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Design, Modeling, and PID-Based Temperature Control of a Low-Cost Mini Convective Food Dryer

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ABSTRACT
Drying is an important post-harvest processing method for extending the shelf life and improving the value of agricultural and food products. This study develops a compact and low-cost convective drying system with an experimentally identified thermal model and a PID-based temperature regulation strategy. The proposed system consists of an electric heating element, a forced-convection fan, a drying chamber, a thermocouple temperature sensor, a solid-state relay, an Arduino-based controller, and a touchscreen interface. The thermal behavior of the dryer was experimentally identified and approximated by a delayed transfer function. Based on this model, an initial PID controller was designed using the Ziegler-Nichols method and then further tuned to reduce overshoot and improve temperature stability. The final PID parameters were selected as $K_P=0.032$, $K_I=0.00003$, and $K_D=1.4$. Simulation and experimental results showed that the system could reach and maintain the desired temperature with small oscillations and acceptable response time. Banana drying experiments were conducted under soft-drying and crispy-drying modes to evaluate the practical performance of the dryer. The obtained products showed acceptable color, texture, and drying quality for small-scale food processing.

Keywords: *Mini food dryer; convective drying; temperature control; thermal modeling; food processing.*

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I. INTRODUCTION

One of the most widely used post-harvest processing methods for agricultural and food products is drying. By reducing the water content of fresh materials, this process helps extend shelf life, reduce microbial growth, decrease transportation weight, and improve the economic value of agricultural products [1]. Traditional drying methods, such as open sun exposure, are simple and inexpensive, but they are highly dependent on weather conditions and require long processing times [2]. Moreover, this approach exposes food products to dust, insects, microorganisms, and uneven solar radiation, which may reduce hygiene and final product quality [3]. In contrast, commercial drying systems can provide better temperature regulation and improved product uniformity; however, many of them are relatively expensive, bulky, and not always suitable for household or small-scale production applications [4]. Therefore, the development of compact, low-cost, and automatically controlled drying systems remains an important practical requirement.

In recent years, several studies have focused on the design, development, and review of emerging drying technologies for food and agricultural products. Ibrahim et al. developed a smart hybrid rotary drum dryer combining infrared and hot-air heating, and reported that the hybrid configuration reduced drying time, improved energy saving, and maintained lemongrass quality [5]. Rulazi et al. designed a solar dryer integrated with thermal energy storage, which significantly shortened the drying time of pineapple and carrot compared with open sun drying and enabled heat supply after sunset [6]. Recent reviews on grain and food drying have also shown that dryer configuration, heat transfer enhancement, airflow distribution, and process control are key factors affecting drying efficiency and product uniformity [7]-[8]. However, many of these advanced systems require complex structures, additional pretreatment modules, or higher investment costs.

To address this gap, this study presents the design, modeling, and PID-based temperature control of a low-cost mini convective food dryer. The main contributions of this paper are summarized as follows. First, the mechanical structure and electrical system of a mini convective dryer are designed and implemented using commonly available components. Second, the thermal dynamics of the dryer are experimentally identified and represented by a delayed transfer function, providing a basis for controller design and simulation. Third, a PID-based temperature regulation strategy is developed, tuned, and experimentally validated through temperature response tests and banana drying experiments.

The remainder of this paper is organized as follows. Section II describes the system design and control methodology, including the mechanical design, electrical system, thermal modeling and PID controller design. Section III presents the simulation and experimental results, including temperature regulation performance, heater power response, and banana drying tests. Section IV concludes the paper and suggests future work.

II. SYSTEM DESIGN AND CONTROL METHODOLOGY

A. Mechanical Design

The mechanical design of the proposed mini convective food dryer was developed to achieve a compact structure, sufficient rigidity, thermal insulation, and effective hot-air circulation. As shown in Fig. 1, the dryer consists of a moisture outlet, outer casing, touchscreen interface, drying tray, material support, convection fan, and electric heating element. The outer casing protects the internal components and reduces heat loss, while the moisture outlet releases water vapor from the chamber. The touchscreen interface allows the user to set and monitor the drying process. Inside the chamber, the drying tray and material support hold the food samples during operation. The electric heating element supplies thermal energy, and the convection fan distributes hot air around the food material to improve heat transfer and reduce temperature non-uniformity.

