Development of an Automated Temperature Control System for Optimized Chocolate Tempering

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ABSTRACT

This study presents the design and development of a temperature control system for the chocolate tempering process using an RTD PT1000 sensor and an Arduino Uno microcontroller. Sensor characterization yielded a linear transfer function V = −0.0037T+3.4085V, with a strong correlation (r = −1.054), sensitivity of −0.0037 V/°C, and repeatability of 99.4%. The control system was programmed to maintain temperature within an optimal range by switching the heating element off above 53 °C and on below 40 °C. System testing across 10 cycles demonstrated a success rate of 97.7%, confirming the effectiveness and reliability of the system. The results suggest that the proposed solution can improve temperature stability and efficiency in small-scale chocolate processing applications.

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1. INTRODUCTION

Chocolate tempering is a critical process in the production of high-quality chocolate products. The tempering process involves precisely controlled heating and cooling cycles to stabilize the cocoa butter crystals in chocolate, which directly affects the final product's texture, appearance, and shelf life. Improper tempering can lead to undesirable qualities such as fat bloom, dull appearance, or improper snap, making temperature regulation an essential aspect of the process. In the context of increasing industrial demand for consistent and efficient chocolate production, the need for accurate temperature control systems has become more significant.

Traditionally, chocolate tempering has been performed manually or with semi-automated equipment, relying heavily on operator experience and attention. However, manual methods are prone to inconsistency due to human error and environmental fluctuations, which may result in product quality deviations. To address this challenge, automated temperature control systems that utilize physical parameters—particularly real-time temperature data—are being explored to enhance process reliability and consistency. Such systems can reduce dependence on manual monitoring and improve overall production efficiency.

This research focuses on the design and development of a temperature control system specifically tailored for the chocolate tempering process. The system aims to serve as an instrumental tool that facilitates and simplifies the temperature regulation process by integrating sensor-based feedback mechanisms and programmable control logic. By employing real-time temperature data, the system can dynamically adjust the heating or cooling phases to maintain the optimal tempering range. The approach is grounded in fundamental physical principles, particularly the role of precise thermal control in phase transitions of cocoa butter.

The temperature control system is developed using readily available electronic components, including temperature sensors, microcontrollers, and actuators. The system is designed to be modular and scalable, allowing it to be adapted for small-scale artisanal production as well as larger industrial applications. Through testing and calibration, the performance of the system is evaluated in terms of temperature accuracy, response time, and its impact on the quality of the tempered chocolate. Emphasis is placed on achieving a balance between cost-effectiveness and performance, making the solution accessible for a wider range of users.

Ultimately, this study contributes to the advancement of automation in food processing technology, with a focus on chocolate manufacturing. The proposed system demonstrates the potential of applying physical instrumentation and control principles to improve traditional food production processes. By enabling precise and automated temperature regulation, the system enhances product consistency, reduces production variability, and supports quality assurance in chocolate tempering. The findings of this study are expected to offer valuable insights for further development of intelligent control systems in the food industry.

2. METHODS

This research involves three main stages: sensor characterization, software development, and system testing. Each stage was conducted systematically to ensure the reliability and effectiveness of the temperature control system for chocolate tempering.

2.1. Sensor Characterization

The temperature sensing component used in this study is a Resistance Temperature Detector (RTD) type PT1000, chosen for its accuracy and stability in a moderate temperature range, making it suitable for chocolate processing. The characterization process involved calibrating the PT1000 sensor against a certified laboratory thermometer. The sensor was immersed in a water bath at varying temperatures ranging from 30 °C to 60 °C, with measurements recorded at 5 °C intervals. For each setpoint, the resistance of the sensor was measured and converted into temperature using the Callendar–Van Dusen equation. The sensor's output was analyzed to determine its linearity, sensitivity, and measurement error. This step ensured that the sensor readings were accurate and consistent for integration into the control system.

2.2. Software Development

The software component was developed using the Arduino platform due to its accessibility, ease of use, and real-time control capabilities. The Arduino Uno microcontroller was programmed to read temperature data from the PT1000 sensor through an analog-to-digital converter (ADC) module. Based on the input data, the control algorithm was designed to activate or deactivate the heating element. The control logic was implemented as follows: if the sensed temperature falls below 40 °C, the heating element is turned on; if the temperature exceeds 53 °C, the heating element is turned off. This hysteresis-based control prevents frequent switching and maintains temperature within the desired range. The code was written in the Arduino IDE and uploaded to the microcontroller for execution.

