

Fuzzy Neo: A Novel Method for Batch Liquid Temperature Control System Using Simpler Fuzzy Rule and Inference

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Abstract. Industries and laboratories heavily rely upon temperature-controlling technology due to the dependencies of their systems on temperature stability. Therefore, temperature control systems were implemented to maintain the stability of the temperature in those systems, including the batch processes. This research aimed to propose and test a novel method for batch liquid temperature control system using Fuzzy Neo which has simpler fuzzy rule and inference compared to the previous methods. The system was developed using an Arduino-based microcontroller to control the heating process of water. The results showed that the implementation of Fuzzy Neo was successfully stabilizing and maintaining the temperature in the system from different temperature references and adapted against the disturbance simulated to the system. The value of RMSE is 0.5347, which showed that the observed value of dimmer frequencies in the system are close to the predicted values calculated using Fuzzy Neo method.

Keywords: fuzzy, neo, batch, liquid, temperature, control

Abstrak. Berbagai sektor industri serta laboratorium sangat bergantung terhadap kestabilan temperatur. Oleh karena itu, sistem pengendalian temperatur umum diimplementasikan sebagai upaya untuk menjaga stabilitas dari temperatur sebagai salah satu parameter fisika yang diukur pada sistem-sistem tersebut. Salah satu implementasi sistem pengendalian temperatur adalah pada proses pemanasan cairan secara *batch*. Penelitian ini bertujuan untuk mengusulkan dan menguji Fuzzy Neo sebagai salah satu metode terbaru dan inovatif untuk pengendalian temperatur cairan secara *batch* dengan aturan dan inferensi fuzzy yang lebih sederhana dibandingkan dengan metode-metode kontrol berbasis fuzzy sebelumnya. Sistem dikembangkan dengan menggunakan mikrokontroler berbasis arduino untuk mengendalikan proses pemanasan air. Hasil pengujian menunjukkan bahwa implementasi Fuzzy Neo mampu menstabilkan dan menjaga temperatur dalam sistem dengan menggunakan temperatur referensi yang berbeda serta dapat beradaptasi terhadap gangguan yang telah disimulasikan ke dalam sistem. Nilai RMSE yang dihasilkan adalah sebesar 0.5347 yang menunjukkan bahwa nilai observasi pada frekuensi *dimmer* dalam sistem yang diimplementasikan mendekati nilai prediksi yang dihitung menggunakan metode Fuzzy Neo.

Kata Kunci: fuzzy, neo, batch, cairan, temperatur, kontrol

I. INTRODUCTION

Temperature is one of the most important and frequently measured physical parameters due to its wide applications in industries and laboratories. There are so many physical, electrical, biological, and chemical systems that depend on and are affected by temperature. Thus, the necessity for temperature-controlling technology for those

systems is inevitable. To stabilize the temperature at a specific point, a temperature-controlling system should be implemented. By definition, a control system is interpreted as the arrangement of physical components to create a system that can regulate itself or other systems [1]. Therefore, the temperature control system is created to regulate the temperature of the system (i.e. reactor and vessel).

One of the most common methods implemented for control systems is Fuzzy Logic Controller (FLC). This method is popular due to (1) the unnecessary of using a mathematical model for controlling the system, and (2) the mechanism for decision-making is fully given to the algorithm in the form of codes, which are embedded into the system and have a role in controlling it. In contrast to the boolean used in crisp logic, fuzzy logic measures the system condition by its variable values in each membership function used. Those values are described in several forms of membership function, such as triangle, trapezoidal, Gaussian, Gaussian-Bell, and sigmoid [2].

