A Fuzzy Logic Approach for Temperature Stability in Infant Incubator Systems

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***Abstract*— An infant incubator is a critical life-support device that provides thermal regulation for premature or low-birth-weight infants who are unable to maintain stable body temperature. Precise temperature control is essential, as instability and prolonged transient responses can increase health risks. Conventional on-off control methods commonly used in basic incubator systems often result in slower stabilization and higher temperature error. Therefore, this study aims to design and implement a baby incubator temperature control system using a fuzzy logic controller (FLC) integrated with a DS18B20 temperature sensor to improve thermal stability. The proposed system was implemented on a physical incubator prototype and evaluated experimentally. System performance was assessed based on dynamic response characteristics, including rise time, peak overshoot, and settling time. Experiments were conducted using three temperature setpoints: 32°C, 35°C, and 36°C. To ensure measurement accuracy, system performance was validated using an Incu Analyzer as a reference device. The experimental results show that the fuzzy logic-based control system achieved a steady-state temperature error of approximately 1% across all setpoints. The maximum observed settling time after peak overshoot was 100 seconds, indicating faster and more stable temperature regulation compared with conventional on-off control methods reported in previous studies. These results demonstrate that fuzzy logic control is effective in handling nonlinear thermal dynamics and improving temperature stability in infant incubator systems. This study focuses on technical performance evaluation; therefore, further investigations related to safety assessment and regulatory compliance are required before clinical implementation. Nevertheless, the proposed system shows strong potential as an intelligent temperature control approach for the development of neonatal incubator technology.**

***Keywords*— Fuzzy Logic, Infant Incubator, Temperature Control, Thermal Stability.**

I. INTRODUCTION

Premature and low-birth-weight infants are highly vulnerable to thermal instability due to immature thermoregulatory systems. Neonatal hypothermia and unstable thermal environments are widely reported to increase the risk of morbidity and mortality [1], [2], making environmental control a critical aspect of neonatal care [3][4]. Infant incubators therefore play an essential role in providing a controlled microenvironment, particularly in terms of temperature and humidity regulation to support neonatal survival and development [5]–[8].

Conventional control approaches such as on–off control and basic PID controllers are still commonly applied in low-cost or prototype incubator systems [9]; however, these methods often exhibit slow stabilization, temperature oscillations, and limited robustness to disturbances [2], [10]–[14]. Consequently, intelligent control techniques, particularly fuzzy logic controllers, have been increasingly explored due to their ability to handle nonlinear dynamics and uncertainty in thermal systems [14]–[16]. Several studies report that fuzzy-based control can improve temperature stability and reduce overshoot when compared with conventional methods. Nevertheless, a critical review of the existing literature reveals common limitations that reduce the clinical and technical relevance of these studies [17].

First, many studies implement fuzzy or intelligent control on non-standard incubator chambers or laboratory-scale prototypes without validation against realistic incubator models [8], [18]–[20]. Second, calibration using medical-grade reference instruments is frequently absent, which raises concerns regarding the reliability of reported performance [21], [22]. Third, several studies present fuzzy controller designs without sufficient justification of membership function selection, rule-base formulation, or controller structure, limiting reproducibility and scientific rigor. In addition, although multi-parameter monitoring systems incorporating IoT and artificial intelligence have been proposed, these systems often lack experimental validation, statistical analysis, or clinical benchmarking [23]–[26]. These limitations indicate that, despite promising technical potential, existing implementations remain under-validated for practical and clinically relevant application.

Based on these gaps, this study proposes the development of a fuzzy logic–based temperature control system implemented on a standard infant incubator model and validated through calibration using a medical-grade Incu Analyzer. This approach is expected to enhance temperature stability, improve neonatal safety, and provide a more adaptive response to environmental fluctuations within the incubator system. The contributions of this work are threefold:

1. Implementation of fuzzy logic control to improve temperature stability and reduce stabilization time,
2. Experimental evaluation on a physical incubator prototype representing realistic operating conditions, and

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3. performance verification using standard calibration instruments to enhance measurement reliability and clinical relevance.

