Design and Construction of Electrical System for Bread Dough Proofer Tool Based on a Microcontroller with PID Control on Donut Dough

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Abstract - This study focuses on the design and implementation of an electrical system for a bread dough proofer tool, specifically optimized for donut dough fermentation, utilizing a microcontroller with Proportional-Integral-Derivative (PID) control. The proofing process is crucial for dough quality, and maintaining precise temperature and humidity conditions is essential for consistent results. The PID control algorithm continuously calculates the error between desired setpoints and measured process variables, adjusting actuator outputs to minimize this error. The PID parameters were tuned using a trial-and-error method to achieve optimal response speed and stability, with values of $K_p = 30$, $K_i = 1$, and $K_d = 1$. Experimental results demonstrate the system's effectiveness in stabilizing the proofing environment. The temperature was maintained at 40.10°C with a minimal overshoot of 0.30°C and a rise time of 10.25 minutes. Humidity was regulated within the range of 80-90% RH for 38.4 minutes, with a rise time of 40.41 minutes. The system exhibited robust disturbance rejection, quickly recovering from external perturbations. Compared to manual proofing, the automated system reduced proofing time by approximately 25% and significantly improved donut dough quality, evidenced by enhanced volume expansion and uniform texture.

Keywords - Bread Dough Proofer, PID Control, Microcontroller, Temperature and Humidity Control, Automated Proofing System

1. INTRODUCTION

In the baking industry, the proofing stage is a pivotal step in dough preparation, where yeast fermentation produces gas, leading to dough expansion, improved texture, volume, and overall quality. For donut dough, precise control of environmental factors such as temperature and relative humidity (RH) is crucial to ensure consistent fermentation, as deviations can result in suboptimal dough characteristics, including uneven expansion, poor texture, and reduced nutritional value. Traditional proofing methods often depend on manual oversight, which is labor-intensive, susceptible to human error, and inefficient for small to medium-scale operations. Studies have shown that variations in yeast levels, proofing time, and environmental conditions significantly affect dough outcomes. For example, Dendegh et al. [1] examined the effects of increased yeast addition and proofing time on bread from wheat and cassava flour, revealing that higher yeast concentrations and extended proofing enhance proximate composition and vitamin levels, but require precise regulation to prevent inconsistencies. Similarly, Kartiwan et al. [2] compared dough preparation methods (straight, sponge, and dough break roll) for sweet bread

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from composite flour fortified with seaweed, noting that methods like dough break roll improve porosity (up to 10.67 pores per unit area) and texture, yet manual approaches lack standardization.

Bread and bakery products, such as donuts, rely heavily on the proofing process, a critical fermentation stage where dough is allowed to rest under controlled temperature and humidity conditions to enable yeast activity and gas production. This process directly influences the dough's volume, texture, and final product quality [3,4]. Maintaining optimal environmental conditions during proofing is essential to ensure consistent dough development and to prevent underproofing or overproofing, which can adversely affect product quality [5]. In small and medium-scale bakeries, proofing is often performed manually or with rudimentary equipment lacking precise control, leading to inconsistent results and inefficiencies in production [6]. The need for an automated, reliable, and cost-effective proofing system is therefore critical to improve product consistency and operational efficiency.

Despite insights from studies on proofing parameters, many systems remain rudimentary, leading to inefficiencies and quality variations. The integration of microcontrollers and control algorithms, such as Proportional-Integral-Derivative (PID), provides a pathway to automation by enabling real-time feedback for temperature and humidity adjustments. Therdthai et al. [7] modeled the influence of RH and temperature on the proving rate of rice-flour-based dough, demonstrating that optimal conditions accelerate kinetics, but their work focused on predictive modeling without practical control implementation. Sensor accuracy is vital for reliable measurements. Saptadi [8] compared DHT11 and DHT22 sensors, showing DHT22's superior precision, which is essential for automated systems. Additionally, microcontroller-based solutions, such as those using Arduino Mega, have been applied in related automation tasks, like automated irrigation for mango plants [9], illustrating hardware versatility for environmental regulation. However, these applications do not address dough proofing. Fuzzy logic has also been explored for dough development. Nurauliya et al. [10] implemented fuzzy logic to determine dough development rates in bakery products, achieving medium results with inputs like temperature and proofing time, offering an alternative to PID for complex, uncertain processes. PID tuning methods have been extensively reviewed by Bharat et al. [11], encompassing both classical approaches, such as the Ziegler–Nichols method, and modern optimization techniques, including genetic algorithms. Their findings indicate that modern tuning methods can significantly enhance system performance by minimizing overshoot compared to traditional approaches. These insights form a strong foundation for developing optimized control strategies in proofing systems that demand precise regulation of temperature and humidity.

