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Waterbath Temperature Control System with Fuzzy Logic

Annastadia Afifah, Levana Forra Wakidi, Her Gumiwang Ariswati, Dyah Titisari, and Shubhrojit Misra

Department of Electromedical Engineering Poltekkes Kemenkes Surabaya, Surabaya, Indonesia

Corresponding author: lep.forra@gmail.com

ABSTRACT Maintaining stable temperature conditions within a controlled range is critical to preserving sample integrity and quality. In this research, we present the development and evaluation of a novel water bath temperature control system using fuzzy logic with seven labels. The system leverages an Arduino UNO as the central processor and employs a DS18B20 sensor for accurate temperature measurement. Additionally, a 16x4 LCD functions as a safety thermostat to ensure precise control. The primary objective of this study is to enhance existing temperature management systems, such as On-Off and PID systems, by introducing the innovative fuzzy logic-based approach. To assess its performance, we conducted a pre-experimental design study, comparing the results against a digital thermometer as a reference device. Subsequently, a post-testing design was employed, measuring the water bath's outcomes against room temperature readings obtained from a digital thermometer. The obtained results showcased the effectiveness of the fuzzy logic-based system, with an impressive maximum error value of only 0.91% at 35°C and the lowest error value of 0.049% at 60°C. While a slightly higher error value of 1.38% was observed at the temperature setting of 30°C, it remained well within acceptable limits. Notably, the system's peak performance was recorded at the highest temperature setting, where the lowest error value of 0.05% was achieved at 60°C. Furthermore, the study evaluated the response times of the system in reaching various temperature settings within the range of 30°C to 60°C. Results indicated an average time of 193 seconds to attain the lowest temperature setting of 27°C–30°C, while the longest duration of 2257 seconds was needed to achieve the highest temperature setting of 27°C–60°C. Overall, this research demonstrates that the fuzzy logic-based method surpasses conventional approaches, showcasing its superiority in maintaining temperature stability. The findings obtained from this study offer valuable insights and practical implications for enhancing temperature management in various applications of water baths, thereby contributing to the preservation of sample integrity and quality.

INDEX TERMS Waterbath, temperature, Fuzzy logic, DS18B20

I. INTRODUCTION

Numerous devices have been developed as a result of the advancement of technology in sectors of life such as communication, industry, education, and health, making it simpler for people to operate in these domains. To encourage the development of increasingly advanced technologies in the field of health, innovations are needed that can encourage the effective and efficient use of medical devices by users, as well as being a supporting factor in the process of obtaining accurate diagnostic results, such as Waterbath. a water bath is an oven, sometimes known as a water heater, used for incubation in microbiological analysis. It can also be used to melt the base, evaporate extracts or tinctures, or heat a substance to speed up solubility. The temperature range used in water baths usually ranges from room temperature to 60°C[1]. The primary purpose of a water bath, which is a type of oven or water heater, is to maintain a steady temperature throughout incubation for microbiological analysis[2]. When used as an incubation device for microbiological examination, water baths serve to maintain a consistent temperature. They can be employed at low temperatures between 30 and 100 °C and at temperatures that are not too high to evaporate substances or solutions[3]. Another function of this device is to react with substances above room temperature and for enzyme activity. Samples incubated in a water bath certainly have different incubation temperatures such as saccharomyces cerevisiae organisms that have optimum temperatures at 30-35°C[4]. The optimum temperature for most enzymes is around 37°C, such as amylase enzymes [5],[6]. The amylase enzyme from both Bacillus subtilis isolates was produced optimally at a temperature of 40°C[7]. Optimum cellulase enzymes at a temperature of 50°C[8]. Thermophilus caliente bacteria choose the optimum temperature of 60°C[9]. In addition, water baths are used to create a constant temperature with a predetermined time. Maintaining a constant temperature required a proper temperature control system.

In 2016, This water bath module made by Ani Maulidia uses the LM35 temperature sensor whose output is still analog, so in this instance, a circuit is still needed, namely, a circuit for analog signals, and on-off control is still used as a temperature regulator, increasing the likelihood of overload[10]. In 2019, Nur Inayati Khoiron developed the Waterbath module using the DS18B20 digital sensor. However, this study continues to employ the on-off approach for temperature management, increasing the likelihood of overloading [11]. In 2019, the Waterbath module was created by Febri Indiana also used a digital sensor that is DS18B20 and uses PID as its temperature control[12].