II. Materials and Methods

A. System Architecture of the Infant Incubator

Fig. 1 illustrates the schematic of the closed-loop infant incubator system used in this study. The incubator operates by circulating filtered ambient air using a fan across the heating and humidifying elements before directing the conditioned air into the plexiglass chamber containing the infant. The air is continuously recirculated to maintain stable environmental conditions. The fan plays a critical role in preventing overheating by ensuring effective heat dissipation from the heating element. Heat transfer inside the incubator occurs through conduction across the chamber walls, convection between internal air and surfaces, and radiative exchange between the chamber components and the surrounding environment. Due to the complexity of these thermal interactions, the system is treated as a practical dynamic system rather than relying solely on physical modeling. Therefore, a fuzzy logic-based control approach is adopted to handle uncertainties and nonlinear characteristics in temperature regulation [1].

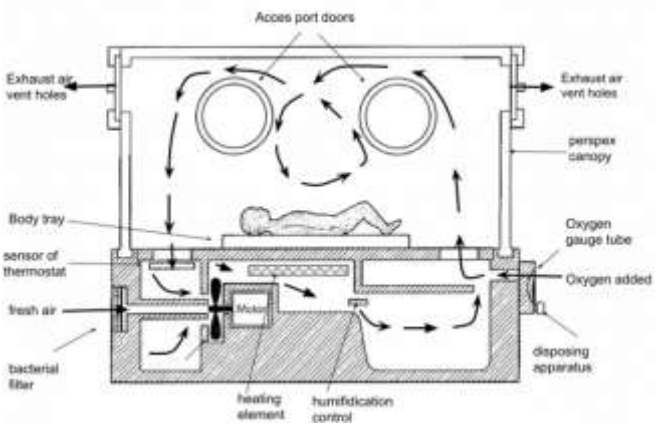


Fig 1. The schematic of the closed-loop infant incubator system used in this study

The physical model of the incubator represents all relevant modes of heat transfer occurring within the system. In this model, the incubator compartment is assumed to be homogeneous in terms of material properties, and the airflow within the incubator chamber is considered to be uniform. All heat transfer processes are assumed to occur in a single direction. Convective and radiative heat exchanges are represented using a global exchange coefficient, while the incubator walls are modeled as thermal resistances characterized by their conduction coefficients, forming a thermal balance between the walls and the internal air node. Equation (1) is an energy balance equation used to model changes in air temperature in an incubator over time due to various heat transfer mechanisms.

$$(\rho c)_{air}\, V_{air}\, \frac{dT_{result}}{dt} \sum_{r} H_{globe}\, S_i (T_{p.int\ erne} - T_{result} + n(\rho c)_{air}\, V_{air}\, (T_0 - T_{result}) + Q_{vent} + P_{(t)} \quad (1)$$

Equation (1) represents an energy balance model describing the dynamic behavior of air temperature inside the incubator. The term $(\rho c)_{air}\, V_{air}\, \frac{dT_{result}}{dt}$ denotes the thermal energy accumulation of the internal air, while the summation term accounts for heat exchange between the incubator walls and the internal air through combined convection and radiation. The ventilation term reflects heat exchange with the ambient environment due to air renewal, and *P(t)* represents the heat input supplied by the heater. Together, these terms describe how the incubator temperature evolves as a result of heating power and heat exchanges with surrounding surfaces and ambient air.

B. Experimental Setup

The experimental evaluation was conducted using a standard infant incubator chamber, which distinguishes this study from many previous works that rely on non-standard laboratory enclosures. Temperature control was implemented using a fuzzy logic controller. Experiments were performed under three temperature setpoints: 32°C, 35°C, and 36°C, with each condition repeated five times. The system performance was evaluated based on dynamic response characteristics, including rise time, overshoot, and settling time. To ensure measurement accuracy, all temperature readings were calibrated against a Fluke Type 2 Incu Analyzer, a medical-grade reference instrument.