Proportional-Integral-Derivative (PID) control is one of the most widely used control strategies in industrial automation due to its simplicity, robustness, and effectiveness in regulating process variables [12]. The integration of PID control with microcontroller platforms, such as Arduino, enables the development of compact and affordable control systems capable of regulating temperature and humidity in proofing chambers [3,6]. Such systems can automate the regulation of temperature and humidity within proofing chambers, leading to improved consistency in dough fermentation and reduced proofing times. The PID controller continuously calculates an error value as the difference between a desired set-point and a measured process variable, and applies corrective actions based on proportional, integral, and derivative terms to minimize this error over time [13]. Despite the proven advantages of PID control in temperature regulation, its application specifically tailored for dough proofing tools, especially for donut dough with unique fermentation characteristics, remains underexplored. Moreover, the design of an electrical system that effectively implements PID control for both temperature and humidity in a proofer tool is critical to achieving optimal proofing conditions. Previous studies have demonstrated the successful application of PID control in temperature regulation for bread proofers, resulting in reduced proofing times and improved product quality [3,6]. However, limited research has focused specifically on the electrical system design of proofing tools tailored

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for donut dough, which may have distinct fermentation characteristics compared to other bread types [3].

Based on the literature review, there is a significant research gap in the development of automated proofing systems specific to donut dough. Previous studies mostly focus on modeling proofing parameters (such as temperature and RH) or PID control applications for general bread, without full integration of electrical systems including hardware design, accurate sensors, and PID tuning for donut fermentation. Additionally, the lack of research combining Arduino Mega microcontroller with specific actuators (such as heater, fan, and lamp) for simultaneous temperature and humidity control in small-scale bakery contexts, as well as direct comparisons with manual methods, indicates the need for practical, cost-effective, and efficient solutions. Based on the literature review, a notable research gap exists in the development of automated proofing systems specifically designed for donut dough. Previous studies have primarily focused on modeling proofing parameters or on the application of PID control for general bread fermentation. However, full system integration that encompasses electrical hardware design, accurate sensing elements, and PID tuning optimized for donut fermentation has not yet been comprehensively addressed. Moreover, limited research has been conducted on the combination of Arduino Mega microcontrollers with dedicated actuators (such as heaters, fans, and lamps) for simultaneous temperature and humidity regulation in small-scale bakery environments. The absence of direct performance comparisons between automated and manual proofing methods further emphasizes the need for practical, cost-effective, and efficient solutions tailored to small bakery operations.

This study aims to design and implement an electrical system for a bread dough proofer tool based on a microcontroller with PID control, optimized for donut dough fermentation. The system incorporates sensors for real-time monitoring of temperature and humidity, and actuators controlled via PID algorithms to maintain optimal proofing conditions. By automating the proofing process, the proposed system is expected to enhance dough development consistency, reduce proofing time, and improve the overall quality of donut products.

The paper is organized as follows: Section 2 reviews about PID control applications; Section 3 details the electrical system design and methodology; Section 4 presents experimental results and analysis; and Section 5 concludes with recommendations for future research.

2. PID CONTROLLER

The proofing process is essential for dough fermentation, where temperature and humidity play vital roles in yeast metabolism and dough expansion. Studies have shown that maintaining stable environmental conditions improves dough quality and reduces proofing time [1]. PID control has been successfully applied in various temperature regulation systems, including food processing equipment. Its ability to minimize error and stabilize process variables makes it suitable for proofing applications [5]. Previous research on automated proofers has demonstrated improvements in product consistency and operational efficiency. However, many systems focus solely on temperature control, neglecting humidity regulation, which is equally important for dough quality [4]. This research addresses these gaps by designing an electrical system that integrates PID control for both temperature and humidity, specifically tailored for donut dough proofing.

The system employs a Proportional-Integral-Derivative (PID) control algorithm to regulate temperature and humidity within the proofer chamber. The PID controller continuously calculates the error between the desired setpoint and the measured process variable, then adjusts the actuator outputs to minimize this error. This output drives actuators to adjust the system until equilibrium is achieved automatically. The core principle of PID control lies in its ability to convert the detected error into a tailored system response, ensuring rapid convergence to the setpoint while minimizing deviations and oscillations [7].