The application of fuzzy logic to control is rising as science and technology advance. Compared to PID control, the fuzzy controller offers higher performance. This results in improved performance, fewer oscillations, and quicker turnaround times[13]. The advantages of fuzzy logic are flexible to use because rules can be changed and modified easily and provide better performance for systems that are not linear and complex[14]. Several studies on temperature control using fuzzy logic, one of which in 2017 has been created a baby incubator module with fuzzy logic as temperature control by using one crisp input that is a temperature error value with 2 types of linguistic variables namely maximum error 1.5 and 0.5 using 5 labels[15]. And in 2018 has been made an infant warmer module, which was still the same as the research of baby incubators whose temperature control uses fuzzy logic, this infant warmer also uses one piece of crisp input that is the value of temperature error with 2 types of linguistic variables that are maximum error 1.5 and 0.5 by using 5 labels.

The author intends to create a module called "Waterbath Temperature Control System with Fuzzy Logic" with a temperature range of 30°C to 60°C and safety controls based on the identification outcomes of the aforementioned problem. If the temperature rises above the chosen level, a safety mechanism will cut off the electricity and turn off the heater. Numerous studies on temperature control for medical equipment have been conducted, one of which is the design and production of a water bath-based microcontroller with fuzzy logic, as science and technology in the field of control utilize fuzzy logic advances [16]. The method used is a control system with Fuzzy Logic to know the changing relationship between temperature and time. The change information can be known by setting PWM on a control. The main purpose of this study using one crips input and 7 labels are expected to make the heating response better. Furthermore, this research is to improve upon the existing temperature management system (On-Off and PID Systems). The contribution of this research is the development of an innovative module that utilizes fuzzy logic to control the temperature in a water bath more effectively. This study provides a contribution to the field of temperature control and enhances the existing temperature management system.

II. MATERIALS AND METHODS

A. EXPERIMENTAL SETUP

This study conducted an analysis of the water bath temperature within the range of 30 to 60 ºC, measuring the speed and stability of temperature using the Fuzzy Logic temperature control system. Each temperature setting was maintained for a duration of 25 minutes to observe the system's performance and evaluate its ability to maintain the desired temperature over an extended period.

1) MATERIALS AND DEVICE

In this study, a comprehensive set of hardware components was utilized, including a heater element, DS18B20 temperature sensor, buoy sensor for water level detection, 16x4 LCD character display, Arduino UNO module as a microcontroller, LED indicators, and a buzzer for audio feedback. Additionally, a thermostat was incorporated as a safety circuit to ensure the system operates within a safe temperature range.

2) EXPERIMENT

Temperature readings between 30 and 60 °C (30, 35, 40, 45, 50, 55, and 60 °C) were used in this investigation. were performed using a comparison in the form of a digital thermometer. Module measurement with comparison thermometer aims to find out if the temperature in the module corresponds to the comparison thermometer *Fuzzy Logic.*

In this study using the fuzzy method with a maximum error of 0.5 using linguistic variable input with 7 labels and using 2 different PWM models namely PWM 1 and PWM 2 to compare which one is better, the output values of PWM 1 and PWM 2 were shown in FIGURE 1 below:

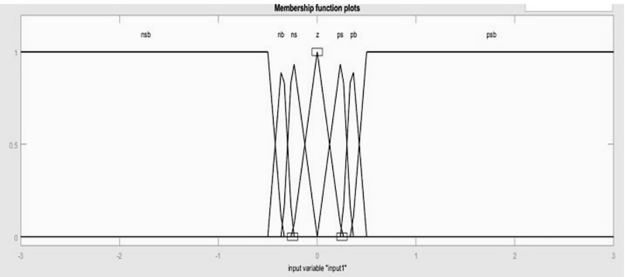

FIGURE 1. Fuzzy Linguistic Variable Graph

FIGURE 2 depicts the output graphic of PWM1, while FIGURE 3 illustrates the output graphic of PWM2. These figures provide visual representations of the respective PWM outputs, offering valuable insights into their characteristics and performance. By analyzing these graphics, one can gain a better understanding of the behavior and effectiveness of PWM1 and PWM2 in the context of the overall study.

