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Development of Adaptive PD Control for Infant Incubator Using Fuzzy Logic

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***Abstract*—This research aims to design an innovative fuzzy logic auto-tuning PD algorithm to control the temperature in a baby Incubator. The proposed Fuzzy-PD method combines fuzzy logic with PD control using the Arduino Mega 2560 microcontroller. The Proportional and Derivative parameters are adjusted by fuzzy logic based on feedback of error values and rate of change of error. The temperature setting range used in data collection is 32-37°C. When the temperature setting is higher, the time required to reach the specified temperature setting becomes longer. The overshoot tends to be low, as the system is designed to respond to temperature changes with high precision. The temperature inside the baby Incubator can be maintained with a low steady-state error value. The adaptive fuzzy-PD system can restore the temperature inside the baby Incubator to the set temperature after a disturbance. Compared to the x device, the average error value is 0.0013%. Independent sample t-tests show no significant difference between the baby Incubator and the Incu analyzer device. It can be concluded that the combination of fuzzy logic and PD control system works well in maintaining temperature stability with low error values. The results are better than previous research focusing on designing a PD algorithm with a maximum rise time of 480 seconds. Furthermore, there is potential for further development with a fuzzy logic auto-tuning PID algorithm to achieve better results.**

Keywords*—*Baby Incubator; Auto Tuning; Fuzzy Logic; PD Controller; Fuzzy-PD.

I. INTRODUCTION

The American Academy of Pediatrics states that premature babies are babies born at 37 weeks of gestation with a body weight of less than 2500 grams [1]. Premature newborns require special care and must be completely isolated as they are more likely to contract infections in public places [2], [3]. Therefore, there is a need for an incubator. One of the electromedical equipment that falls into the "life support" category is a baby incubator. To care for babies born prematurely or with low birth weight by maintaining constant temperature and humidity, it is very important to use a baby incubator whose working principle is similar to the one in the mother's womb [4][5]. When the baby's body temperature exceeds normal limits, hyperthermia will occur. Babies have little mass to function as a heat sink, limited thermal insulation, and a very large surface area. Due to their immature thermal regulation, newborns are unable to control the temperature of their environment or generate heat [6]. Temperature regulation is carried out so that the baby's body temperature, the surrounding environment, and other factors remain constant [7], [8]. Usually, baby incubators are made to help care for and monitor babies in a way that is transparent, clean (sterile), equipped with the necessary electronic equipment, and soundproof [9], [10]. To design a baby incubator, you must use a control system that can stabilize the temperature in the incubator. Several types of controls can be used in incubators, one of which is PD and Fuzzy Control [11]. PD control is a combination of proportional and derivative control, while fuzzy logic is a variable-processing approach that allows several possible truth values to be processed through the same variable [12], [13]. Dallas Semiconductor's DSl8B20 digital temperature sensor is used in temperature testers. The DSl8B20 can replace analog temperature sensors and signal processing circuitry due to its monolithic design. The DSl8B20 and a microcontroller can be quickly connected for complete temperature monitoring and data processing. The DSl8B20 is the only digital temperature sensor that transfers data over a single bus. The DS18B20 sensor uses a single line for data input and output and features a fairly wide measurement range from -55°C to 125°C [14]. Thus, this sensor was chosen due to its easy configuration, which only requires an external 4.7KΩ resistor connected to the VCC and DQ terminals [15]. Arduino Mega is a microcontroller based on ATMEGA 2560. Arduino Mega is simply connected to a computer using a USB cable to start [13]. The use of Arduino Mega 2560 was chosen due to its easy integration with the Nextion TFT LCD, making it easier for users to operate the baby Incubator with a more compact interface design and real-time temperature displayed on the Nextion TFT LCD [16], [17].

In previous research, Sudip Halder et al designed a closed-loop temperature Control System using proportional and integral (PI) control to sense room temperature and maintain it at a fixed desired value. The results of this research are small overshoot, fast response, and high precision. however, the response is slightly slower [18]. Shatha Y. Ismail et al designed a water temperature controller heated by an oil-fired heater using a Proportional-Integral (PI) controller with the Programmable Logic Controller (PLC) technique. Measurable temperature but the PLC system is expensive [19]. Tamanna Afrin Tisa et al developed a temperature control system for baby incubators using pulse width modulation (PWM) and a simple ON-OFF control method [20]. A neonatal incubator with On/Off Control was developed by Wayan Widhiada et al. to help with temperature distribution. The incubator has a temperature setting of 36°C [16]. José Amadeo Dávalos Pinto et al. designed a baby incubator with a Digital PID Temperature controller. The aim was to create and implement a cockpit temperature prototype of the ESVIN newborn life support equipment, based on the international standard IEC 60601-2-19 for the safety and operation of neonatal incubators [21]. Because, according to the researchers, this technique maintains linearity in temperature regulation, allowing premature babies to be maintained at the temperature in the baby incubator [22].

The contribution of this research is to design a fuzzy logic-based adaptive PD control algorithm using a DS18B20 sensor to control the temperature inside a baby incubator [23]. This research also observes the rise time and settling time as well as the overshoot value resulting from the implementation of the adaptive PD control algorithm in real time [24], [25]. By doing this research, it is expected that fuzzy logic-based adaptive PD control to control baby incubators or whether there is still a need for innovation in making temperature control in baby incubators.