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The Proportional-Integral-Derivative (PID) controller is a fundamental feedback mechanism widely employed in automation and process control systems. It operates by computing an error value as the difference between a desired setpoint and a measured process variable, then applying a corrective action through three distinct control actions: proportional, integral, and derivative. These actions work synergistically to achieve rapid response, minimal steady-state error, and system stability, making PID control ideal for applications such as temperature and humidity regulation in environmental chambers like the bread dough proofer developed in this study.

Each PID control action contributes unique advantages to the overall system performance:

a. Proportional (P) Control Action

   This component generates an output signal proportional to the current error magnitude. It accelerates the system's rise time, allowing the process variable to approach the setpoint more quickly. The proportional gain, denoted as, determines the responsiveness; higher values reduce rise time but may introduce overshoot if not balanced [8].

b. Integral (I) Control Action

   The integral term accumulates past errors over time, effectively eliminating residual steady-state errors that persist after the proportional action has acted. By integrating the error signal, it ensures the process variable converges precisely to the setpoint. The integral gain, controls the rate of error accumulation, though excessive can lead to integrator windup and oscillations [6].

c. Derivative (D) Control Action

   This anticipates future errors by evaluating the rate of change of the current error. It dampens overshoot and undershoot, enhancing system stability and reducing settling time. The derivative gain, modulates this predictive effect, but it is sensitive to measurement noise, often requiring filtering in practical implementations [6].

The mathematical formulation of the PID controller is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\ d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

where u(t) is the controller output, e(t) is the error signal, Kp is the proportional gain, Ki is the integral gain, and Kd is the derivative gain. The proportional term responds directly to the current error magnitude, providing an immediate adjustment proportional to the deviation. The integral term accumulates past errors over time to eliminate steady-state offsets, while the derivative term anticipates future errors by evaluating the rate of change, thereby damping overshoot and enhancing stability.

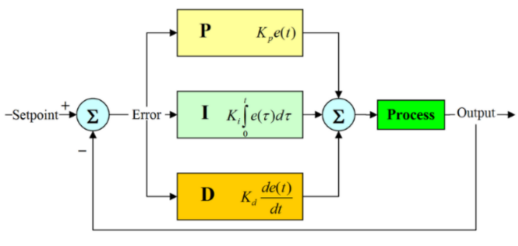

Figure 1. Block diagram of PID control system

The integration of these three control actions is specifically designed to optimize the system's performance in attaining and maintaining the predefined setpoint. In practical implementations, careful tuning of the gains K_p, K_i, and K_d is essential to produce an output

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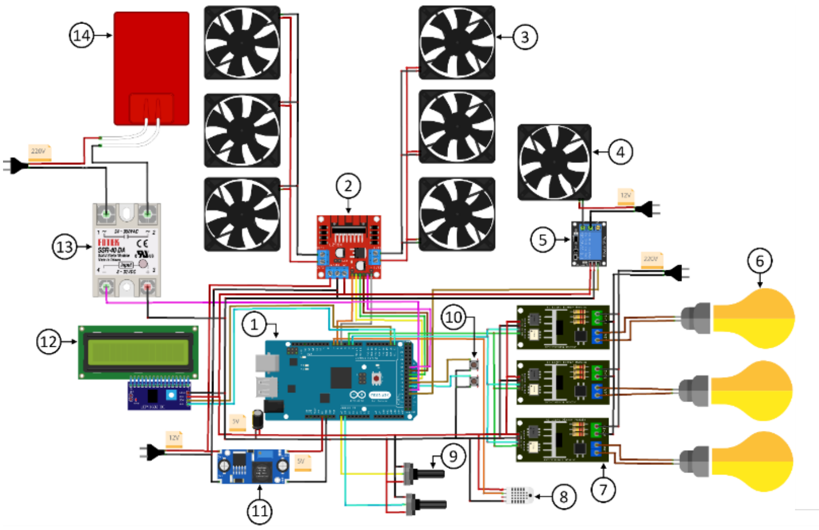
response signal that aligns with the desired characteristics, such as minimal rise time, reduced overshoot, and sustained stability. Improper tuning can lead to sluggish responses or excessive oscillations, underscoring the need for iterative methods like Ziegler-Nichols or trial-and-error to refine these parameters for the specific application [9].