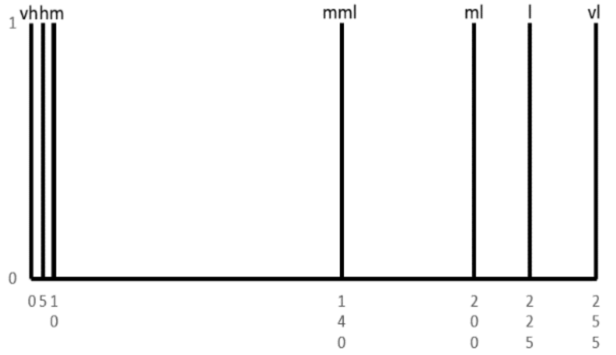

FIGURE 2. PWM1 output Graphic

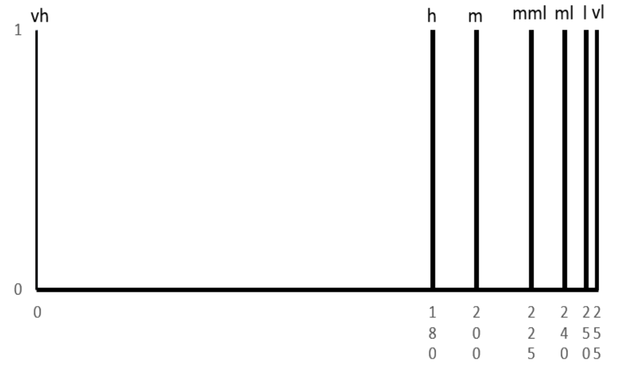

FIGURE 3. PWM2 output Graphic

The fuzzy method consists of three main methods: fuzzification, rule, and defuzzification.

a. FUZZIFICATION

Fuzzyfication is the process of turning linguistic variables (which are numerical variables that are not fuzzy) into fuzzy variables[17]. In this instance, numerical variables are error values that have had their initial values set to a, b, c, d, e, f, and g. The formula for fuzzification in Eq. (1).

Membership functions:

$$\mu[x] = \begin{cases} 0; a \leq x \; atau \; x \geq c \\ \frac{x-a}{b-a}; a \leq x \leq b \\ \frac{c-x}{c-b}; b \leq x \leq c \end{cases} . \qquad (1)$$

b. RULE

Rule Evaluation is a comparative calculation method utilized in this study to determine the fuzzy output. It involves identifying the maximum rule strength value for each output label [18]. By analyzing the rules and their associated strengths, the system can generate an appropriate fuzzy output that corresponds to the given input variables.

The utilization of Rule Evaluation in this study enhances the system's ability to make accurate and context-specific decisions, contributing to the overall effectiveness and performance of the fuzzy logic temperature control system.Rule on fuzzy in the form of if and then Rule commands used in this study is

if (ERROR is nsb) then (PWM is vh)
if (ERROR is nb) then (PWM is h)
if (ERROR is ns) then (PWM is m)
if (ERROR is z) then (PWM is mml)
if (ERROR is ps) then (PWM is ml)
if (ERROR is pb) then (PWM is l)
if (ERROR is psb) then (PWM is vl)

c. DEFUZZIFICATION

Defuzzyfication is the process of calculating all fuzzy output for a given output variable to determine crisp output action[18]. The fuzzification process in this study used the COG (Center Of Gravity) method where singleton value values were combined using average weight. The COG formula for the calculation in Eq. (2) :

$$OutCrisp(y) = \frac{\sum_i (OutFuzzy_i) x (PositionsingleonaxisX_i)}{\sum_i (OutFuzzy_i)} \qquad (2)$$