The fuzzy logic controller (FLC) was developed based on the fundamental concepts of fuzzy set theory, which allows the representation of uncertainty and nonlinearity in control systems. In this study, the controller uses the temperature error as in (2) as the input variable,

$$e(t) = T_{set} - T_{measured} \quad (2)$$

where T_{set} is the desired temperature setpoint and $T_{measured}$ is the actual incubator temperature. The input error is mapped into linguistic variables using triangular membership functions, which are mathematically defined as in (3):

$$\mu(x; a, b, c) = \begin{cases} 0, & x \le a \text{ or } x \ge c \\ \frac{x-a}{b-a}, & a < x \le b \\ \frac{c-x}{c-x}, & b < x < c \end{cases} \quad (3)$$

where a, b, and c represent the lower limit, center, and upper limit of each membership function, respectively. The inference mechanism is based on a set of IF-THEN rules that map the linguistic representation of the error to the control output (heater power). The fuzzy inference process produces fuzzy output sets, which are then converted into a crisp control signal through a defuzzification process. In this study, the weighted average (Sugeno-type) method is used for defuzzification, expressed as in (4):

$$u = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \quad (4)$$

where w_i is the firing strength of the iii-th rule and z_i is the corresponding output weight. The resulting control signal is applied to the heater in the form of a Pulse Width Modulation (PWM) signal, enabling smooth temperature regulation and reducing excessive overshoot around the setpoint. This approach allows the control system to effectively handle the nonlinear thermal dynamics of the incubator and maintain stable operating conditions.

C. Methods

Fig. 2 illustrates the architecture of the proposed infant incubator system. The system employs multiple sensors as inputs, including a DS18B20 sensor for chamber air temperature, a DS18B20 sensor for skin temperature

monitoring, and a DHT11 sensor for relative humidity measurement. All sensor data are processed by an Arduino Mega 2560 microcontroller, which implements the fuzzy logic control algorithm for temperature regulation. The incubator allows the user to select one of three temperature setpoints, namely 32°C, 35°C, and 36°C, which serve as reference values for the control system. The temperature error between the measured chamber temperature and the selected setpoint is processed by the fuzzy logic controller to determine the appropriate heater output. The heater is driven through a driver module, and its power is regulated using Pulse Width Modulation (PWM) to achieve smooth temperature adjustment. System outputs include a heater for thermal regulation and a motorized airflow mechanism to control air circulation inside the chamber. The airflow motor is controlled using a threshold-based humidity strategy: when the relative humidity exceeds 60%, the motor reduces airflow by closing ventilation, and when the humidity falls below 40%, the motor increases airflow by opening ventilation. All real-time measurements, including chamber temperature, skin temperature, and humidity, are visualized on a 7-inch Nextion TFT display in both numerical and graphical formats. This interface enables continuous monitoring of incubator conditions and system performance.

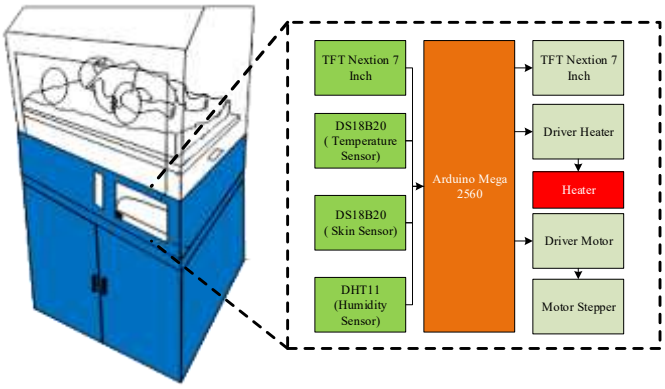


Fig. 2 illustrates the architecture of the proposed infant incubator system

Fig. 3 presents the system flowchart. When the infant incubator is powered on, the system performs an initialization process for the temperature sensors, skin temperature sensor, and communication between the Arduino microcontroller and the TFT display. The TFT interface then provides options for selecting the temperature setpoint to control the operation of the heater and airflow motor. Real-time measurements of chamber temperature, skin temperature, and relative humidity are continuously displayed on the TFT in both numerical and graphical formats. The heater output is automatically regulated by the control algorithm: the heater power is reduced as the temperature approaches the setpoint to maintain stability, and it is increased again when the chamber temperature falls below the selected setpoint. The system begins with a start process followed by initialization, where all sensors, the microcontroller, and the display module are prepared for operation. After initialization, the user selects the desired temperature setting as the target setpoint. If no setting is selected, the system will remain in the setting selection stage. Once the temperature setting is confirmed, the heater is turned on, and the system activates the Fuzzy Logic control algorithm. This controller continuously processes the temperature data from the sensors and determines the appropriate control action to maintain the incubator temperature close to the setpoint. The measured temperature is then displayed on the TFT screen in real time. The system continuously compares the current temperature with the target temperature. If the measured temperature has not yet reached the setpoint, the heater remains active, and the control process continues. When the temperature reaches or exceeds the setpoint, the system automatically turns the heater off to prevent overheating. After that, the system checks whether a reset command is given. If no reset is selected, the system returns to the monitoring and control loop. If reset is activated, the process confirms termination and the system proceeds to end.