The general block diagram of a PID control system is illustrated in Figure 1. In this configuration, the setpoint r(t) is compared with the process output y(t) to generate the error e(t). The PID controller processes e(t) using tunable parameters K_p, K_i, and K_d to produce the control signal u(t), which drives the plant (e.g., the proofer chamber) toward the desired state. By iteratively adjusting these parameters, the output reaches the setpoint within a specified time, minimizing transient errors and ensuring steady-state accuracy.

3. SYSTEM DESIGN AND RESEARCH METHOD

3.1. Electrical System Design

The electrical system of the bread dough proofer is designed to maintain optimal temperature and humidity conditions necessary for effective fermentation of donut dough. The main components of the system shown in Figure 2.



1. Arduino Mega
2. L298N Module
3. Centrifugal Fan
4. Exhaust Fan
5. Relay
6. Lamp
7. AC Light Dimmer
8. DHT22 Sensor
9. Potentiometer
10. Push Button
11. Stepdown
12. LCD 12C
13. SSR Relay
14. Water Heater

Figure 2. Electrical Schematic

After completing the design of the electrical system, the next step is the assembly process that integrating all electrical system components with the mechanical system of the bread proofer. The placement of the electrical components in the bread proofer is shown in Figure 3. This combination of components enables precise monitoring and control of the proofing environment, ensuring consistent dough fermentation.

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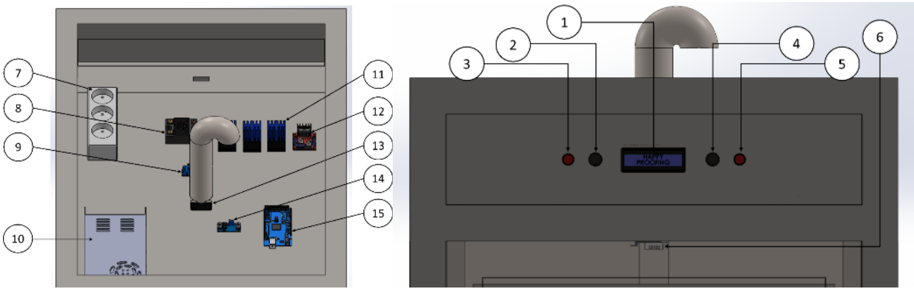

1. LCD 12C 16x2
2. Humidity Potentiometer
3. Push Button System
4. Temperature Potentiometer
5. Push Button Menu
6. DHT22
7. Electric Socket
8. SSR Relay
9. Relay
10. Power Supply
11. AC Light Dimmer
12. L298N Module
13. Exhaust Fan
14.

Figure 3. The placement of the electrical components

3.2. System Block Diagram

The design of this system began with the development of a program to be uploaded into the Arduino Mega using the Arduino IDE application. The next step was wiring the selected components, followed by the assembly of the electrical components on the proofer device. Finally, the electrical system was tested to evaluate its performance.

Figures 4 and 5 illustrate the electrical block diagram of the bread proofer system to be developed. The temperature and humidity set points are read by the Arduino Mega microcontroller. The DHT22 sensor measurements are then compared with the set points by the Arduino Mega. Based on this comparison, the Arduino Mega generates output signals. These signals control the relay, which switches the power supply to the water heater and fan in order to stabilize the humidity. In addition, the output signals regulate the light intensity through a PID control system to maintain the temperature inside the proofer chamber. Once the heater, water heater, and fan are activated, the temperature and humidity inside the chamber are monitored in real time by the DHT22 sensor. The sensor continuously transmits temperature and humidity data to the Arduino Mega during the stabilization process, and the data are displayed on the I2C LCD.