To determine the membership function of the designed fuzzy set, the mathematical equation representing the line in the fuzzy set shall be known [2], which is commonly solved using Triangular Fuzzy Number (TFN). TFN is represented by three points (a, b, and c) as described in Figure 1, which holds the following conditions: [3]

- a to b is a linear increasing function
- b to c is a linear decreasing function
- $a \leq b \leq c$

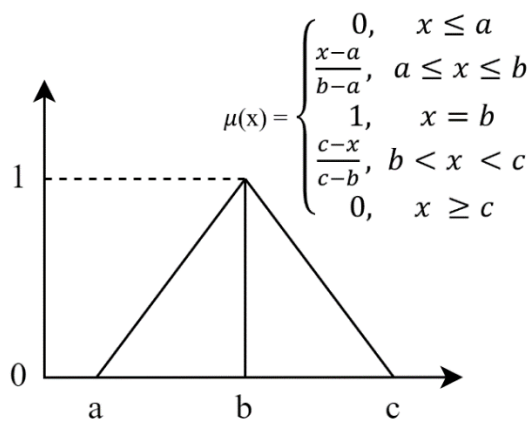


Figure 1. Triangular Fuzzy Number (TFN)

The Triangular Fuzzy Number is the unified form of the linear increasing function and linear decreasing function. Particularly, the linear increasing function has a lower value of the left membership function and linearly increases towards the right side. Whereas, the linear decreasing function has a higher value of the left membership function and linearly decreases towards the right side [4]. In this research, the development of the

Fuzzy Neo method was inspired by the linear increasing and decreasing function in Triangular Fuzzy Number (TFN).

Previously, other types of fuzzy methods have been applied for monitoring and controlling the system's temperature, such as Fuzzy Tsukamoto, Fuzzy Sugeno, and Fuzzy Mamdani. In previous research, to maintain the thermal stability of fresh fish distribution, Wijaya et al. were implementing Fuzzy Tsukamoto in a temperature monitoring system embedded in a styrofoam box [4]. Alsher et al. were using Fuzzy Tsukamoto to control the temperature in a rabbit's cage to prevent illness [5]. Furthermore, Nurdiansyah et al. were implementing Fuzzy Sugeno as a temperature controlling system in the pasteurization process [6]. Rochim et al. used Fuzzy Sugeno for controlling and optimizing the power of solar panels [7]. Prasetyawan and Anifah were also implementing Fuzzy Sugeno for controlling the liquid temperature in an electric kettle using IoT-based system [8]. Furthermore, Iksan et al. were implementing Fuzzy Mamdani to control the temperature and humidity values in the egg incubator machine [9].

However, the implementation of those fuzzy methods are relatively difficult due to the complexity of their inference system, especially for researchers who haven't had enough experience in hardware programming. Therefore, this study aimed to implement the Fuzzy Neo method, which had a relatively simpler inference algorithm compared to the other fuzzy methods, into a real batch liquid temperature control system using a predetermined setpoint. The system was implemented in Arduino-based controllers by testing the control of water heating temperature to prove the robustness of the system [10].

II. METHODOLOGY

A. Equipment

The equipment used in this study are: (1) Arduino Uno ATmega328P, which serves as the microcontroller for the system; (2) Thermocouple Max6675, which serves for obtaining the temperature data from the liquid heated in the electric kettle, (3) Robodyn AC Light Dimmer,

which is used for controlling the frequency of AC signal thus the voltage of the electric kettle is adjusted by the heating rate required (4) LCD i2c 16x2, and (5) Breadboard.

The electrical plug and socket connected to the dimmer was used to provide power for the electric kettle. Furthermore, thermocouple was used to obtain the temperature data from the liquid (water) heated in the electric kettle. The thermocouple had been calibrated and it is known that the temperature data read by thermocouple is equivalent to the actual temperature of the system. In this study, a fix amount of clean water was used for the heating test. The Arduino circuit design for the temperature control system is described in Figure 2.

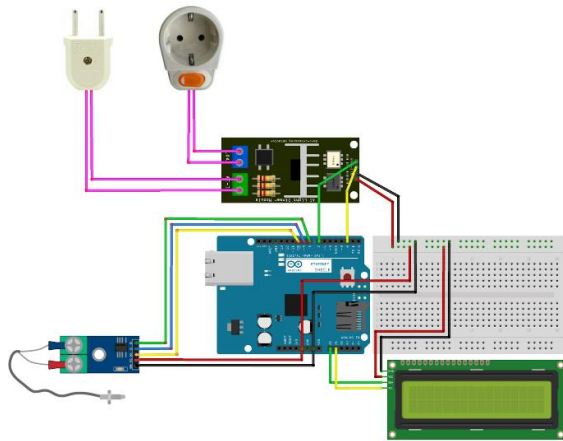


Figure 2. Arduino circuit design for temperature control system

The temperature data of the water obtained by thermocouple were further sent into Data Streamer add-ins in Microsoft Excel using a USB cable. Based on the Arduino circuit design, the real equipment used in this experiment is presented in Figure 3.