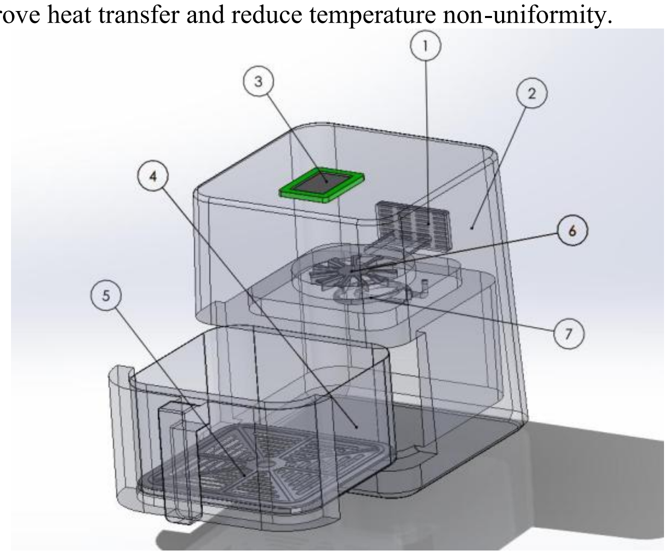

Figure 1: Mechanical structure of the mini food dryer: 1-moisture outlet, 2-outer casing, 3-touchscreen interface, 4-drying tray, 5-material support, 6-convection fan, and 7-electric heating element.

In this design, heat-resistant plastic was used for the frame and outer casing, while stainless steel 304 was used for the tray. The heat transfer through the dryer wall can be approximately described by:

$$Q = kA(T_1 - T_2) / \delta \qquad (1)$$

where Q is the heat loss through the wall, k is the thermal conductivity of the casing material, A is the heat-transfer area, T_1 and T_2 are the temperatures on the two sides of the wall, and δ is the wall thickness.

The electric heating element acts as the main heat source, while the forced-convection fan circulates hot air around the food material. In the prototype, the heater was placed in the upper region of the chamber, and the fan was arranged near the heater to enhance hot-air distribution. The theoretical energy required to heat the air inside the chamber was estimated by:

$$Q = mc\Delta T \qquad (2)$$

where $m = \rho V$ is the mass of air in the chamber, ρ is the air density, V is the chamber volume, c is the specific heat capacity of air, and ΔT is the required temperature increase. Using $\rho \approx 1.29$ kg/m^3, $V = 6\times10^{-3}$ m^3, c = 1005 J/(kg·K), and a temperature increase from 27°C to 100°C, the required energy is calculated as:

$$Q = 1.29 \times 6 \times 10^{-3} \times 1005 \times 73 \approx 567.845 \text{ J} \qquad (3)$$

Since this value only accounts for heating the air, practical heat losses, food heating, and moisture evaporation must also be considered. Therefore, an 800 W heating element was selected to provide sufficient heating capacity and stable drying performance.

B. Electrical Design

The electrical system was designed to supply power, measure chamber temperature, and control the heating and air-circulation components. As shown in Fig. 2, an Arduino Uno is used as the main controller. It receives temperature data from a K-type thermocouple through the MAX6675 module, processes user commands from the TFT touchscreen, and sends control signals to the heating element and convection fan.

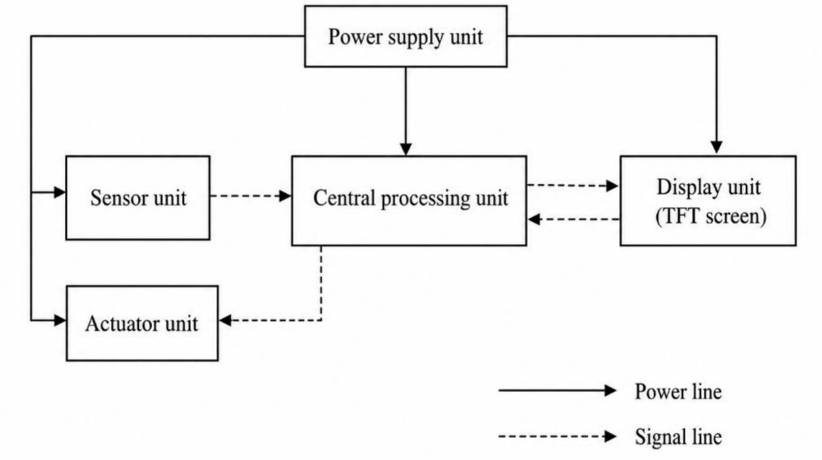

Figure 2: Block diagram of the electrical system of the mini food dryer.