II. Research Method

This research paper focuses on designing a new fuzzy logic auto-tuning PD algorithm for temperature control in baby Incubators. This system aims to improve performance and reduce temperature fluctuations to obtain results with a high degree of precision along with more precise accuracy [26]. Of course, premature babies must warm their bodies according to medical indications. The proposed Fuzzy-PD method combines fuzzy logic with PD control using an Arduino Mega 2560 microcontroller [27]. KP and KD parameters are set by fuzzy logic according to the needs of different processes in the PD monitoring system[28]. The PD controller can convert voltage into temperature in the system through a 1200W heater in a baby incubator box of size length = 86 cm, width = 41 cm, and height = 66,5 cm. The first step taken by the author is to organize the hardware into a baby incubator circuit which can be seen in Fig. 1.

The DS18B20 sensor is used as a process input that functions as a temperature-measuring component. The Nextion TFT LCD functions as an HMI (Human Machine Interface) interface for interaction with the user when setting the temperature to operate the baby Incubator. The Arduino Mega 2560 microcontroller is used to process the value obtained by the DS18B20 sensor, which will then be processed with a fuzzy logic auto-tuning PD and implemented on the heater as an output [29]. The placement of the Arduino Mega 2560 microcontroller and heater is right behind the Nextion TFT LCD in the baby Incubator box. The DS18B20 sensor is placed at the end of the right side (end of air circulation) in one room with premature babies.

A. PD Control Design

PD (Proportional-Derivative) control is one type of control used in automatic control systems as depicted in Fig. 2. Proportional provides a response that is proportional to the difference between the setpoint (desired value) and the current value of the process [30], [31]. The larger the difference, the larger the response produced by the proportional element [32], [33]. This response serves to reduce the error between the setpoint and the process value. derivative responds to the rate of change of error. If the error changes rapidly, the derivative element provides a larger response to reduce the overshoot effect and improve system stability [34], [35].

There is an error variable as the input of the PD control system. The error value is obtained when we have set a setpoint as the intended value, but there is a difference between the value to be addressed and the value recorded by the sensor as feedback on the input. After being processed by the three settings, the output value will control an object that is used[36].

To operate PD control on a system, each method has a defined constant value. PD tuning is the process of determining the PD value [37]. Ziegler-Nichols formula with reaction curve approach is one of the methods for PD tuning. The Ziegler-Nichols tuning method is a heuristic method of tuning a PD controller. This method is applied by looking at the response of the system when given input [38].

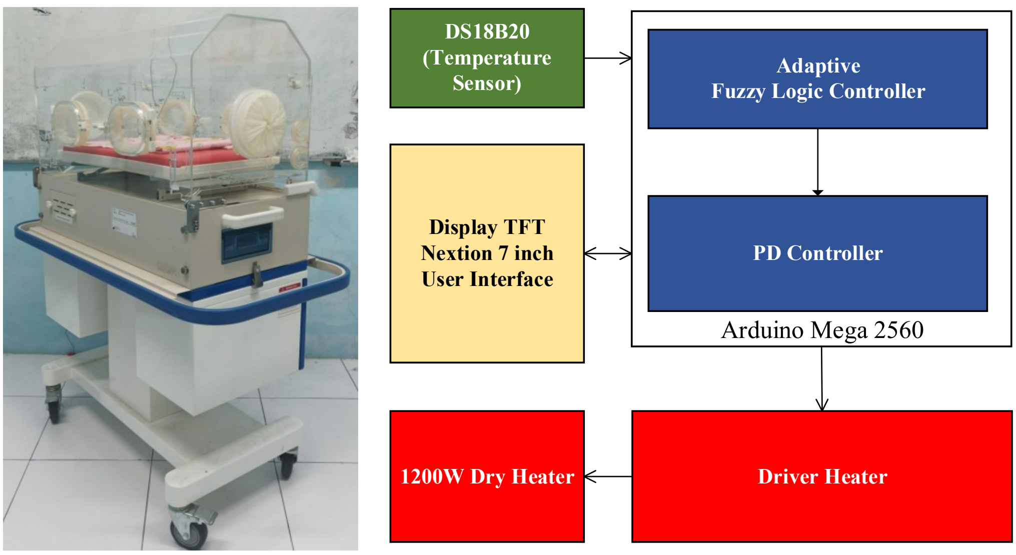

Fig. 1. Block diagram of baby incubator circuit

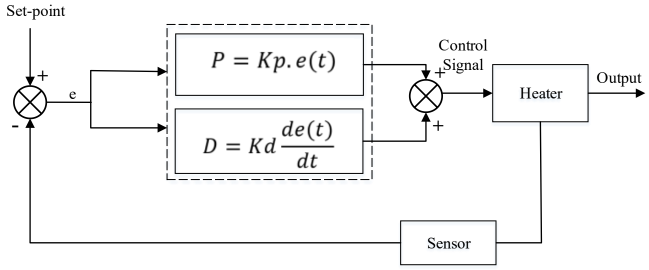

Fig. 2. Design of PD control used for temperature control in baby incubator

The system response is presented in the form of a reaction curve (Fig. 3) and is characterized by two parameters by 2 parameters, namely L (time delay), and T (time constant) [20]. These two times will be used to obtain the initial K_p and Kd values that will be used in this research. This results in the following formulas and values for $K_p a$ and $K_d a$:

$$K_p a = 1.2 \times \frac{T}{L} \tag{1}$$

$$K_d a = K_p a \times L \times 0.5 \tag{2}$$

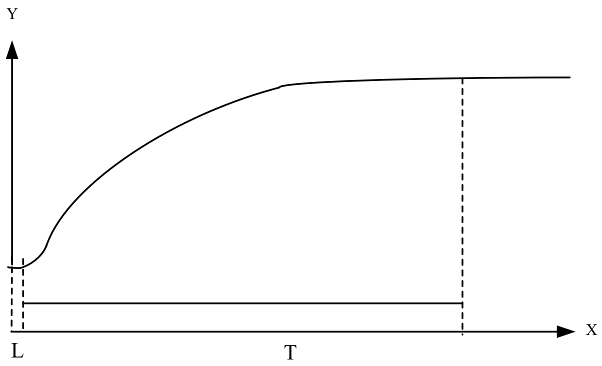

Fig. 3. "S" curve reaction

B. *Fuzzy Logic Control Design*

Fuzzy Logic Control (FLC) is one of the automatic controls proposed in the 1970s. This control system has two types, namely Mamdani and Sugeno. Fuzzy Inference System Mamdani method is known as Max-Min theory control which was first developed in 1975 by Ebrahim Mamdani. In Mamdani's Fuzzy Inference System method, input and output values are represented in the form of fuzzy sets. Sugeno's Fuzzy Inference System method in its membership function is Singleton. First introduced in 1986 by Takagi Sugeno Kang (TSK) [39], [40], [41]. Unlike the Mamdani model, input values are represented in fuzzy sets, and the output values of fuzzy rules are expressed as polynomial equations. Fuzzy Logic Control (FLC) is a basic control technique that eliminates the need for knowledge of the numerical parameters of the system [42][43]. In terms of obtaining desired values, Fuzzy Logic Control (FLC) based control systems outperform conventional techniques. In addition, these systems have the advantage of being stable in managing an item [44], [45]. Fuzzy logic control, also known as Fuzzy Inference System (FIS), is a control system that incorporates fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning [46], [47]. The Fuzzy Inference System (FIS) accepts linguistic variables and crisp variables as inputs, but the output is almost always a fuzzy set. In the form of a fuzzy set. When a fuzzy inference system (FIS) is used as a controller, it requires a precise or numerical output [48]. Defuzzification is a method for transforming a fuzzy set to a crisp value. Fuzzy logic control includes fuzzification, database (membership functions of fuzzy sets used in fuzzy rules), rule base, fuzzy decision (fuzzy rule inference), and defuzzification (see Fig. 4) [49], [50].

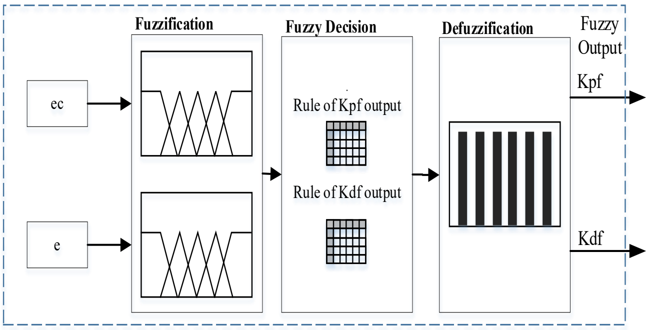

Fig. 4. Architecture of fuzzy logic control

This research uses two input values that will be processed by the fuzzy control system, namely e and ec. The two input values are converted into fuzzy values in the fuzzification process. Fuzzification is the process of converting non-fuzzy variables (numerical variables) into fuzzy variables (linguistic variables) [51], [52]. The numerical variable in this case is the error value that has been initialized with a, b, c, d, e, f, and g. Researchers use several membership functions, namely triangular and trapezoidal membership functions [53], [54]. We design a membership function as shown in Fig. 5 for error input and Fig. 6 for error change input. The input value of error and error change consists of 7 members, namely Very Large Negative (NSB), Large Negative (NB), Medium Negative (NS), Normal (N), Medium Positive (PS), Large Positive (PB), and Very Large Positive (PSB) [55]. Likewise, the fuzzy logic output section consists of 7 members, namely Zero (N), Small Medium (KS), Small (K), Medium (S), Large (B), Large Medium (BS), and Very Large (SB).

A rule base is a set of decision-making logic, which simulates the human decision-making process [56]. The rule base is formed by using inputs and their associated outputs, that is what should be the output for a given set of inputs [57]. Seven membership functions were considered for the inputs and outputs resulting in a total of 49 rules. The rules are displayed using Table I and Table II.

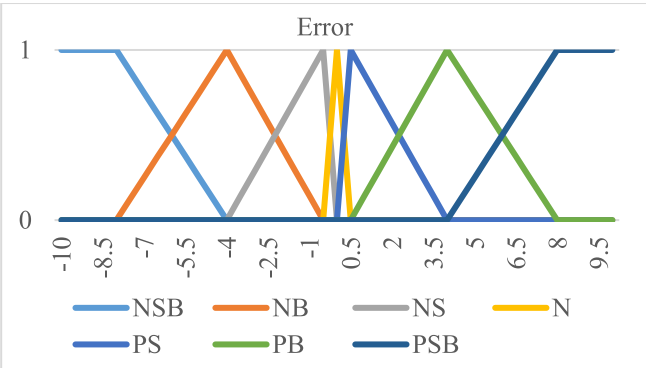

Fig. 5. Member function plot of input error

Fig. 6. Member function plot of input change error

TABLE I. FUZZY LOGIC RULE FOR KPF OUTPUT

EC/E	NSB	NB	NS	N	PS	PB	PSB
NSB	SB	SB	SB	SB	SB	SB	SB
NB	BS	BS	BS	BS	BS	SB	SB
NS	B	B	B	B	BS	BS	SB
N	N	N	N	KS	K	K	SB
PS	B	B	B	B	BS	BS	SB
PB	BS	BS	BS	BS	BS	SB	SB
PSB	SB	SB	SB	SB	SB	SB	SB