Figure 3. Equipment used for testing the system

B. Fuzzy Neo Method

The development idea of the Fuzzy Neo method was based on the heat transfer principle described as equation as follows:

$$Q = m \times C_p \times \Delta T \quad (1)$$

where Q is the heat transfer rate, C_p is the heat capacity of the materials in the system, and ΔT is the temperature difference [11]. By assuming that the mass (m) and heat capacity (C_p) in the system is constant, the total heat transfer needed to increase the temperature will also be constant. By this principle, there should be an appropriate heating rate given into the system to maintain the temperature of the electric kettle in the predetermined setpoint.

The steps needed for solving batch liquid temperature control problems using the Fuzzy Neo method are:

1) Fuzzification

Fuzzification is the mapping of crisp sets into fuzzy sets. All members of the crisp set must be included in the fuzzy set [11]. In the Fuzzy Neo Method for batch liquid temperature control system, fuzzification is needed to convert the temperature data read by the thermocouple into the value of the temperature fuzzy set. Fuzzification of Fuzzy Neo involves the linear increasing function of the fuzzy set as follows:

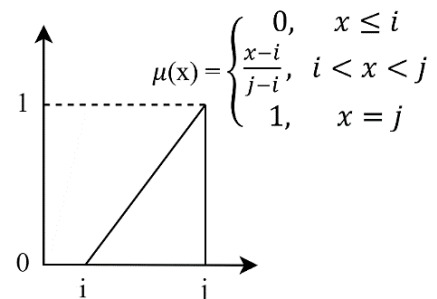


Figure 3. Temperature fuzzy set

where i is the pseudo setpoint temperature ($^{\circ}\text{C}$), j is the real setpoint temperature ($^{\circ}\text{C}$), and x is the present temperature of the system ($^{\circ}\text{C}$). The pseudo setpoint is needed as a base point to gradually decrease the heating rate until the real setpoint is achieved. In this study, the pseudo

and real setpoints used for the water heating process are 40°C and 60°C, respectively. The pseudo setpoint was determined by previously doing the trials and errors. The temperature fuzzy set implemented can be seen in Figure 4.

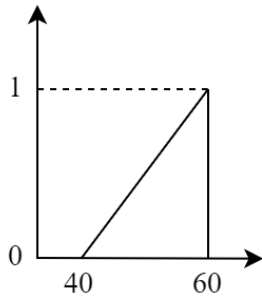


Figure 4. Temperature (°C) fuzzy set implemented in the system

2) The Rule of Fuzzy Neo

The fuzzy Neo method for batch liquid temperature control system only has one rule statement, which is written as "IF temperature is high, THEN dimmer frequency is low". By following this rule, the frequency of the dimmer is gradually decreased by the gradual increase of the temperature in the system.

3) Inference

Fuzzy inference is a series of activities that includes: (1) applying the rule into the fuzzy set from input [12], and (2) picking up a conclusion based on the rule. The inference system in the Fuzzy Neo method is done by implementing direct value conversion, where the present value of temperature fuzzy set is converted into the value of dimmer frequency fuzzy set using the equation below:

$$\mu(x) = \mu(y) \quad (2)$$

where $\mu(x)$ is the present value of the temperature fuzzy set and $\mu(y)$ is the value of the dimmer frequency fuzzy set.

4) Defuzzification

Defuzzification is the mapping of a fuzzy set into a crisp set [11]. In the Fuzzy Neo method for batch liquid temperature control system, defuzzification is implemented to convert the value of dimmer frequency fuzzy set into the crisp digital value to control the

frequency of the dimmer, thus controlling the heating rate in the system.