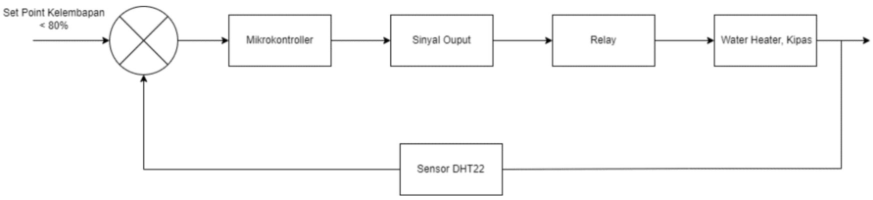

Figure 4. Humidity Block Diagram

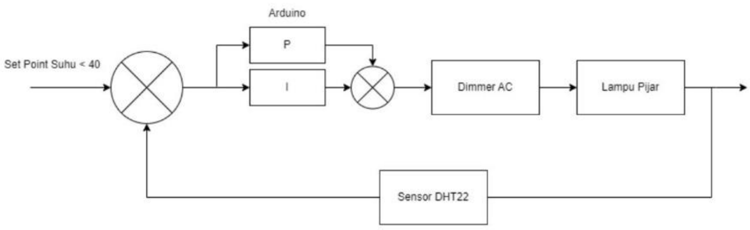

Figure 5. PID Block Diagram

3.3. Experimental Method

In this study, testing of the electrical system of a bread proofer developed for the dough fermentation process was carried out. The PID parameters (K_p, K_i, and K_d) are tuned using the trial and error method to achieve a balance between response speed and stability, minimizing

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overshoot and steady-state error. The testing involved determining the proportional (K_p), integral (K_i), and derivative (K_d) parameters of the PID control system. The procedure began by adjusting K_p until the system reached the set point, followed by tuning K_i to eliminate the steady-state error in the system response. Next, K_d was adjusted to improve system stability and accelerate the transient response. The tuning process was considered complete once the system response achieved an overshoot of ≤ 5% and a stable steady-state at the set point of 40 °C. The obtained values of K_p, K_i, and K_d were then implemented into the overall system program.

For the stability testing of temperature and humidity, the proofer was evaluated by integrating the temperature stabilization program using PID control with the humidity stabilization system. This test was conducted to observe the effectiveness of temperature and humidity regulation. The results to be discussed include the time required to achieve stable temperature and humidity, as well as the degree of stability attained.

After the testing was successfully completed, the next step was to analyze the experimental results. The analysis focused on the PID tuning outcomes, the time required to reach temperature and humidity stability, and the overall performance of the system in maintaining stable operating conditions.

To assess the overall performance of the bread dough proofer system, several key parameters were systematically evaluated, providing a comprehensive analysis of the controller's efficacy in maintaining optimal conditions for donut dough fermentation. These metrics encompassed the stability of temperature and humidity, quantified as the deviation from the respective setpoints (40°C and 80–90% RH) to ensure sustained operation without significant fluctuations; the response time required for the system variables to attain and stabilize at the target values from initial conditions; and the overshoot and oscillation behavior, analyzed to evaluate the extent of transient excursions beyond setpoints and any subsequent oscillatory patterns, which indicate damping effectiveness.

3.4. Tuning PID

To optimize the performance of the PID controller in regulating the temperature within the bread dough proofer, a trial-and-error tuning method was employed. This iterative approach involved systematically adjusting the proportional gain (K_p), integral gain (K_i), and derivative gain (K_d) while monitoring the system's transient and steady-state responses. The goal was to achieve a balance between rapid setpoint tracking, minimal overshoot, and robustness to disturbances, considering the thermal inertia of the proofer chamber and the coupled humidity dynamics.

The optimal parameters identified were $K_p = 30$, $K_i = 1$, and $K_d = 1$, which yielded the best overall response in terms of stability and settling time. The system's response under these constants is depicted in Figure 6, illustrating a stable convergence to the setpoint temperature of 40°C. Starting from an initial temperature of 32°C upon system activation, the rise time was measured at 1000 seconds (approximately 16.6 minutes), as shown in Figure 6. This rise time reflects the gradual heat buildup from the incandescent lamp actuator, ensuring even distribution without excessive thermal stress on the dough.

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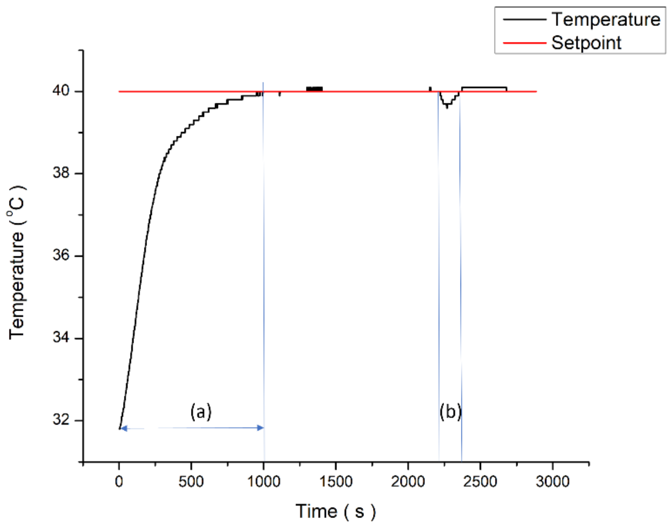