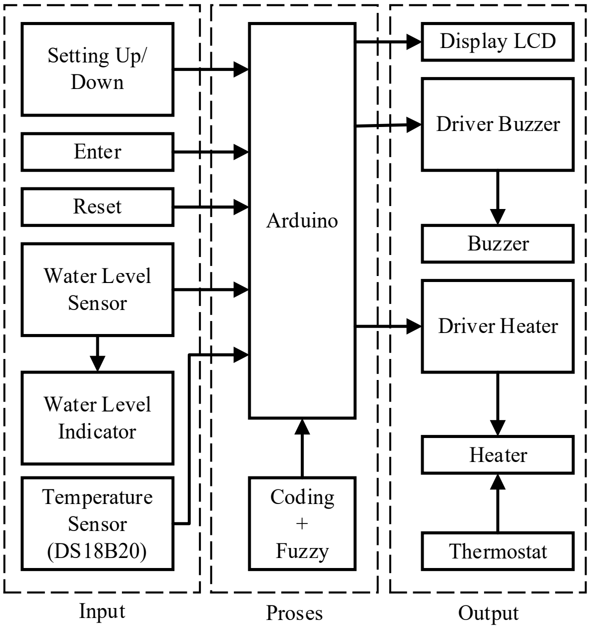

FIGURE 4. The diagram block of the Waterbath Temperature Control System with Fuzzy Logic

B. THE DIAGRAM BLOCK

The study's schematic block, which used an Arduino as a source of time, water level, and temperature control factors, is shown in FIGURE 4 Information in the form of temperature and a timer will be displayed on the character LCD. The data from the DS18B20 temperature sensor, which measures the waterbath's temperature, is transferred to the Arduino so that it can process it and manage the heater so that the temperature is maintained between 30°C and 60°C. Push Button up and down serves to lowering and raising the temperature and the length of time, the Enter button serves as the start of the waterbath device, and the Reset button ends the work of this waterbath and restores the look as it was at the beginning. The buzzer will sound if the temperature is reached and the time has run out which is controlled by the buzzer driver of the Arduino. And thermostat serves to turn off the heater if the temperature is excessive (exceeding the settings).

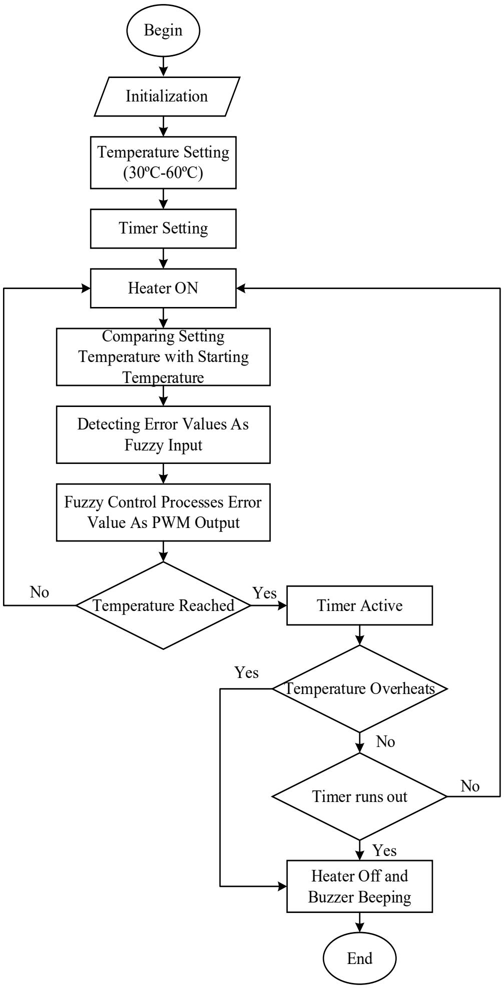

FIGURE 5. The Flowchart of the water bath Temperature Control System with Fuzzy Logic

C. THE FLOWCHART

The flowchart for this study is shown in FIGURE 5 After the start (start) microcontroller initializes, the user sets the heater's temperature before it turns on, and the microcontroller then calculates the error value, It represents the variation between the temperature at the fixed point and the actual temperature When the actual temperature matches the set temperature or the error value is zero (0), the fuzzy control stops processing the error value and decides the PWM output value. The temperature sensor measures the real temperature, which is then compared to the predetermined temperature once more. The fuzzy control will continue to process the error value and determine the PWM output value until the actual temperature is equal to the specified temperature or the error value is zero. The timer starts when the temperature is attained; if not, the microcontroller continues to read the error value and uses the fuzzy control to process it until the error value is zero. And if the temperature rises above the predetermined point, the thermostat kicks in, turning off the heater and sounding the buzzer. The heating is then turned off and a beep is heard when the timer expires. If everything is finished, the procedure is over.