TABLE II. FUZZY LOGIC RULE FOR KDF OUTPUT

EC/E	NSB	NB	NS	N	PS	PB	PSB
NSB	N	N	N	K	S	B	SB
NB	N	N	K	S	B	SB	SB
NS	N	K	B	BS	SB	SB	SB
N	K	S	BS	SB	SB	SB	SB
PS	S	B	SB	SB	SB	SB	SB
PB	B	SB	SB	SB	SB	SB	SB
PSB	SB	SB	SB	SB	SB	SB	SB

The syntax for defining rules in a rule base table is:

If (E is NSB) and (EC is NSB)
then
(K_p is SB) and (K_d is N)

Defuzzification is the process of converting linguistic variables into numeric variables, where crisp data will be sent to the PD control system. The output of this fuzzy system is constant values of K_pf and K_df[58]. In the defuzzification part, the membership function uses the Sugeno method. Fuzzy logic with the Sugeno method is a fuzzy system inference process in the form of a constant fuzzy system in the form of constants or linear equations [59], [60]. Sugeno method fuzzy rules are expressed in IF-THEN form. Based on the theory of the Sugeno method, the researcher designs the output membership function to determine the value of K_pf and K_df. The design is shown as Fig. 7. The input error and change error values are processed and classified according to the fuzzy rules for each KP and KD parameter.

From the defuzzification process, the value of each membership function is obtained, such as Normal (N) = 0, Small medium (KS) = 0.5, Small (K) = 0.75, Medium (S) = 1, Large (B) = 1.25, Large Medium (BS) = 1.5, and Very Large (SB) = 2. The above results have been simulated with Matlab 2016 software using the fuzzy logic designer feature, starting from designing membership functions to producing constants at the output [38]. Simulations are carried out to design fuzzy membership sets, followed by creating rules containing 49 rules for each parameter. Then perform linguistic conversion of each membership function according to the range 0 to 2 [61].

Then, the Fuzzy controller output will produce a value that we call the fuzzy KP value that the author short (K_pf) and the author's fuzzy Kd value (K_df). This value is a multiplying factor with the constant values K_pa and K_da [62]. The resolution of the constant output value set is 0.25 from Medium (KS) to Medium Large (BS) for a triangular function and 0.50 for Normal (N) and Very Large (SB) for a trapezoidal function. Therefore continues to combine the two methods into an adaptive control design (fuzzy-PD) which will be explained in the adaptive control design subchapter (fuzzy-PD)[63].

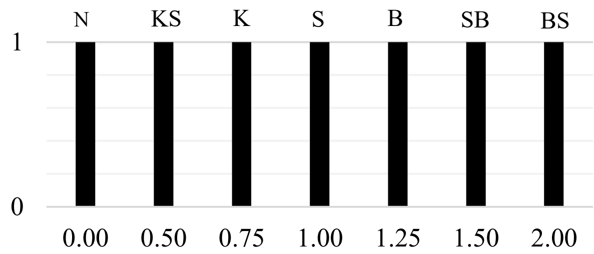

Fig. 7. Plot of Output Member Functions K_pf and K_af

C. Fuzzy-PD Control Design

Fig. 8 is a design drawing of the fuzzy-PD adaptive control used in this study. Where the main framework of this system is like a PD control system, but fuzzy logic is added. Fuzzy logic plays a role in the adaptive K_p and K_d values of PD control [64][65].

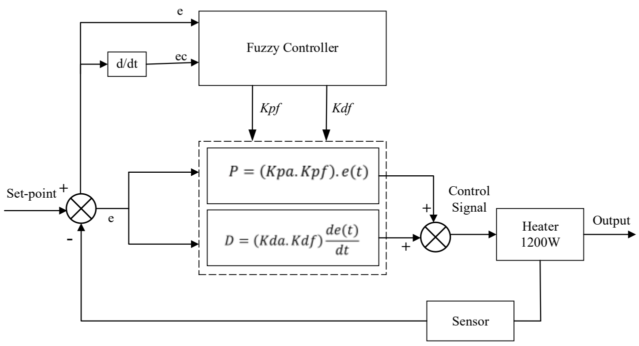

Fig. 8. The overall design of adaptive control using combined two fuzzy-PD methods

Fuzzy-PD control or Fuzzy-based PD control is a dual rule mode to determine the value of proportional and derivative constants in the hope that the resulting response is faster [66]. The input of Fuzzy-PD Control is the error value (3) and the change in error value (4) [67], [68]. In Fig. 8 by using Fuzzy control, the parameters K_p and K_d on the PD can change according to the existing conditions. In this study, to make changes to the PD constants, the values of K_pa and K_da as the initial constant values of the PD constants will be multiplied by the values of Kpf and Kdf derived from the fuzzy logic output [69]. The initial constant value of the PD constant is determined based on observations and calculations according to the Ziegler-Nichols formula with a reaction curve approach so that the adaptability of the system can be as precise as expected. So the K_p formula is as in (5) and the K_d formula is as in (6) [70].