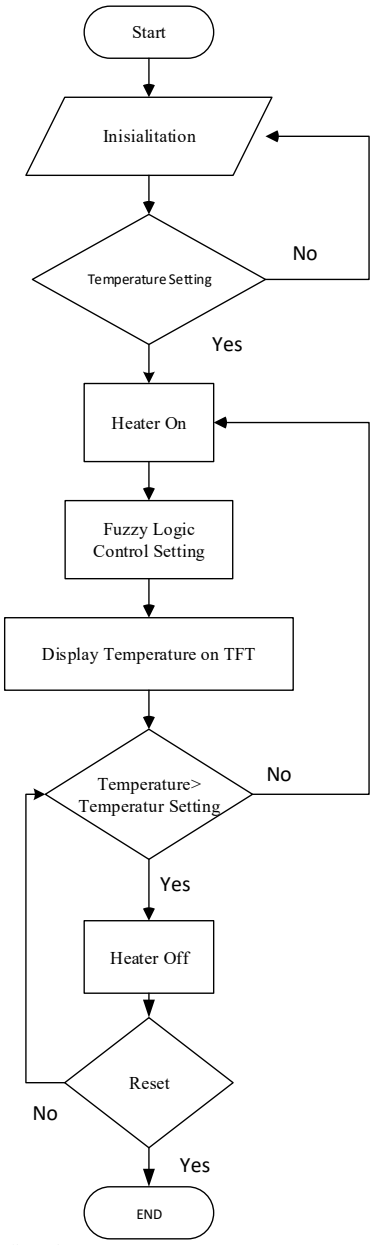


Fig. 3. The system flowchart

III. RESULTS

The performance of the proposed fuzzy logic–based temperature control system was evaluated experimentally using a calibrated medical-grade Fluke Type 2 Incu Analyzer as the reference instrument which is explained in Fig.4. The evaluation focused on three aspects: (1) measurement accuracy, (2) temperature distribution inside the chamber, and (3) dynamic response of the fuzzy control system under different temperature setpoints (32°C, 35°C, and 36°C). In this study, a medical-grade Incubator Analyzer (Incu

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Analyzer) was used as a reference instrument to validate the temperature performance of the proposed infant incubator system. The Incu Analyzer is a standardized calibration device specifically designed for evaluating the performance of neonatal incubators, including temperature accuracy, spatial temperature distribution, and environmental stability.

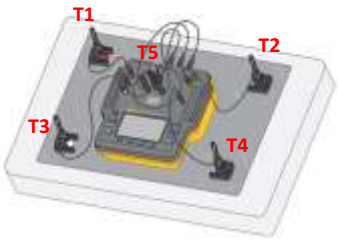


Fig. 4. Calibrated medical-grade Fluke Type 2 Incu Analyzer as the reference instrument

A. Validation Using Incu Analyzer



Fig. 5. The incubator module was compared with measurements obtained from the Incu Analyzer

To ensure measurement reliability, the temperature readings from the incubator module were compared with measurements obtained from the Incu Analyzer. The analyzer sensors were positioned at five measurement points (T1–T5) inside the incubator chamber, as illustrated in Fig. 5. This setup follows standard practice for evaluating temperature uniformity and accuracy in infant incubators.

Table I summarizes the temperature measurement results for the three setpoints. Across all conditions, the maximum observed error was below 0.5°C, with average error values corresponding to less than 1% deviation from the reference instrument. The uncertainty values for all measurements were also below 0.5°C, indicating good precision and stability of the measurement system. These results demonstrate that the developed system provides acceptable accuracy for infant incubator temperature monitoring.