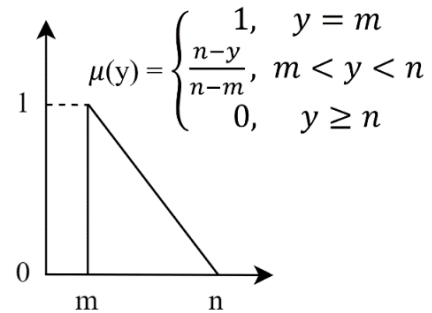


Figure 5. Dimmer frequency fuzzy set

Defuzzification of Fuzzy Neo involves the linear decreasing function of the fuzzy set as described in Figure 5, where m is the bottom frequency (%), n is the upper frequency (%), and y is the present frequency (%). Upper frequency is implemented in the dimmer at pseudo setpoint temperature, whereas bottom frequency is implemented in the dimmer at real setpoint temperature. The applicable range for the frequency of the dimmer used in this study is between 0-100%. The different percentage values of the frequency used in the dimmer will give different heating rates due to the change in the voltage that went into the electric kettle.

When the system temperature is equal to or under the pseudo setpoint (i), the heating rate will be in the upper frequency of the dimmer, which is also the maximum value of the dimmer frequency used in the system. Whereas, when the system temperature is equal to the real setpoint (j), the value of the dimmer frequency will be equal to the bottom frequency (n) which is the minimum value of the dimmer frequency set in the system.

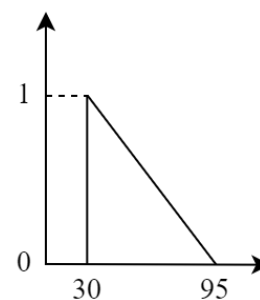


Figure 6. Dimmer frequency (%) fuzzy set implemented in the system

In the system, the bottom and upper dimmer frequencies used for the water heating process are 30% and 95%, respectively. Bottom frequency was previously determined by trials and errors until the appropriate bottom frequency value is obtained for maintaining the heating rate required to keep the system temperature constant in the real setpoint. The dimmer frequency fuzzy set implemented can be seen in Figure 6.

By using the logic of Fuzzy Neo, the frequency of the dimmer will gradually decrease along with the increase of the water temperature inside the electric kettle. When the temperature of the real setpoint is achieved, the bottom frequency will maintain the heat needed by the system to withstand the real setpoint temperature.

To increase the efficiency of electrical power used and enhance the cooling rate of the liquid in the system by natural convection when the system temperature is passing the real setpoint, there must be a compulsory IF-THEN logic outside the fuzzy system added to turn off the heating process when the temperature is passing the real setpoint, which is stated as "IF temperature is less than equal to real setpoint THEN dimmer is on ELSE dimmer is off". This was achieved by using boolean logic implemented in the codes.