$$Error(e) = TSP - ATV \quad (3)$$

$$Error\ Change(ec) = Error(e) - Previous\ Error \quad (4)$$

$$K_p = K_p a \times K_p f \quad (5)$$

$$K_d = K_d a \times K_d f \quad (6)$$

TSP is the temperature setting point value, while ATV is the actual temperature value. $K_p a$ is the initial proportional constant value of the PD controller tuning result, $K_p f$ is the output proportional constant value of fuzzy logic, $K_d a$ is the initial derivative constant value of the PD controller tuning result, $K_d f$ is the output derivative constant value of the fuzzy controller, after the K_p and K_d values are obtained, then enter the calculation for the P value in (7) and the D value in (8) [71][72].

$$P = (Kpa.Kpf).e(t) \quad (7)$$

$$D = (Kda.Kdf)\frac{de(t)}{dt} \quad (8)$$

Where $e(t)$ is the difference between the setpoint value that has been set in the baby incubator and the actual value produced by the sensor, dt is the time interval that measures the change in system values over time, $de(t)$ is the derivative of the error to time change to measure how quickly the value of the error value changes from increasing or decreasing [73]. The membership function determination of the value of $e(t)$ is given a range of values from -10 to 10, to provide a wide enough range for the storage of the value of $e(t)$ so that the system can work flexibly when the baby incubator is first operated. Of course, when the baby incubator is first operated on, the value of $e(t)$ is very large. While the membership function value of $de(t)$ is only given a range of values from -0.5 to 0.5 based on observations of changes in error against time that have been made, In addition, the determination of this value is intended so that the resolution of changes in error over time that have been obtained is monitored in detail so that the constant time (T) can be controlled and does not cause excessive overshoot. This can make the proposed fuzzy logic system adjust the output values of Kpf and Kdf with proper adaptability and significant changes in each existing condition. After the values of P and D are obtained, enter the PD calculation so that the calculation becomes like in (9) [74].

$$Fuzzy\_PD = (Kpa.Kpf).e(t) + (Kda.Kdf)\frac{de(t)}{dt} \quad (9)$$

Fuzzy-PD is the final value of the control system as the value of Pulse width modulation (PWM) which will be used as a control heater in the baby incubator [75]. After the design of the control system in the baby incubator was completed, the researchers carried out the data collection process.

D. Experimental Setup

In this experiment, a comparison was made between a standard Incu analyzer type Fluke Incu II with a baby incubator (see Fig. 9). In addition, the use of Delphi 7 GUI is needed to monitor the output results of each parameter starting from the KP parameter, KD parameter, error value, Change Error value and PWM value. Temperature parameters are plotted in real-time coupled with a time signature in the form of minutes and seconds to find out how long the data collection has been done. Serial communication between the computer and the baby incubator device uses a USB-B serial cable that is directly connected to the Arduino Mega2560. The Delphi 7 GUI is designed to automatically save the monitoring results according to the time that has been set and collected into Excel files and BMP images in the form of temperature plots from the data collection results.

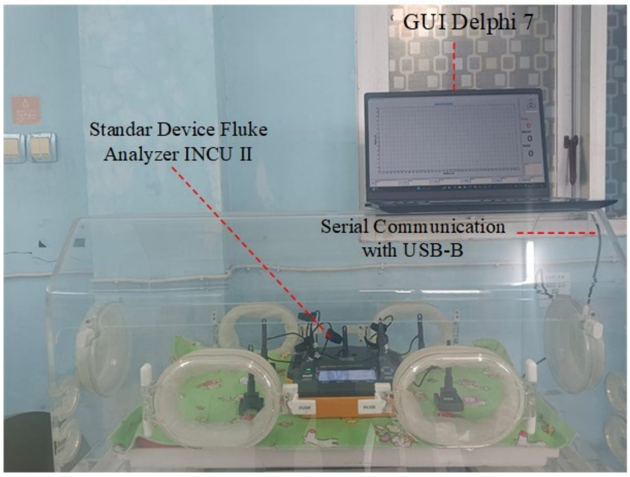

Fig. 9. Fluke Incu II type standard Incu analysis with infant incubator

III. RESULTS AND DISCUSSION

A. Results

The collection process aims to see the significant response of the control implanted in the infant incubator. The data collection room was conditioned according to the conditions in the Neonatal Intensive Care Unit (NICU) in hospitals in Indonesia. The temperature ranged from 23-26°C [76]. In addition to the adjusted temperature conditioning. The data collection process was carried out for 1 hour. The temperature settings used in data collection were 32°C, 33°C, 34°C, 35°C, 36°C, 37°C with 10 times recorded. The use of these temperature settings is because they are often used in baby incubators. For temperature data collection, it is recorded using Borland Delphi7 on a computer. The connection of the device design is made with the computer using serial communication. The results of the data collection are shown in Fig. 10.