TABLE I. SUMMARIZES THE TEMPERATURE MEASUREMENT RESULTS FOR THE THREE SETPOINTS

Temp. Setting (°C)	Incu Analyzer (°C)					Error (°C)	Uncertainty (°C)
	T1	*T2*	*T3*	*T4*	*T5*		
32	31.8	31.5	31.7	31.6	31.7	0.346	0.23
35	34.7	34.7	34.5	35	34.8	0.2752	0.21
36	35.6	35.5	35.9	35.9	35.7	0.28	0.26

B. Temperature Distribution Inside the Chamber

Temperature distribution was evaluated to assess the uniformity of heat inside the incubator chamber. Measurements were recorded simultaneously at five positions (T1–T5) using the Incu Analyzer. Fig. 6, Fig. 7, and Fig. 8 illustrate the temperature distribution graphs for setpoints of 32°C, 35°C, and 36°C. At Fig.6 the 32°C setpoint, the temperature across all points remained within the acceptable tolerance range of ±0.5°C, indicating good spatial uniformity. At the 35°C setpoint, a brief overshoot was observed during the transient phase; however, the temperature quickly returned to the acceptable range and remained stable thereafter.

At the 36°C setpoint, no significant overshoot occurred, and the temperature distribution remained stable across all sensor positions. These results indicate that the airflow and heating mechanisms, combined with fuzzy logic control, are able to maintain both stability and spatial uniformity of temperature inside the incubator chamber.

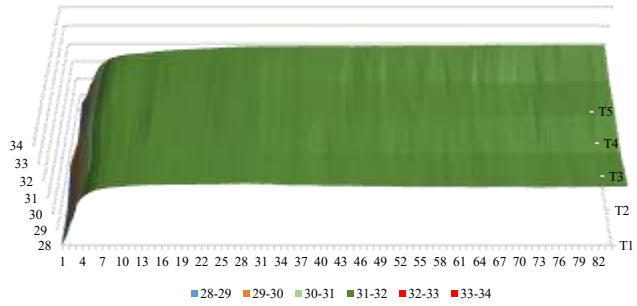


Fig. 6. The temperature distribution graphs for setpoints of 32°C

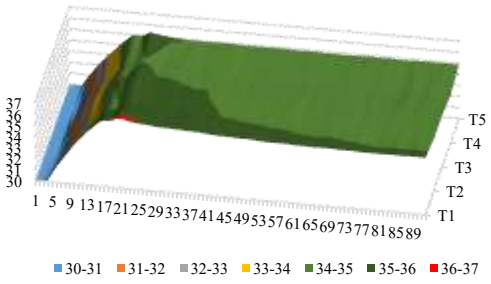


Fig. 7. The temperature distribution graphs for setpoints of 35°C

Fig. 7 shows the three-dimensional temperature distribution inside the incubator chamber at a setpoint of 35°C, measured at five positions (T1-T5). A brief overshoot, indicated by the red-colored region, appears during the initial transient phase. However, the overshoot rapidly diminishes, and the temperatures at all measurement points converge to a stable range (34-36°C). After stabilization, the profiles at T1-T5 remain consistent, indicating good temperature stability and spatial uniformity of the proposed control system.

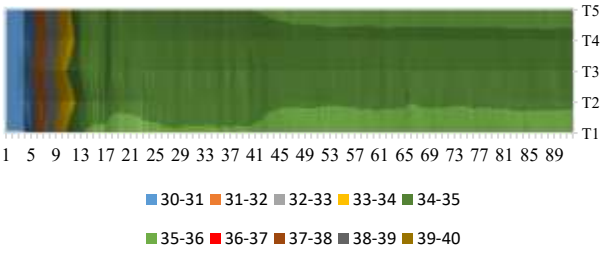


Fig. 8. The temperature distribution graphs for setpoints of 36°C

Fig. 8 presents the three-dimensional temperature distribution inside the incubator chamber measured at five positions (T1-T5). The temperature profiles remain consistently within the green color range (34-36°C) throughout the observation period, indicating that the system reaches the setpoint without experiencing overshoot. The minimal variation among T1-T5 demonstrates good temperature stability and spatial uniformity, confirming the effectiveness of the proposed control system in maintaining stable thermal conditions.