C. Arduino Codes for Fuzzy Neo

The codes embedded in Arduino Uno ATmega328P for the implementation of the Fuzzy Neo method to control the temperature of the electric kettle were based on the circuit design described in Figure 3 were as follows:

```
1  #include <RBDdimmer.h>
2  #define outputPin 7
3  #define zerocross 2
4  #include "max6675.h"
5  #include <LiquidCrystal_I2C.h>
6
7  LiquidCrystal_I2C lcd(0x27, 16, 2);
8  MAX6675 thermocouple
   (thermoCLK, thermoCS, thermoDO);
9  dimmerLamp dimmer(outputPin);
10 int thermoDO = 4;
```

```
11 int thermoCS = 5;
12 int thermoCLK = 6;
13 int outVal;
14 float temperatur;
15 float frekuensi;
16 boolean dimmerState = true;
17
18 void setup() {
19   dimmer.begin(NORMAL_MODE, ON);
20   lcd.begin();
21   lcd.backlight();
22   Serial.begin(9600);
23 }
24
25 void loop() {
26   float x=thermocouple.readCelsius();
27   float Tsetpoint[ ] = {40,60};
28   int frekuensiD[ ] = {30,95};
29   int heartz;
30   temperatur = x;
31   frekuensi = setpoint(temperatur,
   Tsetpoint[0], Tsetpoint[1]);
32   heartz = dimmerF(frekuensi,
   frekuensiD[0], frekuensiD[1]);
33   lcd.setCursor(0,0);
34   lcd.print("Temp: ");
35   lcd.print(x);
36   lcd.setCursor(0,1);
37   lcd.print("Dimm: ");
38   if(heartz == 0){
39     lcd.print("OFF");
40   }
41   else {
42     lcd.print(heartz);
43     lcd.print("%");
44   }
45   dimmer.setPower(heartz);
46   Serial.print(x);
47   Serial.print(",");
48   Serial.print(heartz);
49   Serial.print(",");
50   Serial.println();
51   delay(500);
52   lcd.clear();
53 }
54
55 float setpoint(float temp, float tempLow,
   float tempHigh){
56   float j =
   (temp-tempLow)/(tempHigh-tempLow);
57   return j;
58 }
59
```

```

60 int dimmerF
61 (float frek, float frekLow, float frekHigh){
62     if (frek > 1){
63         dimmerState = false;
64         dimmer.setState(OFF);
65         return 0;
66     }
67     else if (frek <= 0){
68         if (dimmerState == false){
69             dimmerState = true;
70             dimmer.setState(ON);
71         }
72         return frekHigh;
73     }
74     else {
75         int c =
76             (frekHigh-(frek*(frekHigh-frekLow)));
77         if (dimmerState == false){
78             dimmerState = true;
79             dimmer.setState(ON);
80         }
81         return c;
82     }

```

D. System Responses Testing

The system responses were tested by: (1) using fixed reference, and (2) giving the disturbance; which both were adapted from research done by Madyanto et al. [13]. In the experiment of system responses using fixed reference, the initial temperatures of the system were 30°C and 75°C. Further, the experiment of disturbance simulation of the system was given by turning off the electricity connected to the electric kettle for 5 minutes to observe the ability of the system to restore the temperature back to its real setpoint value.

The system accuracy was tested by another heating process of water using initial temperature of 32°C, and calculated using *Root Mean Squared Error* (RMSE) as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (yi' - yi)^2} \quad (3)$$

where yi' is the prediction data of frequency, yi is the observed data of frequency, and n is the total amount of data used. The RMSE was calculated from (1) the dimmer frequency observed in the

experiment, and (2) the frequency dimmer predicted using the Fuzzy Neo method.

III. RESULTS AND DISCUSSIONS

A. System Responses Using Fixed References

The system responses using a lower temperature reference (30°C) are presented in Figure 7. The heating process was taking place for 2 minutes and 30 seconds until the real setpoint was achieved. However, the increase in the system temperature still took place even after the dimmer is off, due to the heat transfer from the materials in the heating element to the body of water.

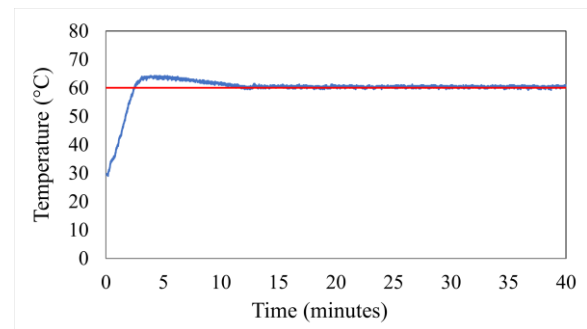


Figure 7. System responses using lower temperature reference (30°C)

Afterward, the temperature was decreasing naturally for 8 minutes and 30 seconds due to the absences of the heating process. When the real setpoint at 60°C was achieved at the 11th minute, the system started to become stable and successfully maintained its stability until the end of the testing time at 60±1°C.