Fig. 10 shows the graph of PD-Fuzzy control at all temperature settings, from the graph, monitoring of rise time, settling time, and overshoot. On the X-axis indicates the temperature reading time and on the Y-axis indicates the temperature. Is taken with 10 trials at each temperature setting so that it is found that at a temperature setting of 32°C the average time required to reach the setting temperature is 261 seconds, and the time required to stabilize is 922 seconds, with an overshoot of only 0.6°C. At a temperature of 33°C, the average time to reach the setting temperature is 275 seconds, and to stabilize is 922 seconds, with an overshoot of only 0.6°C. At 33°C, the average time to reach the setting temperature is 275 seconds, to reach stable the time required is 1078 seconds with an overshoot of 0.6°C. At 34°C, the average time to reach the setting temperature is 409 seconds, to reach stable the time required is 827 seconds with an overshoot of only 0.1°C. At 35°C, the average time to reach the setting temperature is 393 seconds, to reach stable the time required is 912 seconds with an overshoot of 0.2°C. At 36°C, the average time to reach the setting temperature is 344 seconds, to reach stable the time required is 773 seconds with an overshoot of 0.2°C. At 37°C, the average time to reach the setting temperature is 436 seconds, to reach stable the time required is 838 seconds with an overshoot of 0.1°C. The author summarizes the response time from Fig. 10 so that it can be easier to analyze. The summary is shown in Table III.

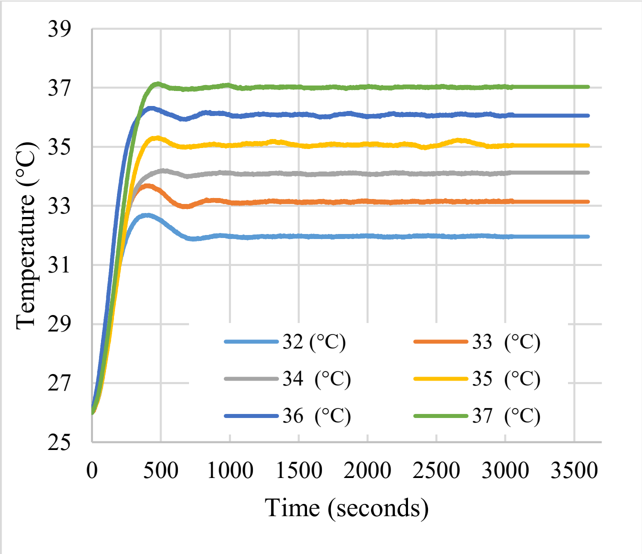

Fig. 10. Temperature Response in the Fuzzy-PD Adaptive Control System

TABLE III. MONITORING RISE TIME, SETTLING TIME, OVERSHOOT, AND STEADY STATE ERROR

Temperature (°C)	Rise Time (s)	Settling Time (s)	Overshoot (°C)	Error Steady State (%)
32	261	922	0.6	0.00653
33	275	1078	0.6	0.002108
34	409	827	0.1	0.003948
35	393	912	0.2	0.002
36	344	773	0.2	0.003522
37	436	838	0.1	0.0062

As seen in Table III, the higher the temperature, the longer it takes to reach the setting temperature. Overshoot tends to be low because the system is designed to rapidly respond to temperature cha. The system's response to temperature changes varies as it depends on the specific situation [77]. On this monitoring, it can be concluded that the combination of a fuzzy logic system and PD control works well because it can control the work of the heater so that it can maintain temperature stability with a low steady-state error and requires a shorter time because it can minimize overshoot [78]. When compared to the calibrator, the author found that the average error value for the design against the calibrator was 0.0013%.

The temperature control used in this study also affects the percentage level of humidity in the baby incubator. As seen in Fig. 11, monitoring of humidity is taken from the Fluke Incu analyzer to know the difference in humidity at each temperature setting. From this monitoring, it is also seen that during the heating session, the humidity value in the baby incubator decreases and gradually rises again when the temperature in the baby incubator is in a stable condition. The higher the temperature setting of the baby incubator, the lower the humidity inside the baby incubator.

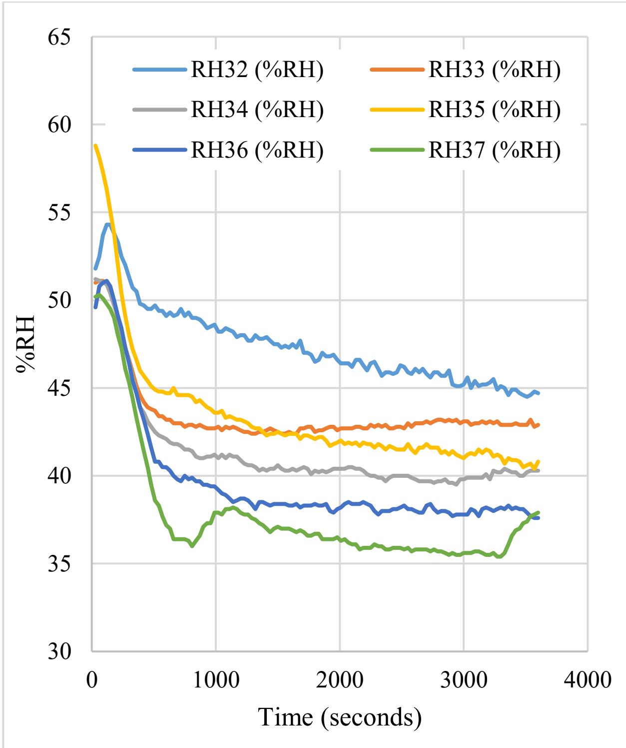

Fig. 11. Humidity measurement in the baby incubator

To see the distribution of each temperature setting, the author created the box plot in Fig. 12. The box plot is here to analyze the temperature distribution, where the center line in the box is the median value of the data, The bottom of the box indicates the median value of the lower half of the data. The top of the box indicates the median value of the higher half of the data. It can be seen that the temperature distribution at each temperature setting is still spread at a point that is not far away. At temperature setting 32°C there is a range of 31.91°C to 32.00°C, at temperature setting 33°C there is a range of 33.1°C, at temperature setting 34°C there is a range of 34.00°C to 34.14°C, at temperature setting 35°C there is a range of 35.00°C to 35.10°C, at temperature setting 36°C there is a range of 35.97°C to 36.17°C, and at temperature setting 37°C there is a range of 36.96°C to 37.06°C.