III. RESULT

In this study, temperature measurements in the water bath chamber were compared to a comparison in the form of a digital thermometer. And use the stopwatch to know how long it reaches the setting temperature. Waterbath chamber compared to a comparison in the with a digital thermometer is shown in FIGURE 6.

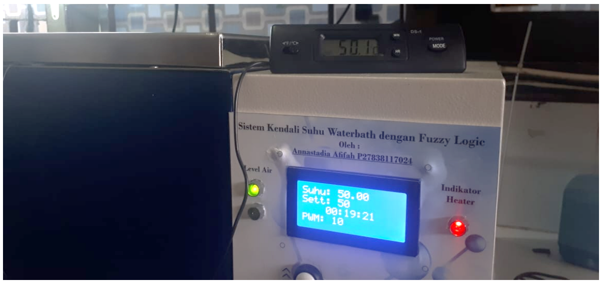

FIGURE 6. The Comparison Between the Module and The Thermometer

1) TIME TO REACH THE SETTING TEMPERATURE

TABLE 1 shows data in the form of the length of time required heater to heat the water in the waterbath chamber until it reaches the temperature setting with a fuzzy control system with PWM1 and PWM2.

TABLE 1
Heater Achieved Time on Fuzzy Method

Temp	Mode	Stopwatch (Second)
27-30	PWM1	193
	PWM2	203
27-35	PWM1	368
	PWM2	396
27-40	PWM1	696
	PWM2	787
27-45	PWM1	1266
	PWM2	1270
27-50	PWM1	1618
	PWM2	1625
27-55	PWM1	1938
	PWM2	2015
27-60	PWM1	2257
	PWM2	2410

From the TABLE 1 above-obtained data in the form of the length of time required heater to heat the water in the chamber water bath until it reaches the temperature setting with a fuzzy control system with models PWM1 and 2. The PWM1 model took the longest, on average, to attain the desired temperature of 27–60 ºC, 2257 seconds (or 37 minutes, 37 seconds), compared to the PWM2 model, which took 2410 seconds (or 40 minutes, 10 seconds). The PWM1 model took 193 seconds, or 3 minutes and 13 seconds, on average to attain the desired temperature, whereas the PWM2 model took 203 seconds, or 3 minutes and 23 seconds.

2) MEASUREMENT RESULTS WITH THERMOMETER

Measurements were taken 6 times when reaching the setting temperature by taking samples every 5 minutes for 25 minutes (0th minute, 5th, 10th, 15th, 20th, and 25th) and comparing them with a comparison of digital thermometers. Here are the measurement results between the temperature in the module and the digital thermometer. Table 2. shows the average or mean value comparison data, errors, and uncertainties of modules and thermometers.

In TABLE 2, the comparison of average values, errors, and uncertainties between the modules and thermometers at different temperature settings is presented. The mean values indicate the average readings obtained from the module and thermometer devices, while the %Error represents the percentage difference between the module's average value and the thermometer's average value. Ua denotes the measurement uncertainty associated with each temperature setting. For example, at a temperature setting of 35°C, the average value of the module is 35.27 while the average value of the thermometer is 34.95, resulting in an %Error of 0.91%. The measurement uncertainty (Ua) for the module at this setting is 0.07, while for the thermometer it is 0.12.

TABLE 2
Comparison of Average Values, Errors, and Uncertainties between Modules and Thermometers

Temp Setting (ºC)	Mean		%Error	Ua	
	Module	Thermo-meter		Module	Thermo-meter
30	30.34	30.28	0.19%	0.07	0.05
35	35.27	34.95	0.91%	0.07	0.12
37	37.22	37.07	0.4%	0.07	0.18
40	40.29	40.15	0.34%	0.06	0.10
45	45.20	45.15	0.11%	0.05	0.13
50	50.10	50.27	0.33%	0.05	0.08
55	55.10	55.13	0.05%	0.04	0.04
60	60.02	60.05	0.049%	0.01	0.11

The TABLE 2 data above obtained the largest uncertainty values at temperatures 30, 35, and 37, as well as the smallest measurement uncertainty value at 60. The concept of uncertainty is based on the observed magnitude obtained by measurement. The uncertainty value of the spread size can be reasonably associated with the measured value that provides the range, centered on the measured value, where within that range lies the correct value with a certain possibility. While the error value is the difference from the average device module with the average true value where the thermometer value (calibrator) is considered always correct.