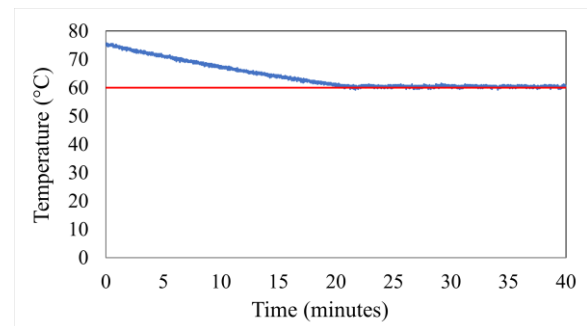


Figure 8. System responses using higher temperature reference (75°C)

The system responses using a higher (75°C) temperature reference are presented in Figure 8. At the initial point, the dimmer was in the off state, thus

the heating process was not working and the temperature was decreasing due to heat transfer by conduction and natural convection from the system to the environment for 21 minutes. When the real setpoint at 60°C was achieved, the system temperature started to become stable and successfully maintained its stability until the end of the testing time at 60±1°C.

B. System Response Against Disturbance

The system responses against the disturbance simulation were presented in Figure 9 and were done by turning off the electrical power for 5 minutes when the system was in stable condition. Afterward, the electrical power was turned back on and the system started the heating process and stabilized itself for 6 minutes.

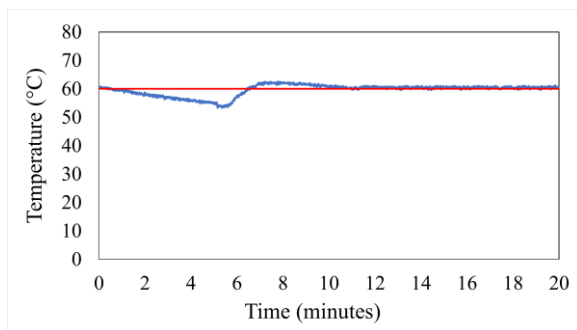


Figure 9. System responses against disturbance

After the 11th minute, the system temperature was successfully maintained to be stable at 60±1°C until the end of testing time.

C. RMSE Calculation

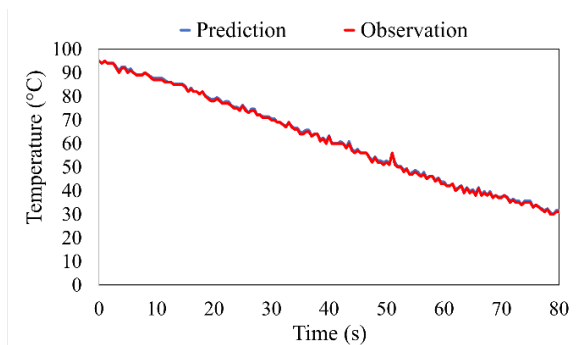


Figure 10. Observed and predicted value of dimmer frequency

The RMSE was calculated in the region where the fuzzy set was working [14]. The comparison between the observed and predicted dimmer

frequency calculated by Fuzzy Neo method is presented in Figure 10.

The data used are presented in Table 1. The RMSE value calculated was 0.5437. This result showed that the observed value of dimmer frequencies in the system are close to the predicted values calculated using Fuzzy Neo method.

Table 1. The calculation of RMSE

Time (s)	Temperature (°C)	Dimmer Frequency (%)	
		Observed	Predicted
0	40	95	95
0.5	40.25	94	94.1875
1	40	95	95
1.5	40.25	94	94.1875
2	40.25	94	94.1875
2.5	40.25	94	94.1875
...	...	...	...
80	59.5	31	31.625
80.5	60	30	30
81	59.75	30	30.8125
81.5	59.75	30	30.8125
82	59.5	31	31.625
82.5	59.75	30	30.8125
83	60	30	30
Root Mean Squared Error (RMSE)			0.5347

IV. CONCLUSIONS

Fuzzy Neo was successfully implemented for controlling batch liquid temperature using an Arduino-based microcontroller, thermocouple, and AC Dimmer. The system showed the ability to stabilize and maintain its temperature at 60±1°C from lower and higher temperature references and adapt itself against the disturbance simulation. The RMSE value calculated from the observed and predicted dimmer frequency was 0.5437. However, the recent implementation of the Fuzzy Neo method is limited only to batch liquid temperature control systems. Thus, future research for the improvements or implementations of the method shall be needed.

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