Performance Analysis of Fuzzy Logic Controller Applied on Portable Roaster

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Abstract. Roaster is a device commonly used to roast various products, especially for food processing. In the roasting process, temperature parameter plays a major role in determining the final quality of the roasted product. In real-world applications, some products must be roasted at low temperatures such as cocoa products and others must be roasted at high temperatures such as coffee products. In addition, roasting is sometimes not always carried out at a constant temperature, but sometimes it must be done at various roasting temperature levels for the purpose of forming the optimal flavour. Thus, a roaster must be able to operate at the desired operating temperature, not only a constant operating temperature but also able to work with varying operating temperatures. For this purpose, a roaster must be equipped with a reliable temperature controller. Several control models have been developed by many researchers, including fuzzy logic control. This research was conducted to design, implement, and evaluate the performance of a control system based on fuzzy logic on a laboratory scale portable roaster. For this study, a fuzzy control system with two input variables, namely the difference in temperature and changes in temperature difference as well as one control signal output variable, had been designed to regulate the roasting temperature on the roaster. To evaluate its performance, the domain membership function of the input and output variables was varied. The design was then applied to the microcontroller-based control system hardware attached to the portable roaster. The test results show that the fuzzy logic control was able to regulate the roast temperature stably. With a varied roast temperature setpoint, the control system can follow and maintain the target with small temperature variation.

Keyword: performance, fuzzy logic controller, portable roaster, temperature, roasting

1. Introduction
Roasting is one of the stages of processing food or agricultural products through heat treatment without oil applied to the material for a certain period of time. The heat treatment encourages changes in the physical properties of the material, causing a number of physical and chemical changes to the ingredients that make up the product which will form the final flavour of the agricultural product [1] [2]. With the roasting process, agricultural products will achieve optimal quality characters. Several agricultural products that require a roasting process include coffee, cocoa, and beans.
Aroma, colour and taste are the main quality parameters of several processed agricultural products. The quality parameter as a product character plays a role in determining whether a product can be accepted by the market or not. It can be said that a product can be accepted by the market if the quality parameters are in accordance with consumer desires. These quality parameters can be established and achieved through a proper roasting process. In the roasting process, seeds (agricultural products) will experience a series of physical and chemical reactions, which lead to the desired character, both physical properties and chemical composition [3] [4] [5]. To produce optimal quality character targets, a number of parameters must be considered. Many factors influence the roasting process. Several factors that affect the roasting process can be categorized into two, namely internal factors such as size, moisture content and uniformity of grain; as well as external factors such as roast temperature. The internal factor of the material will affect the speed of heat transfer that will have a direct impact on the speed of the roasting process of each grain, thus it will affect the overall roast quality. While the temperature factor as a driving force for the roasting process also greatly determines the success of the final product character formation, in this case, temperature stability has an important role in ensuring the roasting process runs optimally.

To ensure the roast process runs well, a number of roasting technology innovations have been developed. At first, the roasting process was mostly done by heating directly above the stove which was given a roasting pan. This roasting process is known as traditional roasting. This technique is still widely practiced by most home food processing industries. Along with the development of technology, roasting equipment began to be developed from the beginning to be operated manually, nowadays, a roaster that can be operated automatically has been developed [6]. Automatic roasting machines are generally equipped with a control device that functions to control the operating temperature, most of which apply a thermostat device. In its application, the thermostat technology is able to maintain a constant operating temperature in modern roasting machines. However, with the development of roasting process technology, a constant roast temperature is not sufficient for an optimal roasting process.

The roasting process sometimes requires varying temperature settings. In this process, the roast temperature is set to vary, the value of which depends on the needs of the process. Several references state that the roasting of agricultural products requires varying temperatures, for example for cocoa products. In the early stages of roasting, cocoa beans must be roasted at high temperatures in order to speed up the drying stage and break down the husks [7]. After the drying stage, the flavour formation of the roasting process can be carried out at a lower temperature. Likewise, for coffee products, which may be done with multiple roasting temperatures. The varied roast temperature setting is believed to provide higher quality roasted products. Thus, multiple roast temperature settings will be indispensable for the development of a roaster in the future.

Some modern commercial roasters are equipped with control devices, especially roast temperature. With this device, the roaster can be operated at a set temperature. Generally, the control device will provide an action in the form of a constant temperature setting during the roasting process. Of course, this kind of setting is less relevant to apply to roasting processes that require multiple temperature settings. Therefore, this study aims to design a temperature control system and apply it to roasting machines. The control system is designed on the basis of fuzzy logic (FLC), using the actual temperature input which is read by a temperature sensor.

2. Materials and Methods

2.1 Time and Research Location
The research was conducted from March to December 2017 and was carried out at the Laboratory of Energy and Agricultural Machinery, Department of Agricultural and Biosystem Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada.