Researchers have also conducted trials by disrupting baby incubators as shown in the Fig. 13. The test was conducted by opening the front baby incubator door for 2 minutes. After the time reaches 2 minutes, the front baby incubator door will be closed again. This is done to see the performance of the fuzzy-PD adaptive system in maintaining the temperature of the baby incubator after getting a disturbance in the form of a decrease in temperature because it is influenced by the cold room temperature which ranges from 23°to 26°C with the position of the baby incubator right under the air conditioner

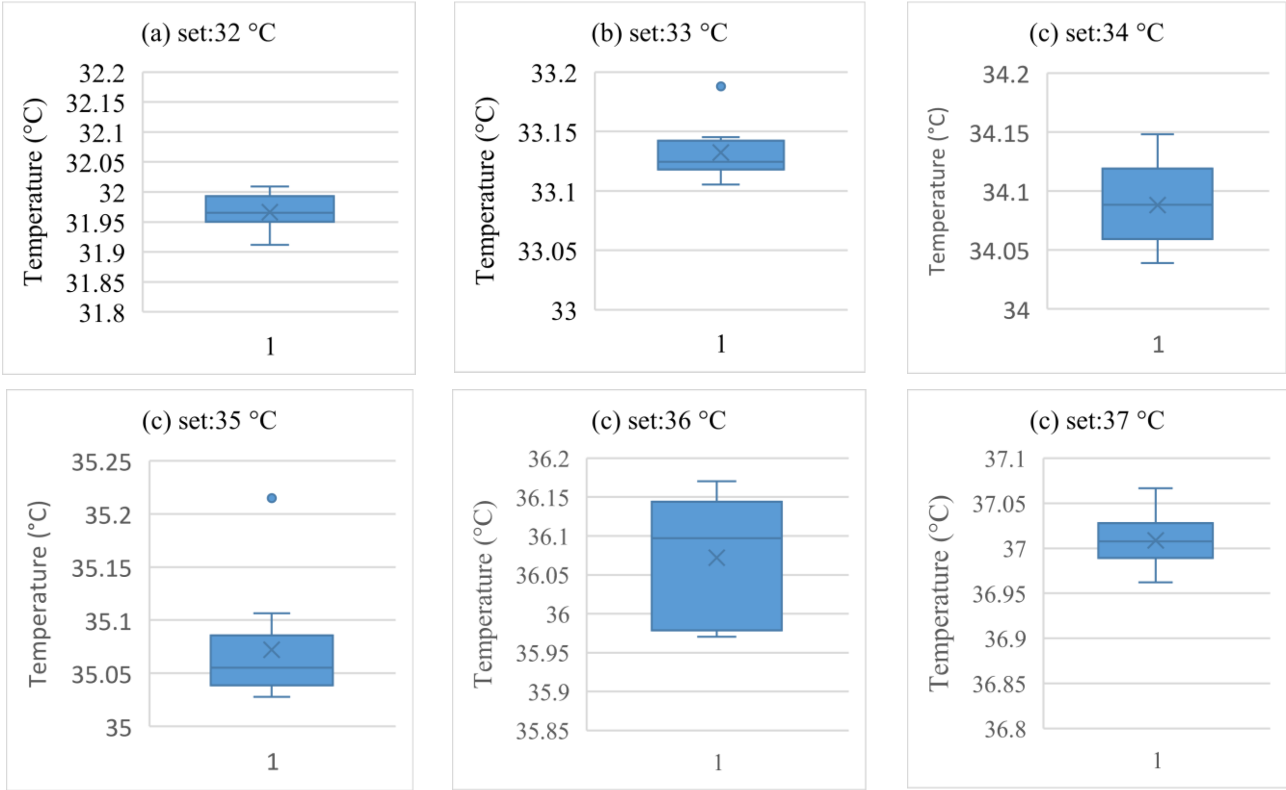

Fig. 12. Box plot temperature distribution in the baby incubator

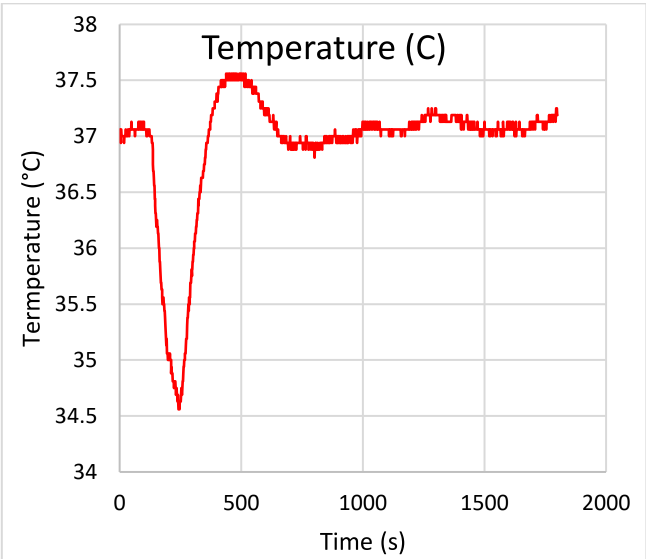

Fig. 13. System response to disturbances

After the baby incubator door is opened for 2 minutes and closed again, the lowest temperature when given a disturbance is 34.56 ° C. Then the incubator immediately adjusts again to reach the set temperature. To reach the set temperature the incubator takes about 460s.