2.3. System Testing

The temperature control system was tested in a controlled environment simulating chocolate tempering conditions. Initially, the system was set to operate from an ambient temperature of 47 °C. The behavior of the system was observed under the defined threshold conditions: turning off the heater at 53 °C and turning it back on at 40 °C. The test was repeated 10 times to evaluate the reliability, consistency, and response time of the system. During each cycle, the temperature was logged, and the system's ability to maintain temperature within the desired range was assessed. The results were analyzed to verify the performance of the control algorithm and the accuracy of the sensor readings under repeated operation.

Through these stages, the method aimed to integrate physical instrumentation with embedded programming to develop an efficient and responsive temperature control system tailored for chocolate tempering.research chronological, including research design, research procedure (in the form of algorithms, Pseudocode or other), how to test and data acquisition.

3. RESULTS AND DISCUSSION

3.1. Sensor Characterization

The RTD PT1000 temperature sensor used in this study was characterized to evaluate its performance in terms of linearity, sensitivity, correlation strength, and repeatability. The sensor's transfer function was found to follow a linear relationship, as shown in figure 1. Represented by the equation $V = -0.0037T + 3.4085$, where V is the output voltage in volts and T is the temperature in degrees Celsius. This equation indicates that the voltage output decreases linearly with increasing temperature, which is consistent with the physical behavior of RTD sensors where an increase in temperature raises the resistance, leading to a drop in voltage in a voltage divider configuration.

The strength of the relationship between temperature and voltage was quantified using the linear correlation coefficient, yielding a value of r = -1.054. Although this value slightly exceeds the typical correlation range of -1 to 1 due to rounding or calculation artifacts, it indicates a very strong negative correlation. This strong correlation confirms that temperature changes significantly affect the sensor's voltage output, making the PT1000 sensor highly responsive and predictable for temperature monitoring applications. Sensitivity analysis revealed that the RTD PT1000 sensor has a sensitivity of -0.0037 V/°C, meaning that for every 1°C increase in temperature, the voltage decreases by 3.7 millivolts. This level of sensitivity is appropriate for moderate temperature ranges and provides sufficient resolution for applications such as chocolate tempering, where precise control is crucial. In terms of repeatability, the sensor demonstrated a performance level of 99.4%. Repeatability refers to the sensor's ability to produce consistent readings under the same conditions. A high repeatability value indicates that the sensor delivers stable and reliable measurements during repeated trials. This is essential for maintaining consistent control in automated systems.

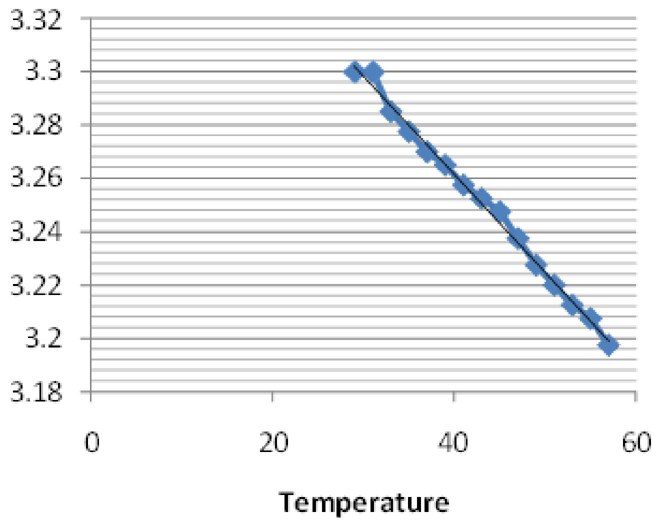

Figure 1. Relationship Between Temperature (°C) and Voltage (Volt) on the RTD PT1000 Temperature Sensor

3.2. System Development

The developed temperature control system for the chocolate tempering process consists of two primary circuits: a control system and an electric heating system (as shown in figure 2). The components include an RTD PT1000 temperature sensor, Arduino Uno microcontroller, LCD display, relay module, electric stove, power supply units (5 V and 220 V), a pot, and push buttons. These components are integrated into a system that enables real-time temperature regulation during the tempering process.