C. Dynamic Response of Fuzzy Logic Control

The dynamic performance of the control system was further analyzed using temperature data recorded directly from the module sensors. For the 32°C setpoint in Fig. 9, the system required approximately 179 seconds to reach the setpoint. An overshoot occurred between 180 and 220 seconds, followed by a recovery time of about 40 seconds. After stabilization, the temperature remained within ±0.5°C for the remainder of the 30-minute observation period. The overall error value was calculated as 0.012.

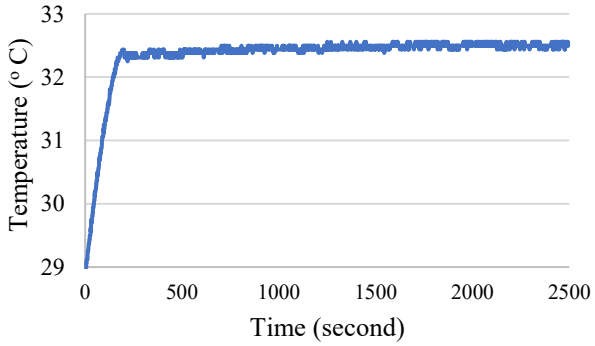


Fig. 9. The module reading temperature sensor at a set temperature of 32ºC

Based on the data presented in Table II, the temperature control performance at the 32°C setpoint demonstrates stable system behavior. The average measured temperature during minutes 10–30 reached 32.43°C and 32.45°C, which falls within the acceptable tolerance of ±0.5°C, indicating that the system successfully achieved and maintained the target setpoint. During the initial phase (minutes 1–10), a higher standard deviation (0.88) was observed due to the transient heating process, where the temperature increased from ambient conditions and reached the setpoint at approximately 179 seconds. A brief overshoot occurred between 180 and 220 seconds, followed by a recovery time of approximately 40 seconds to return to the stable region. After stabilization, the temperature remained within the tolerance band from approximately 250 seconds to 1800 seconds (30 minutes), indicating good steady-state stability. The overall error value of 0.012 further confirms the reliability of the control system, demonstrating that temperature fluctuations around the setpoint are minimal.

TABLE II. TEMPERATURE SENSOR VALUES AT A SET TEMPERATURE OF 32 ° C

Temperature Setting 32 ° C				
Time	*Temperature Average*	*Deviation Standard*	*Error*	*All Error*
Minute 1 – 10	31.92	0.88	0.036	
Minute 10 - 20	32.43	0.35	0.001	0.012
Minute 20 - 30	32.45	0.03	0.001	

For the 35°C setpoint in Fig.10, the rise time was approximately 200 seconds, followed by an overshoot occurring between 200 and 300 seconds. The system required around 100 seconds to return to stable conditions. Once stabilized, the temperature remained within the tolerance band. The overall error value obtained was 0.02.

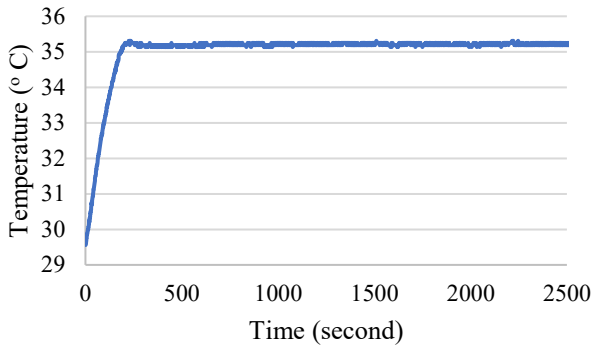


Fig. 10. The module reading temperature sensor at a set temperature of 35ºC

Based on the data presented in Table III, the temperature control performance at the 35°C setpoint shows a clear transient response followed by stable operation. During the first 10 minutes, the average temperature was 34.4°C with a relatively high standard deviation of 1.47, indicating the warm-up phase as the system approached the target temperature. In the subsequent intervals (minutes 10–20 and 20–30), the average temperature reached 35.2°C with a much lower standard deviation of 0.03, demonstrating that the system successfully achieved and maintained the setpoint within the acceptable tolerance of ±0.5°C. The overall error value of 0.02 indicates that temperature fluctuations around the setpoint were small and that the control system provided stable regulation. The significant reduction in deviation from the first interval to the later intervals confirms the effectiveness of the fuzzy logic controller in suppressing oscillations and improving temperature stability after the initial transient phase.