3) ARDUINO PROGRAM FOR TEMPERATURE CONTROL SYSTEM WITH FUZZY LOGIC

```
void fuzzification() {
 if (error <= a)
 {
  nsb = 1;  nb = 0;
  ns = 0;   z = 0;
  ps = 0;   pb = 0;
  psb = 0; }
 else if (error >= a && error <= b)
 {
  nb = (error - a) / (b - a);
  nsb = 1 - nb;
  ns = 0;
  z = 0;   ps = 0;
  pb = 0;   psb = 0;
 }
 else if (error >= b && error <= c)
 {
  ns = (error - b) / (c - b);
  nb = 1 - ns;
  nsb = 0;
  z = 0;   ps = 0;
  pb = 0;   psb = 0;
 }
 else if (error >= c && error <= d)
 {
  z = (error - c) / (d - c);
  ns = 1 - z;   nb = 0;
  nsb = 0;   ns = 0;
  pb = 0;   psb = 0;
 }
 else if (error >= d && error <= e)
 {
  ps = (error - d) / (e - d);
  z = 1 - ps;   nsb = 0;
  nb = 0;   ns = 0;
  pb = 0;   psb = 0;
 }
 else if (error >= e && error <= f)
 {
  pb = (error - e) / (f - e);
  ps = 1 - pb;
  z = 0;
  nsb = 0;   nb = 0;
  ns = 0;   psb = 0;
 }
 else if (error >= f && error <= g)
 {
  psb = (error - f) / (g - f);
  pb = 1 - psb;
  ps = 0;
  z = 0;   nsb = 0;
  nb = 0;   ns = 0;
 }
 else if (error >= g)
 {
  psb = 1;
  pb = 0;
```

```
    z = 0;    ps = 0;
    nb = 0;    ns = 0;
    nsb = 0;  }
}
void rule() {
  fuzzifikasi();
  vh = nsb;
  rule1 = 0;
  h = nb;
  rule2 = 5;
  m = ns;
  rule3 = 10;
  mml = z;
  rule4 = 140;
  ml = ps;
  rule5 = 200;
  l = pb;
  rule6 = 225;
  vl = psb;
  rule7 = 255;
PWM = ((rule1 * vh) + (rule2 * h) + (rule3 * m) + (rule4
* mml) + (rule5 * ml) + (rule6 * l) + (rule7 * vl) / (vh + h
+ m + mml + ml + l + vl));
analogWrite(3, PWM);
}
```

The program above is a fuzzy program that goes from input to output (fuzzification, rules, defuzzification). By using this program, we can generate output graphs for each configuration such as FIGURE 7, FIGURE 8, FIGURE 9. These graphical representations provide a visual depiction of the fuzzy program's results.