The system is powered by a 220 VAC supply. The high-power components, including the 800 W heating element and the 220 VAC convection fan, are supplied directly from the AC source. Meanwhile, a 220 VAC-9 VDC adapter is used to power the Arduino Uno, which provides 5 VDC to the low-power modules. The main electrical specifications of the main components are listed in Table 2. The heating element is the dominant load, operating at 220 VAC with a maximum current of approximately 3.6 A and a rated power of 800 W. The convection fan requires only 0.07–0.12 A, while the control and sensing modules consume much lower current.

Table 1: Electrical specifications of the main components.

No.	Component	Operating voltage	Average current	Note
1	Arduino Uno	5 VDC	50 mA	
2	SSR relay	3–32 VDC input	10 mA	Load side: 24–380 VAC, max. 40 A
3	Mechanical relay	5–12 VDC	70 mA	Load side: 125–250 VAC, max. 10 A
4	MAX6675 module	3–5.5 VDC	1–1.5 mA	
5	TFT touchscreen	3.3–5 VDC	120–150 mA	
6	Heating element	220 VAC	0–3.6 A	Rated power: 800 W
7	Convection fan	220 VAC	0.07–0.12 A	

For the low-voltage control branch, the total current consumption of the Arduino and peripheral modules is approximately 0.28 A. To provide sufficient reserve capacity, a design current of 0.5 A was selected, corresponding to an estimated power consumption of:

$$P = VI = 5 \times 0.28 = 1.4 \text{ W} \quad (4)$$

Therefore, a 220 VAC-9 VDC adapter rated at about 0.6 A was selected. For the high-power branch, the heating element and fan can draw a maximum current of approximately 3.72 A. Thus, a design current of about 4 A was used, with the corresponding maximum power consumption estimated as:

$$P = UI = 220 \times 3.72 = 818.4 \text{ W} \quad (5)$$

This value is consistent with the 800 W heating element and the additional power required by the fan. The use of separated power branches and relay-based switching allows the low-voltage controller to safely regulate the high-power drying components.

C. Thermal Modeling and PID Controller Design

The temperature control system was designed to maintain the drying chamber temperature close to the desired setpoint. In this study, a PID controller was implemented on an Arduino Uno, and the heater power was regulated through a solid-state relay (SSR).

1. Thermal Model Identification

The thermal behavior of the dryer was identified from the experimental step response, where the input was the heating power and the output was the chamber air temperature. The dryer was approximated as a delayed first-order thermal system. The general transfer function is expressed as:

$$G(s) = C(s) / R(s) \quad (6)$$

where R(s) is the input signal and C(s) is the output temperature response. Since the input was treated as a unit step signal:

$$R(s) = 1/s \quad (7)$$

The output response can be approximated by a delayed first-order thermal response:

$$c(t) = f(t - T_1) \quad (8)$$

where $f(t) = K(1 - e^{-t/T_2})$. Here, K is the temperature gain, T_1 is the time delay, and T_2 is the thermal time constant. Applying the Laplace transform and the time-delay theorem, the output response becomes:

$$C(s) = Ke^{-T_1 s} / [s(1 + T_2 s)] \quad (9)$$

Thus, the transfer function of the dryer can be expressed as:

$$G(s) = Ke^{-T_1 s} / (1 + T_2 s) \quad (10)$$

For controller design and simulation, the time-delay term was approximated by a first-order lag element:

$$G(s) = K / [(1 + T_2 s)(1 + T_1 s)] \quad (11)$$

From the experimental thermal response, the identified parameters were: K = 210, T_1 = 39, T_2 = 218. Therefore, the approximate transfer function of the dryer is:

$$G(s) = 210 / [(1 + 218s)(1 + 39s)] \quad (12)$$

2. PID Controller Tuning

After identifying the thermal model, the PID parameters were determined using the first Ziegler-Nichols tuning method. Based on the identified values of K, T_1, and T_2, the Ziegler-Nichols formulas for PID tuning are:

$$K_C = 1.2T_2 / (KT_1) = 1.2 \times 218 / (210 \times 39) \approx 0.032 \quad (13)$$

$$T_I = 2T_1 = 2 \times 39 = 78 \quad (14)$$

$$T_D = 0.5T_1 = 0.5 \times 39 = 19.5 \quad (15)$$

where K_C is the controller gain, T_I is the integral time, and T_D is the derivative time.