TABLE III. TEMPERATURE SENSOR VALUES AT A SET TEMPERATURE OF 35 ° C

Temperature Setting 35 ° C				
Time	*Temperature Average*	*Deviation Standard*	*Error*	*All Error*
Minute 1 - 10	34.4	1.47	0.036	
Minute 10 - 20	35.2	0.03	0.001	0.02
Minute 20 - 30	35.2	0.03	0.001	

For the 36°C setpoint in Fig. 11, the system reached the setpoint at approximately 350 seconds, with overshoot occurring between 350 and 450 seconds. The recovery time after overshoot was about 50 seconds, and the overall error value was 0.027. Despite the higher initial transient response, the steady-state temperature remained within the acceptable clinical tolerance. Based on the data presented in Table IV, the temperature control performance at the 36°C setpoint shows a transient warm-up phase followed by stable operation. During the first 10 minutes, the average temperature was 34.56°C with a standard deviation of 1.20, reflecting the heating process as the system approached the target temperature. In the subsequent intervals (minutes 10–20 and 20–30), the average temperatures increased to 36.09°C and 36.12°C, respectively, while the standard deviation decreased to 0.049 and 0.040, indicating that the system

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successfully achieved and maintained the setpoint within the acceptable tolerance of ±0.5°C**.** The overall error value of 0.027 indicates that temperature fluctuations around the setpoint were minimal. The progressive reduction in deviation over time demonstrates the effectiveness of the fuzzy logic controller in suppressing variability and ensuring stable temperature regulation after the initial transient response.

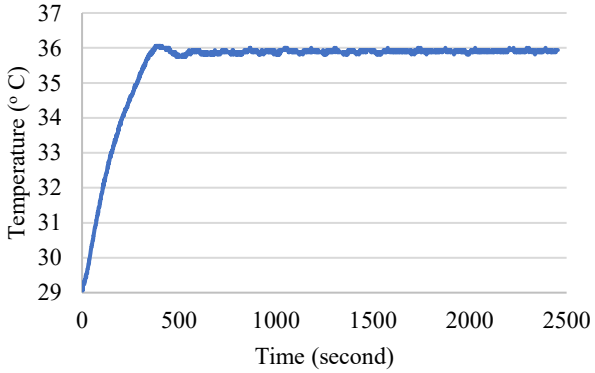


Fig. 11. The module reading temperature sensor at a set temperature of 36ºC.

TABLE IV. TEMPERATURE SENSOR VALUES AT A SET TEMPERATURE OF 36 ° C

Temperature Setting 36 ° C				
Time	*Temperature Average*	*Deviation Standard*	*Error*	*All Error*
Minute 1 - 10	34.56	1.2	0.079	
Minute 10 - 20	36.09	0.049	0.002	0.027
Minute 20 - 30	36.12	0.04	0.001	

III. DISCUSSION

This study evaluated the performance of a fuzzy logic-based temperature control system implemented in a physical infant incubator prototype and validated using a medical-grade Incu Analyzer. The discussion focuses on three key aspects: measurement accuracy, temperature stability, and control performance compared with previous studies. The validation results show that the average temperature error across all setpoints (32°C, 35°C, and 36°C) remained below 0.5°C, corresponding to less than 1% deviation from the reference instrument. This indicates that both the sensing subsystem and control output are sufficiently accurate for experimental incubator evaluation. Compared to several previous studies that lacked calibration using certified instruments, this work provides stronger measurement reliability and improves the technical credibility of the reported performance.

The analysis of temperature distribution using five spatial measurement points (T1–T5) demonstrates that the incubator chamber maintained a relatively uniform temperature under all test conditions. This indicates that the combination of airflow circulation and fuzzy-controlled heating was effective in minimizing spatial gradients. Although a brief overshoot was observed at the 35°C setpoint, the system was able to recover rapidly and return to the acceptable tolerance band (±0.5°C). Importantly, the overshoot duration did not persist long enough to cause sustained thermal instability, which is critical in neonatal applications.