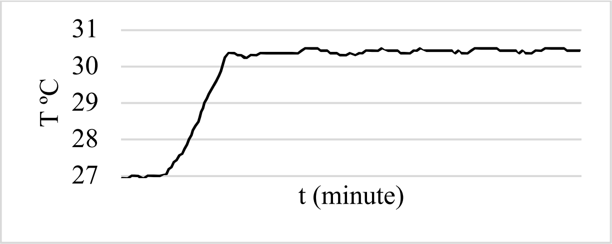

FIGURE 7. **Graph Setting Temperature 30 °C Using Fuzzy PWM 1**

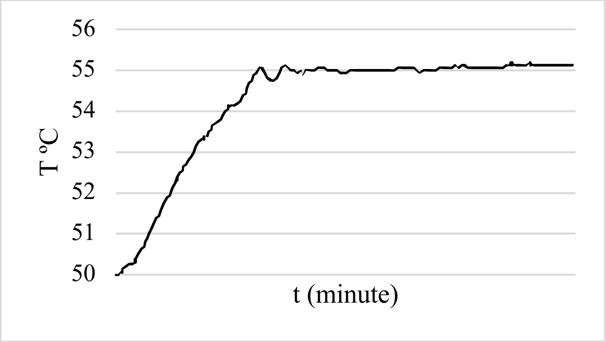

FIGURE 8. **Graph Setting Temperature 55 °C Using Fuzzy PWM 1**

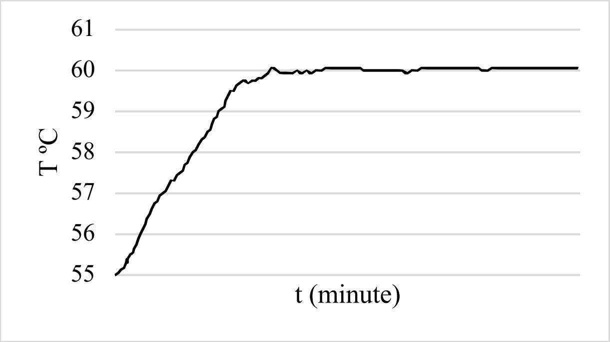

FIGURE 9. **Graph Setting Temperature 60 °C Using Fuzzy PWM 1**

4) MEASUREMENT RESULTS USING PWM1, PWM2, AND CONVENTIONAL MODE

In TABLE 3, the impact of using a fuzzy method compared to a conventional method. The table provides a detailed analysis of the differences and effects observed when employing the fuzzy method as opposed to the conventional method.

TABLE 3 shows the results of measurements on the module with a conventional devicey, the highest error value at 37ºC is 1.42, while in the fuzzy PWM 1 system the highest error value is at 40ºC with a value of 0.62, and at a temperature setting of 40°C, the fuzzy PWM 2 readings have the largest error value, coming in at 3.55.

TABLE 3
Comparison Between Conventional and Fuzzy Methods

Method	**Parameter**	**Temperature Setting (ºC)**					
		37	**40**	**45**	**50**	**55**	**60**
Fuzzy PWM 1	**$\bar{X}$**	37.22	40.25	45.23	50.12	55.04	60.03
	%Error	0.59	0.62	0.51	0.23	0.07	0.05
	St.Dev	0.16	0.16	0.17	0.09	0.08	0.04
	Ua	0.07	0.004	0.004	0.002	0.002	0.001
Fuzzy PWM 2	**$\bar{X}$**	37.73	41.42	46.44	50.49	55.48	60.47
	%Error	1.97	3.55	3.19	0.98	0.88	0.78
	St.Dev	0.22	0.28	0.23	0.09	0.09	0.07
	Ua	0.008	0.007	0.006	0.002	0.002	0.002
Conventional	**$\bar{X}$**	37.52	40.42	45.16	50.16	55.24	61.08
	%Error	1.42	1.05	0.36	0.33	0.43	0.15

