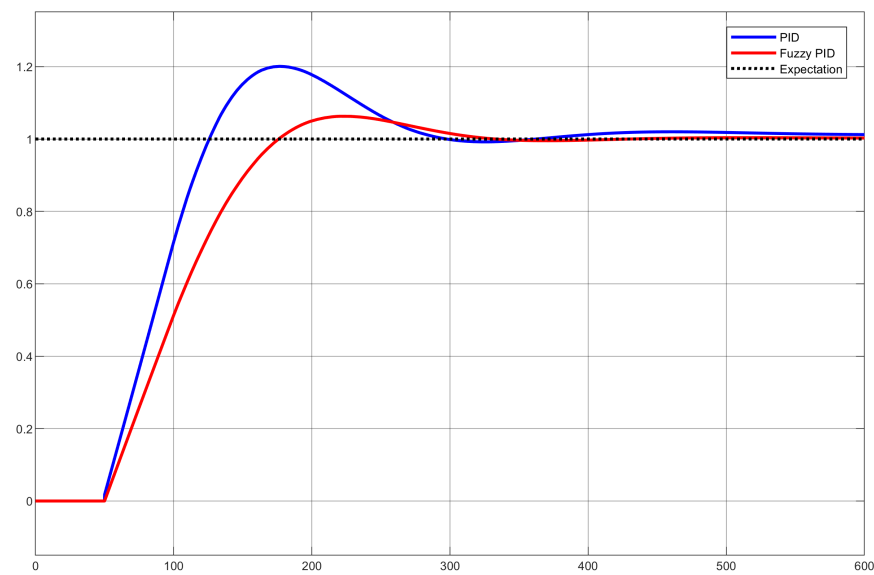


Figure 11. Comparison of response curves between conventional PID and fuzzy PID.

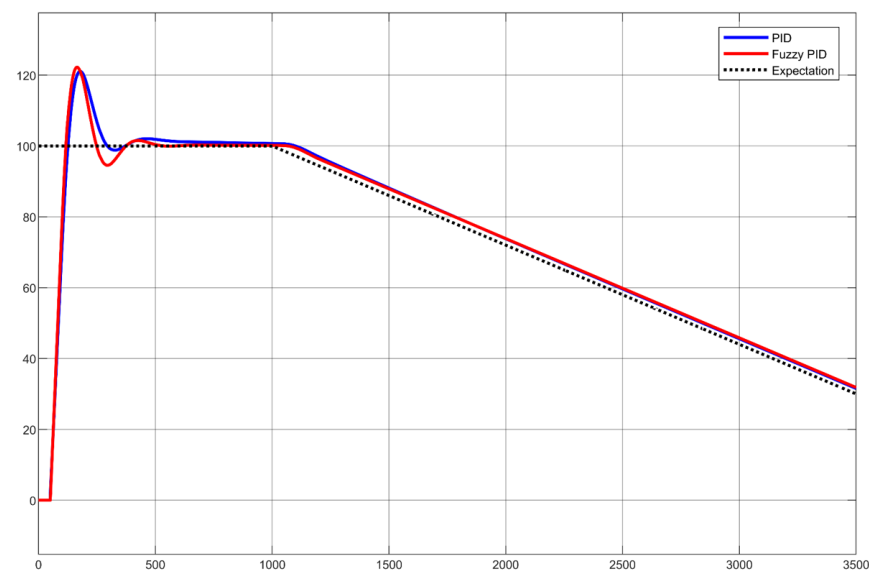


Figure 12. Temperature change output response curve.