From a dynamic control perspective, the fuzzy logic controller exhibited a reasonable rise time and effective stabilization behavior. At the 32°C setpoint, the recovery time after overshoot was approximately 40 seconds, while at 35°C it increased to around 100 seconds, and at 36°C, approximately 50 seconds. These variations reflect the nonlinear thermal characteristics of the chamber and heater system. Nevertheless, the controller consistently maintained a stable steady-state performance after transient conditions. This confirms that fuzzy logic control is well-suited for managing the nonlinear and uncertain dynamics of infant incubator thermal systems.

When compared with earlier studies using on–off or PID-based controllers, the stabilization performance achieved in this study is competitive. Several previous works report longer settling times and larger oscillations around the setpoint, whereas the present system demonstrates reduced overshoot duration and acceptable stabilization time. The practical implication is that the risk of prolonged temperature fluctuation, which may affect neonatal thermal comfort, can be minimized through intelligent control strategies such as fuzzy logic. However, this study also has limitations. The evaluation focused primarily on technical performance under laboratory conditions. Long-term reliability, safety assessment, electromagnetic compatibility, and compliance with medical device standards were not addressed in this work. Therefore, while the results demonstrate strong technical feasibility, further studies are required before clinical deployment.

In this research, an analysis of the temperature distribution in the infant incubator was carried out. Measurements were carried out using an incubator analyzer at T1, T2, T3, T4, and T5. The temperature distribution is shown in a graph where green is the color for the setting temperature of ± 0.5 °C. From the results of measurements with the Incu analyzer, the average error compared to the standard was below 0.5 ºC or 1%. These results are better than previous research by [21], [27]–[29]. The temperature distribution in all settings appears to be within the allowable range. There was an overshoot at the temperature setting of 35 °C, but the time needed to return to stability was only 11 seconds. Fuzzy logic system testing shows that the infant incubator at a setting of 32 °C takes 30 minutes to stabilize, while the time needed to stabilize after overshoot takes 40 seconds. At a temperature setting of 35 ºC, it takes 30 minutes to stabilize and takes 100 seconds to return to stability from overshoot. For a temperature setting of 36 ºC it takes 35 seconds to return to stability after overshoot. These results are better than previous studies [30]. The benefit of this research is that by minimizing the time used to return to stability after overshoot, the baby will avoid temperature spikes.

IV. CONCLUSION

This study aimed to design, implement, and experimentally evaluate a fuzzy logic-based temperature control system for an infant incubator prototype, with validation conducted using a medical-grade Fluke Type 2 Incu Analyzer to ensure measurement reliability. The evaluation focused on temperature accuracy, stability, spatial uniformity, and dynamic response performance under three operating setpoints (32°C, 35°C, and 36°C).

The experimental results demonstrate that the proposed system achieved temperature accuracy within ±0.5°C, corresponding to less than 1% steady-state error across all setpoints. The use of multi-point measurements (T1–T5) confirmed that the temperature distribution inside the

incubator chamber remained relatively uniform, indicating that the integration of airflow circulation and fuzzy-controlled heating effectively minimized spatial temperature gradients. In terms of dynamic behavior, the system exhibited acceptable transient performance, with recovery times after overshoot ranging from 40–100 seconds, depending on the operating temperature. These findings confirm that the fuzzy logic controller is capable of handling the nonlinear thermal dynamics of the incubator and maintaining stable operating conditions.

The primary contribution of this study lies in the implementation of an intelligent control approach that is not only tested on a physical prototype but also validated using a certified medical calibration instrument, thereby enhancing the technical credibility compared with many previous prototype-based studies. The results indicate that fuzzy logic control provides a promising strategy for improving temperature stability in neonatal incubator systems. Future work should focus on extending the evaluation toward long-term reliability testing, safety analysis, electromagnetic compatibility (EMC), and compliance with medical device standards (e.g., IEC 60601-2-19). In addition, further improvements can be achieved by optimizing chamber design to enhance temperature uniformity, refining the fuzzy rule base, and integrating adaptive or intelligent learning mechanisms to further improve control performance under varying environmental conditions.

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