The corresponding PID gains are $K_P = K_C = 0.032$, $K_I = K_C/T_I = 0.032/78 \approx 0.00041$, and $K_D = K_C \times T_D = 0.032 \times 19.5 \approx 0.624$. The original simulation showed that although the initial PID controller could drive the system toward the desired temperature, the response still exhibited relatively large overshoot and damped oscillation. Therefore, the controller gains were further adjusted to improve stability. The final tuned parameters were selected as: $K_P = 0.032$, $K_I = 0.00003$, $K_D = 1.4$.

As shown in Fig. 3, the tuned PID controller enables the system temperature to approach the desired value smoothly while the heater power decreases and stabilizes as the setpoint is reached.

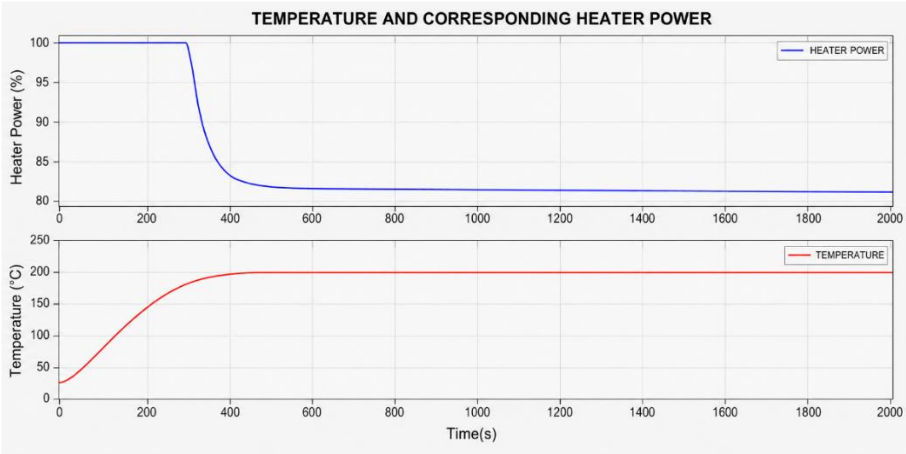

Figure 3: System response with K_P = 0.032, K_I = 0.00003, and K_D = 1.4.

III. RESULTS AND DISCUSSION

The prototype was experimentally evaluated under indoor conditions, with an ambient temperature of approximately 25–30°C. The experiments focused on two main aspects: the temperature regulation performance of the PID controller and the practical applicability of the dryer for banana processing.

A. Temperature Control Performance

The temperature control performance was evaluated by comparing the simulated and experimental responses. As shown in Fig. 4, both curves increased toward the target temperature of 120°C, showing that the identified model could describe the main thermal behavior of the dryer. Although the simulated response rose faster due to the simplified model, both responses reached a stable region after approximately 200–250 s and remained close to the setpoint without significant overshoot or large oscillations.

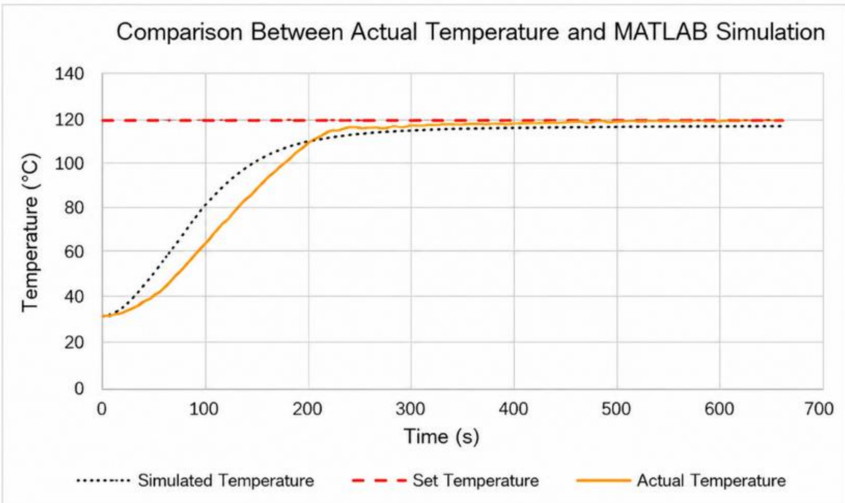

Figure 4: Comparison between simulated and experimental temperature responses.