6.2. Experimental Testing

To validate the feasibility and superiority of the fuzzy PID temperature control system, comparative experiments were conducted using two different algorithms under the same environmental temperature conditions. The physical picture of the biomass hot air furnace is shown in Figure 13, and its human-computer interaction interface is shown in Figure 14. The experiments utilized a biomass hot air furnace developed in collaboration with a biomass energy equipment company. The average temperature at the outlet was calculated using 4 PT100 thermocouples. The outlet area was 0.18 m², and the inlet area was 0.13 m². Control was achieved using an EV4300 type variable frequency drive, with a controllable frequency range of 0–50 Hz. The environmental temperature was 31 °C, and the humidity was 40%. The target temperatures were set at 90 °C, 110 °C, and 130 °C, with the temperature trends over time recorded every minute for different controllers, as shown in Figure 15. The temperature performance parameters of PID and Fuzzy PID are shown in Table 5.



Figure 13. Physical picture of the biomass hot air furnace.

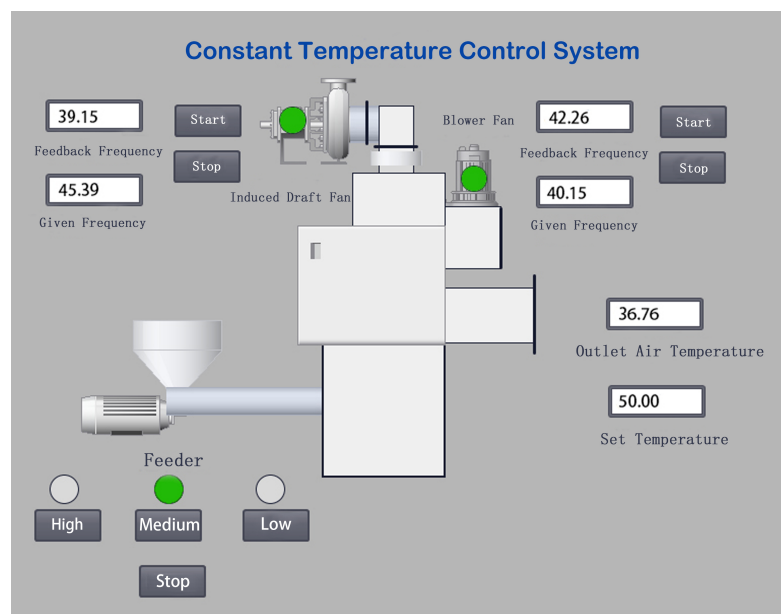


Figure 14. Human–computer interaction interface.

The drying temperature experiments showed that using adaptive fuzzy PID control at 90 °C and 110 °C, the temperature control precision reached ± 5 °C, and the time was consistently controlled within 1300 s, demonstrating a better temperature control performance compared to traditional manual control and classic PID control. At 130 °C, due to higher temperature requirements, the response time was longer, but the temperature control precision was higher with smaller errors.