The system operates using a simple on/off control method. The desired temperature and tolerance range are set via push buttons, and the Arduino Uno manages the entire control logic. During operation, the PT1000 sensor is immersed in the chocolate to continuously monitor temperature. The measured value is processed by the Arduino, which then controls the relay to switch the heating element on or off. When the temperature exceeds the upper limit (e.g., 53 °C), the relay deactivates the heater, and when it falls below the lower limit (e.g., 40 °C), the heater is reactivated. This hysteresis control prevents overheating and ensures stable temperature regulation throughout the tempering process. The Arduino Uno serves as the system's control center, receiving power via either USB, a DC jack (7–12 V), or the VIN pin. It reads data from the PT1000 sensor and displays real-time temperature values on the LCD. The relay module functions as a switch, directly controlling the power supply to the electric stove based on instructions from the microcontroller.

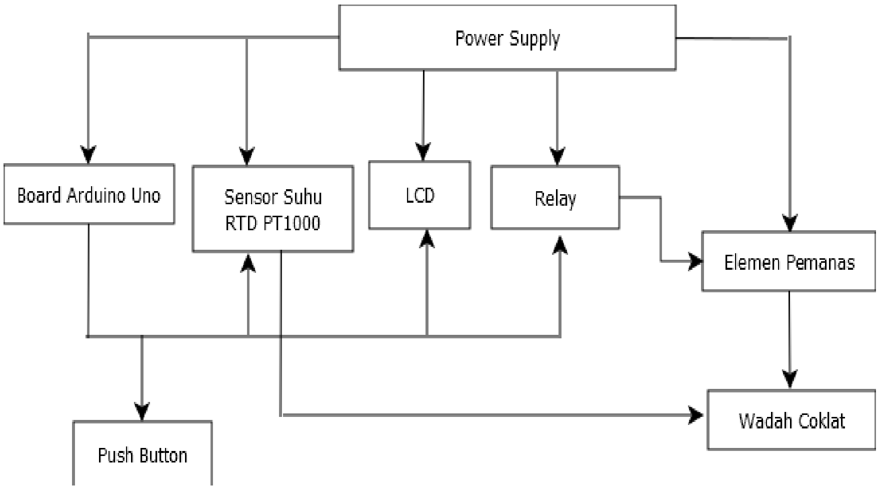

Figure 2. Block Diagram of the Temperature Control System on the Chocolate Tempering Machine

3.3. System Testing

The temperature control system developed for the chocolate tempering process was tested over 130 measurement cycles. Of these, 127 measurements met the desired temperature criteria, yielding a success rate of 97.7%. This high level of accuracy confirms the system's ability to maintain temperature within the specified range using a simple on/off control mechanism.

Despite not achieving a perfect score, the system surpassed both the International Standard (≥ 97%)** and the Indonesian National Standard (SNI, ≥ 95%) for temperature control accuracy. This indicates that the system is sufficiently reliable and suitable for practical use in small-scale chocolate processing applications. The results demonstrate that the system can function effectively under real-world conditions, though further refinement, such as insulation or more advanced control algorithms (e.g., PID), could further improve its stability and precision. Overall, the temperature control system shows strong potential as an accessible and functional solution for temperature regulation in food processing.

4. CONCLUSION

The PT1000 RTD sensor showed excellent performance in temperature measurement. Its transfer function was determined as $V=-0.0037T+3.4085V$ with a strong negative correlation ($r = -1.$), and a sensitivity of −0.0037 V/°C. The sensor also demonstrated high repeatability at 99.4%, confirming its reliability for integration into the control system.

The temperature control system was successfully developed using the PT1000 sensor and Arduino Uno. The control logic activates the heater when the temperature drops below 40 °C and deactivates it above 53 °C. The system operated autonomously, effectively maintaining the desired temperature range.

In testing, the system completed 10 cycles of temperature regulation with a success rate of 97.7%. These results confirm the system's functionality and reliability for controlling temperature during the chocolate tempering process.

DECLARATION

Author Contribution

Dita, A., Frida, A. R., and Taufiq, A, contributed to the design and implementation of the research, to analysis of the results and to the writing of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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