The corresponding heater power response is shown in Fig. 5. At the beginning of the process, the heater operated near full power to rapidly increase the chamber temperature. As the temperature approached the setpoint, the PID controller gradually reduced the heater power to prevent overheating and maintain stability. The experimental heater power fluctuated more than the simulated curve due to drying load variation, heat loss, sensor noise, and SSR switching behavior. Nevertheless, the heater power remained within a suitable range, allowing the chamber temperature to be maintained near the desired value. These results confirm that the PID-based control system can provide stable temperature regulation for the mini dryer.

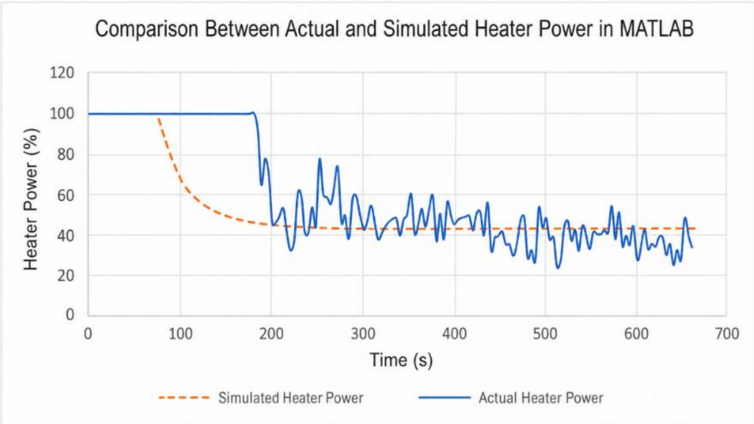

Figure 5: Comparison between simulated and experimental heater power responses.

B. Banana Processing Performance

Banana samples were used to evaluate the practical applicability of the proposed mini convective food dryer. Two processing modes were considered: soft-drying and crispy-drying. These experiments were conducted not only to observe the temperature regulation capability of the system, but also to examine whether the controlled hot-air environment could produce acceptable final products in terms of color, texture, and visual uniformity.

For the soft-drying mode, the banana slices gradually changed from fresh samples to a yellow-brown product with a dry surface and low stickiness, as shown in Fig. 6. The final product retained a soft and flexible texture, indicating that the selected temperature profile was suitable for gradual moisture reduction without excessive thermal damage.

Figure 6: Visual changes of banana slices during the soft-drying process.

For the crispy-drying mode, thinner banana slices were used to promote faster moisture removal. As shown in Fig. 7, the samples gradually shrank and became darker during the process. The final product showed a dry and crispy appearance, although some differences in color and texture were observed due to non-uniform slice thickness and airflow distribution.

Figure 7: Visual changes of banana slices during the crispy-drying process.

Overall, the results show that the proposed mini convective dryer can be used for small-scale banana drying applications. The soft-drying mode produced more uniform results, while the crispy-drying mode was more sensitive to slice thickness, airflow distribution, and final moisture content. Future improvements should focus on tray design, airflow circulation, and humidity-based feedback to enhance product uniformity.

IV. CONCLUSION

This paper presented the design, modeling, and PID-based temperature control of a low-cost mini convective food dryer for small-scale food processing applications. The proposed system integrates a compact drying chamber, an electric heating element, a forced-convection fan, a temperature sensor, an Arduino-based controller, an SSR heater control circuit, and a touchscreen interface. The thermal behavior of the dryer was experimentally identified and used for PID controller design and tuning.

Simulation and experimental results showed that the proposed PID controller could regulate the chamber temperature with acceptable stability and small oscillations. Banana drying experiments under soft-drying and crispy-drying modes demonstrated that the system can produce products with acceptable color, surface dryness, and texture. These results indicate that the developed prototype is suitable for household and small-scale production applications.

However, some limitations remain, including non-uniform airflow distribution, the absence of humidity feedback, and limited quantitative evaluation of moisture content and energy consumption. Future work will focus on improving chamber airflow, integrating humidity or moisture sensors, optimizing drying profiles, and applying advanced control methods to enhance product uniformity and energy efficiency.

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