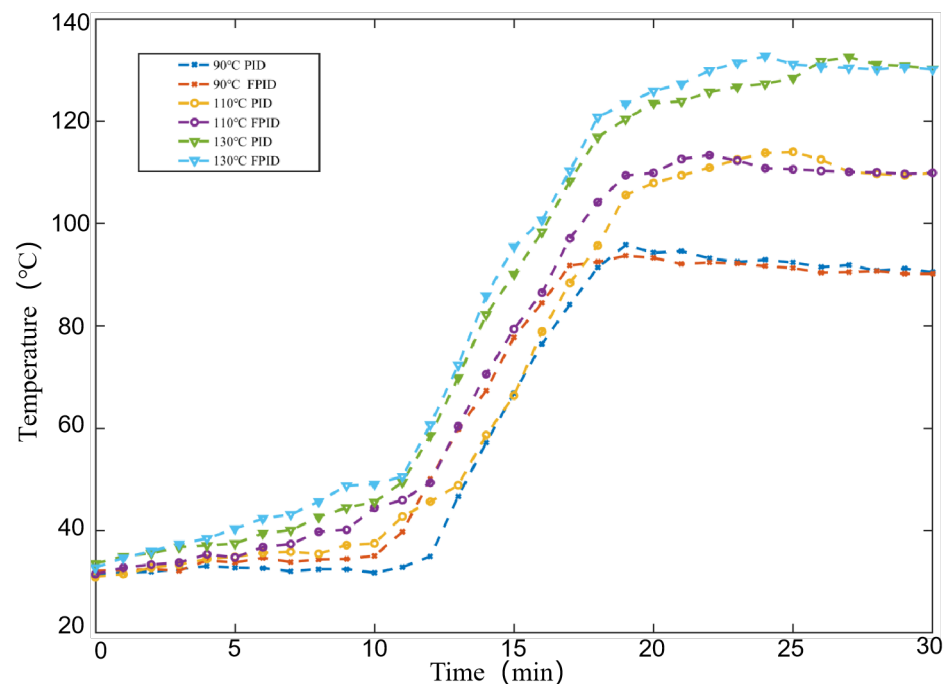


Figure 15. Temperature time trend chart.

Table 5. The temperature performance parameters of PID and Fuzzy PID.

Sequence Number	Control Mode	Temperature Setting (°C)	Stabilization Time	Steady State Error	Overshoot (%)
1	PID	90	1068	5.8	6.4
2	Fuzzy PID	90	1014	3.7	4.1
3	PID	110	1290	4.0	3.6
4	Fuzzy PID	110	1207	3.4	3.1
5	PID	130	1704	2.5	1.9
6	Fuzzy PID	130	1506	2.7	2.0

Under the regulation of adaptive fuzzy PID, the temperature variation was within a reasonable range, meeting the drying requirements for rapeseed. There was no overshoot, and the curve was almost smooth, indicating that the temperature control was overall stable. Through a comparative analysis of the simulation tests and experiments, it was demonstrated that the improvements based on adaptive fuzzy PID effectively enhanced the precision of temperature control. This provides robust support for the design and improvement of control systems for biomass hot blast furnaces.

7. Conclusions

Through an understanding of the working principles of drying equipment and the temperature requirements during the rapeseed drying process, this study focused on a biomass hot air furnace and established a temperature model based on fuzzy PID control. The aim was to complete the rapeseed drying process in an economical and effective manner. The use of biomass for combustion not only reduces energy consumption but also lowers emissions.

1. This paper presents a structural design for a multi-channel circulating biomass hot air furnace. The prototype developed offers energy efficiency and thorough combustion, meeting the technological requirements for drying agricultural products. This provides a theoretical basis for the structural and performance design of drying systems for related agricultural products;

2. Using automatic control theory and experimental data, a mathematical model of the biomass hot air furnace was derived. Considering the nonlinearity and long time-delay characteristics of the combustion furnace, advanced computer simulations were conducted under different operating conditions. It was found that adopting a fuzzy PID control strategy could effectively regulate the temperature of the biomass hot air furnace;
3. Compared to a traditional uncontrollable controller, the fuzzy PID controller could adaptively adjust the PID parameters based on the system's real-time feedback and a predefined rule base, to accommodate the dynamic changes during the operation of biomass hot air furnaces. The operational characteristics of biomass hot air furnaces exhibit significant non-linearity, which traditional PID control may not flexibly manage. By incorporating fuzzy logic, fuzzy PID control can better handle such non-linearity, enhancing the system's response speed and stability. Fuzzy PID control can effectively minimize the phenomena of overshoot and oscillations when the system reaches set temperatures or other operational parameters, ensuring smoother and more reliable furnace operation.

In future research and practical applications. We look forward to conducting research on biomass combustion technology from the following perspectives: (1) Fuel diversity and adaptability: To explore the combustion performance of different types of fuels in hot air furnaces, assessing their impact on thermal efficiency, sustainability, and cost-effectiveness. (2) Environmental impact assessment: To conduct more in-depth studies to evaluate the environmental impact of operating biomass hot air furnaces, including a detailed analysis of the types and quantities of emissions. (3) Economic analysis: To perform comprehensive economic analyses of biomass hot air furnaces, considering cost-benefit ratios, operational costs, and maintenance expenses.

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