St.Dev	0.145	0.272	0.343	0.48	0.306	0.371
Ua	0.059	0.111	0.140	0.196	0.125	0.151

IV. DISCUSSION

The present study focuses on a meticulous examination and testing of the water bath design, with the aim of achieving precise temperature control. Temperature measurements were taken within the range of 30 to 60 ºC, encompassing specific points such as 30, 35, 40, 45, 50, 55, and 60 ºC. These measurements were carried out using a digital thermometer, which served as the reference for comparison against the water bath temperature output. The objective was to determine whether the temperature readings obtained within the module aligned with those of the reference thermometer. Upon analyzing the data, discrepancies between the module's temperature readings and those of the DS18B20 sensor with the digital thermometer were observed. The most significant deviation occurred at the 35ºC temperature setting, where the error reached 0.91%. Conversely, the smallest error of 0.049% was recorded at the 60ºC setting. It is important to note that as the temperature setting increased, the time taken to reach the desired temperature also increased, implying a correlation between temperature setting and stabilization time. To place our findings in a broader context, we compared our results with a previous study conducted by Ani Maulidia in 2016. This comparison involved evaluating both a conventional method and a fuzzy logic system. The results indicated that the fuzzy control system exhibited a lower error percentage of 0.59% at 37ºC, whereas the conventional method showed a higher error percentage of 1.42% [19]. Additionally, we analyzed the standard deviation for both systems. The fuzzy control system demonstrated lower standard deviation values compared to conventional systems. At 45ºC, the standard deviation was 0.17, and at 60ºC, it reduced further to 0.04. This suggested that the PWM 1 fuzzy system maintained higher stability as the temperature setting increased. A crucial aspect of our investigation involved scrutinizing the temperature distribution within the water bath chamber. Regrettably, we observed that the current module design did not maximize temperature distribution and exhibited unevenness across different sections of the chamber. Achieving a uniform temperature distribution is paramount, especially when conducting experiments where samples are placed at various locations within the bath. A uniform distribution ensures consistent and reliable results throughout the experiment. Based on our comprehensive analysis, we propose several key recommendations to improve the water bath design and temperature control system. Firstly, further optimization of the fuzzy logic control system is necessary to minimize temperature errors, especially at lower temperature settings. Fine-tuning the fuzzy control parameters can enhance the system's accuracy and responsiveness. Secondly, modifications to the water bath design are crucial to achieving a more uniform temperature distribution within the chamber. This may involve strategically repositioning heating elements and integrating additional temperature sensors for real-time feedback control. Our study presented a thorough evaluation of the water bath design and temperature control system. The comparison between the module's temperature measurements and the reference thermometer readings revealed minor discrepancies, signifying the system's overall accuracy and stability. Moreover, our comparative analysis with a previous study emphasized the advantages of employing the fuzzy logic control system over conventional methods. Additionally, we addressed the issue of non-optimized temperature distribution within the water bath chamber and highlighted the significance of achieving uniformity. By implementing the proposed recommendations, the water bath design can be significantly improved, thereby enhancing its applications in scientific and industrial settings. A more efficient and precise water bath system will undoubtedly contribute to the advancement of various research and industrial processes.

While the study on water bath design and temperature control provides valuable insights and findings, it is essential to acknowledge its limitations and weaknesses to ensure a balanced assessment of its conclusions. Some potential limitations and weaknesses of the study include. Study focused on temperature measurements within a specific range of 30 to 60 ºC. While this range may be relevant for certain applications, it may not cover the full spectrum of potential temperature settings required in various experiments and industrial processes. The study may have utilized a limited number of data points or experimental runs for temperature measurements. A larger sample size would have provided more statistical significance and confidence in the study's results. Replication of the experiments under similar conditions by different researchers would have enhanced the study's validity and reliability. Without replication, it is challenging to verify the consistency and robustness of the findings. The study relied on a single type of digital thermometer as the reference for temperature comparison. Using multiple types of thermometers could have offered a broader perspective on the accuracy and reliability of the temperature measurements. The study may not have accounted for potential control variables that could influence temperature readings, such as ambient temperature, humidity, or variations in the water bath design. Identifying and controlling these variables would have strengthened the study's control over confounding factors. The application of the water bath design and temperature control system in real-world scenarios may introduce additional challenges and factors that were not considered in the study. The study's findings and conclusions may be specific to the particular water bath

Recognizing and addressing the limitations and weaknesses of a study is critical for maintaining scientific rigor and ensuring the credibility of its findings. While the study on water bath design and temperature control offers valuable contributions, future research should aim to address these limitations to further advance the field and optimize water bath systems for various applications.

V. CONCLUSION

This study aims to develop a waterbath temperature control system using fuzzy logic with seven labels. This research shows that the fuzzy method is superior to the traditional method. with an average error value at the measurement temperature setting from 30 to 60 ºC as much as 0.345 in the Fuzzy PWM 1 system, 1.89 in Fuzzy PWM 2, 0.623 in conventional mode. This fuzzy logic produces a better control system compared to conventional temperature control systems and produces devices good temperature stability. To improve this research several modifications can be made such as adding a delta error input variable as a determinant of the amount of heating output, reducing or adding the number of input labels so that the heating response is better, improving the heating distribution system in the device room so that heating becomes faster and more even.

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ATTACHMENT

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