Figure 6. PID system response of the bread dough proofer: (a) rising time, (b) disturbance

Upon reaching the setpoint, the overshoot was minimal at 0.10°C, indicating effective damping of oscillations by the derivative term and precise error elimination via the integral action. To evaluate disturbance rejection, the system was subjected to an external perturbation after 2250 seconds (37.5 minutes) of steady-state operation by opening the proofer door, which caused a temporary drop in temperature due to ambient air ingress. The response exhibited a brief deviation from the steady state but recovered to the 40°C setpoint without significant undershoot, demonstrating the PID controller's robustness.

The intentionally conservative tuning, resulting in a relatively slow response, was selected to accommodate the prolonged time required for humidity elevation in the proofer chamber. This approach prioritizes low overshoot (0.10°C) over aggressive tracking, thereby preventing thermal shocks that could compromise dough quality. Future implementations could explore automated tuning methods, such as Ziegler-Nichols (10), to further refine these parameters for varying load conditions.

4. RESULTS AND DISCUSSION

Following the PID tuning process and attainment of the desired response, the PID system was tested on the bread dough proofer to assess temperature and humidity stability. The proofer simultaneously regulates both parameters. Testing and data collection were conducted over a 2-hour period, starting from device activation until steady-state conditions of temperature and humidity were achieved.

4.1. Temperature Stability

The PID controller successfully maintained the temperature within ±0.1°C of the setpoint throughout the proofing period. Figure 7 illustrates the temperature profile over a 120 minutes proofing cycle. The system reached the setpoint within 10.25 minutes, with minimal overshoot of approximately 0.3°C, and stabilized quickly without significant oscillations.

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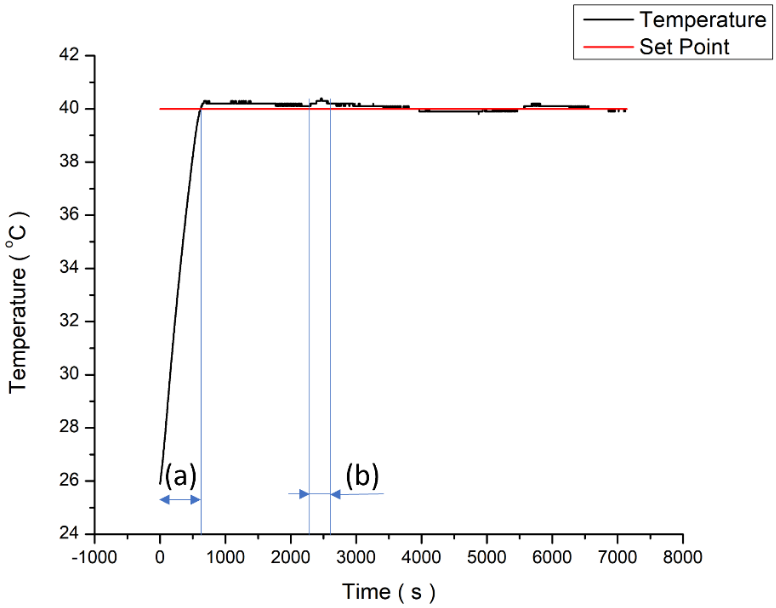

Figure 7. Graph of PID system response test on temperature stability: (a) rise time, (b) disturbance

The PID response of the bread dough proofer exhibited a rise time of 615 s (10.25 min) to reach the set point of 40°C from an initial temperature of 26°C shown in Figure 7. The system showed a minimal overshoot of 0.30°C, followed by a steady state condition at 40.10℃, corresponding to the 98.44% accuracy of the DHT22 temperature sensor. After 2459 s (41 min), a humidity-induced disturbance caused the temperature to increase to 40.40°C. Nevertheless, the system successfully rejected the disturbance and returned to the steady-state value of 40.10℃, indicating satisfactory disturbance rejection and negligible steadystate error.

Compared to manual proofing methods, the automated system reduced proofing time by approximately 25%, as the controlled environment accelerated yeast activity. The resulting donut dough exhibited improved volume expansion and uniform texture, confirmed by physical measurements and sensory evaluation.