Independent sample t-test compares sample means and standards to identify whether the difference between the means is statistically significant. Statistical significance is determined by looking at the p-value. The p-value provides the likelihood of observing the test results under the null hypothesis. The lower the p-value, the lower the likelihood of obtaining the result as observed if the null hypothesis is true. The cut-off value for determining statistical significance is usually 0.05 or less. This is equivalent to a 5% (or less) chance of obtaining the result if the null hypothesis is true. The null hypothesis here states that there is no significant difference between the standard design and the baby incubator created when the resulting p-value is greater than alpha. T-test results will be shown in Table IV.

From Table IV, it can be seen that the p-value = 0.471297 and the value of the specified significance level is 0.05. So the H0 hypothesis is accepted, which states that there is no significant difference between the baby incubator and the standard device. So it can be concluded that the temperature in the incubator has been calibrated properly and provides accurate readings by the standards set by the calibrator.

TABLE IV. TWO INDEPENDENT SAMPLE T-TEST RESULTS ON ALL TEMPERATURE SETS

T TEST: Equal Variances				**Alpha: 0.05**					
	Std err	t-stat	df	p-value	t-crit	lower	upper	sig	effect r
One Tail	0.408086	0.07227	70	0.471297	1.666914			no	0.008638
Two Tail	0.408086	0.07227	70	0.942593	1.994437	-0.7844	0.843395	no	0.008638

B. Discussion

The system made has gone through a suitability test process using a calibrator, where the system made has gone through the T-Test there is no significant difference with the calibrator. From this study, it was obtained that the highest rise time at a set temperature of 37°C was 436 s. The highest settling time value was at a set temperature of 33°C, which was 1078 s and the highest overshoot value was at a set temperature of 32°C and 33°C, worth 0.6°C.

Widhiada et al. researched a baby incubator using a PID control system. In this study, temperature regulation was only carried out at 36 ° C and humidity of 80%-60% using LM35 and DHT22 sensors. This research resulted in a maximum overshoot value Mp = 0.833889%, signal average error e = 0.011033% and the temperature reached a steady level at the 218th second in testing the baby prototype without load. Rahman, et al. researched baby incubator devices using the Fuzzy-PID algorithm system. However, these researchers are only limited to simulations and do not collect data on baby incubator devices. The difference between our research and these researchers is that using 7 membership functions does not use the trapezoidal function, but only the triangle function combined with the defuzzification process using the Mamdani method [79]. Utomo et al. researched baby incubator devices using a Fuzzy-PID automatic system. There are differences in design from our research, namely the membership function used is only 3 in the fuzzification process to process error and derivative error values. The defuzzification process also uses the Mamdani method. Data collection starts from a temperature of 32°C to 35°C using a load or no load. Alimuddin et al, conducted research on baby incubator devices with a hybrid Fuzzy-PID control system. However, the research only uses 5 membership functions in the fuzzification process when processing error and derivative error values and uses a different method, namely the Mamdani method in defuzzification. Researchers took data at a room temperature of 32.2°C during the day without comparing it with the incubator analyzer [80].

The implication of this research is to get a control design that has been tested on a baby incubator box, where the resulting temperature response is included in the baby incubator standard so that the design can be used in the NICU (Neonatal Intensive Care Unit) room.

IV. Conclusion

After completing this research, the author can conclude that it is possible to create an adaptive PD system using fuzzy logic that can stabilize the air temperature inside the baby incubator at 32°C, 33°C, 34°C, 35°C, 36°C, and 37°C. T-test results can prove that the proposed baby incubator device states that there is no significant difference between the baby incubator and the INCU Analyzer standard device with a p-value of 0.471297. The Fuzzy-PD system takes time to reach a predetermined and stable temperature and has the lowest rise time with a very low overshoot value. The highest Overshoot value is 0.6°C at temperature settings of 32°C and 33°C. The coefficient value of the fuzzy component affects the results produced by fuzzy logic. The combination of a fuzzy logic system and PD control works well because it can control the heater so that it can maintain temperature stability with low error and shorter time requirements because overshoot can be reduced. The largest steady state error generated in this controller is only around 0.006% which occurs at temperature settings of 32°C and 37°C. The DS18B20 sensor is used as a temperature sensor in baby incubators because it has a low error value. It can be concluded that the combination of a fuzzy logic system and PD control works well because it can maintain temperature stability with a low error value. the average error value for the design against the standard tool is 0.0013%. The factor that affects the performance of the heater is not optimal is the change in current and voltage of electricity as a power source for the baby incubator. Fuzzy-PD system can be recognized as one of the compact adaptive controls that can regulate the power of an actuator with a fairly fast response when compared to the neuro-fuzzy adaptive system which is more complicated in its design. It is expected that in future research, PD control can be adapted beyond the use of fuzzy logic or the addition of baby condition monitoring.

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