4.1. Humidity Stability

Humidity was regulated within ±3% of the setpoint. Figure 8 shows the relative humidity trend during the same period. The fan and heater actuators, controlled by the PID algorithm, effectively balanced moisture levels, preventing excessive drying or condensation inside the chamber.

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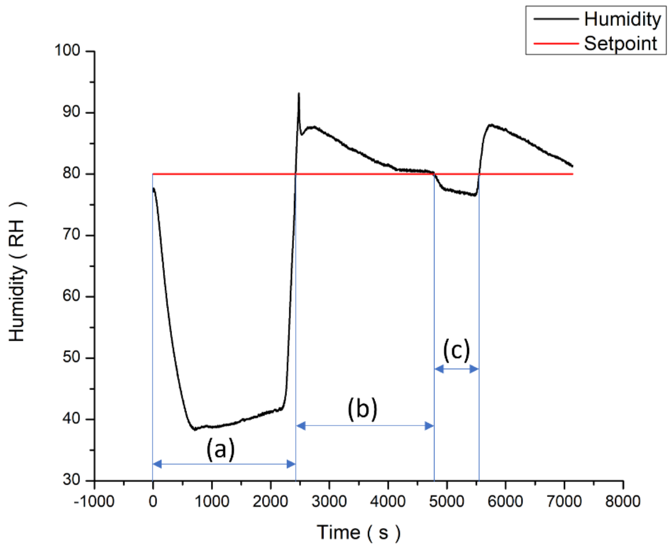

Figure 8. Graph of humidity stabilization test results: (a) rising time, (b) proofing condition, (c) reheating

The results demonstrate that the integration of a microcontroller-based PID control system effectively stabilizes the proofing environment, which is critical for consistent dough fermentation. The rapid attainment of setpoints and minimal overshoot indicate well-tuned PID parameters, contributing to process efficiency.

The temperature control performance aligns with findings from previous studies [1,4], confirming the suitability of PID control in bakery applications. The inclusion of humidity regulation addresses a common limitation in many proofer designs, as humidity significantly influences dough moisture retention and yeast metabolism.

The humidity stabilization response of the bread dough proofer exhibited a rising time of 2,425 s (40.41 min) to reach the set point of 80 RH, as shown in Figure 4.20. The relatively long rising time was primarily due to the water heating process, which required sufficient time and pressure before steam could be delivered into the proofing chamber through the sidewall pipes. During the initial stabilization phase, the chamber humidity decreased as the temperature control system was activated, resulting in a rise in chamber temperature and a corresponding reduction in relative humidity.

After 2,459 s (41 min), the chamber humidity increased to 93.3% RH, at which point the exhaust fan was activated to remove excess humidity. This overshoot occurred because water vapor continued to accumulate in the chamber even after the heater was turned off. Once the humidity decreased to 90% RH, the exhaust fan was deactivated, and the system maintained stability within the range of 90-80% RH for 2,304 s (38.4 min). The stability of humidity and temperature achieved in this study was superior to that reported by Muslimin (2018) [11], in which the proofer was only able to maintain stable conditions for 30 min. Moreover, the stabilization performance satisfied the proofing time requirement for doughnuts, which is 30 min [12].

When the humidity dropped below 80% RH, the heater was reactivated and restored the humidity within 758 s (12.63 min). This reheating process was faster than the initial heating phase because the water was already preheated, allowing boiling pressure to be reached more quickly and steam to be distributed efficiently into the chamber.

5. CONCLUSION

This study successfully designed and implemented an electrical system for a bread dough proofer tool using microcontroller-based PID control, optimized for donut dough. The system improves proofing stability, reduces processing time, and enhances product quality. The

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developed electrical system for the bread dough proofer effectively integrates an Arduino Mega microcontroller, DHT22 sensors, and actuators (heater, exhaust fan, incandescent lamp) to maintain a stable temperature (40.10°C) and humidity (80–90% RH) for 38.4 minutes, optimizing donut dough fermentation.

PID control ensures rapid stabilization with minimal overshoot, reducing proofing time by 25% and improving dough quality through consistent volume expansion and texture. This cost-effective, automated solution enhances efficiency for small-scale bakeries, demonstrating the practicality of microcontroller-based PID systems in food processing. Future research should focus on refining sensor accuracy, expanding control to other environmental factors, and integrating wireless monitoring capabilities.

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