2.2 Material
The equipment used in this study was a portable laboratory-scale roaster with a roasting capacity of 0.5 kg / batch; which is equipped with a 2 kW of electric heater. While the equipment used to design the
control system consists of two K-type of thermocouples, IC Max6675, solid state relay as a heating element driver, ATmega8535 microcontroller, and software to program the microcontroller. The material used to test the roaster was coffee beans.

2.3 Research Procedure

The research activity begins with the stage of designing the hardware, followed by software design, and control system testing. The hardware used in this research includes the components used to create the control system, which includes temperature sensor, microcontroller, heating element driver, and computer. The components are then assembled into a one-unit controller so that they can interact with one another, forming a temperature control device. The arrangement of the temperature control hardware is presented in Figure 1. Based on this figure, the heating element as the main device will be controlled by a driver, in which case the solid-state relay device was used. The controlling action by the driver was obtained from the FLC output signal embedded in the microcontroller device. The output of the FLC signal is the result of processing the input signal in the form of target temperature, actual temperature, and changes in actual temperature to target temperature. In this control, the temperature of the heating room is used as the target setting with the aim that the roasting heat treatment process can take place as needed. By holding on to the control system design scheme in Figure 3, then the hardware components are assembled. The results of a series of control system hardware applied to a roaster machine are presented in Figure 2.

![Figure 1. Block diagram of the FLC applied to the portable roaster](image1)

![Figure 2. Experimental setup](image2)

After the control hardware was designed, the next step was to design the software for controlling the temperature. This software included a controller device which in this case used a fuzzy logic controller, and interface software, which was used as a communication device that connects hardware and operators.

2.4 Input and output variable

The FLC is designed with two input variables, namely error (E) and change of error (d_E) and an output variable in the form of a control signal (O). Variable of E is defined as the temperature difference between the target and the heating chamber read by the thermocouple, while the variable of d_E is defined as the difference between the E variable at time t and the value of E at t-1. The two input variables are fed into the FLC, and the output signal is sent to the heating element driver.
variables are designed with a membership function, as shown in Fig 3 and Fig 4. For the membership function, variable of \( E \) consists of 5 membership functions, namely Zero Error (ZE), Small Positive Error (SPE), Medium Positive Error (MPE), Big Positive Error (BPE) and Very Big Positive Error (VBPE) with the limits specified for \( a_1, a_2, a_3, a_4, \) and \( a_5 \) respectively are -5 °C, 0 °C, 5 °C, 10 °C, and 15 °C; while the \( d_E \) membership function also consists of 5 membership functions, namely Big Negative \( d_E \) (BNdE), Small Negative \( d_E \) (SNdE), Zerro \( d_E \) (ZdE), Small Positive \( d_E \) (SPdE), and Big Positive \( d_E \) (BPdE), with values of parameters of \( b_1, b_2, b_3, b_4, \) and \( b_5 \) are -10 °C, 5 °C, 0 °C, 5 °C, and 10 °C respectively. As for the FLC output, output variables are designed with singleton membership sets, namely Zero Output (ZO), Small Output (SO), Medium Output (MO), Big Output (BO), Very Big Output (VBO). Each membership function in the output variable is associated with the real output value in the form of a percentage of the duty cycle used to regulate the heating element, as shown in Fig 5.

![Figure 3. Membership function of error (E) variable](image)

![Figure 4. Membership function of change of error (d_E) variable](image)

![Figure 5. Membership function of output variable](image)

2.5 Fuzzy rule
Based on the predetermined input and output variables, some fuzzy rules were formed. These rules were a possible combination of the two input variables as a reference to determine the magnitude of the output variable. The fuzzy rules defined in this study were presented in Table 1. In this study, seven (7)
variations of the fuzzy rules were carried out in the form of variations in the first output (O_01) to last output (O_25) according to the membership function in the output variable.

| \(dE\) | BNdE | SNdE | ZdE | SPdE | BPdE |
|-------|------|------|-----|------|------|
| ZE    | O_01 | O_02 | O_03| O_04 | O_05 |
| SPE   | O_06 | O_07 | O_08| O_09 | O_10 |
| MPE   | O_11 | O_12 | O_13| O_14 | O_15 |
| BPE   | O_16 | O_17 | O_18| O_19 | O_20 |
| VBPE  | O_21 | O_22 | O_23| O_24 | O_25 |

2.6 Inference and defuzzification

This fuzzy logic control system used MIN inference design. The degree of membership of each input was compared using the AND or minimum value relationship to produce a \(\alpha\)-predicate value. The \(\alpha\)-predicate value obtained was used to determine the FLC output based on the defined fuzzy rules. Defuzzification in this fuzzy logic control system used the centroid method. The value of the output crips from FLC was determined by the following equation:

\[
Z = \frac{\sum_{t=0}^{n} \alpha(t) \ast O(t)}{\sum_{t=0}^{n} \alpha(t)}
\]

2.7 Performance analysis

Control system performance can be assessed from a number of variables. This variable is in accordance with the main goals of a control system, namely accelerating the rise time, reducing spikes, shortening oscillations, and maintaining the stability of the operating temperature according to the target. Thus, in this study, the variables used to assess the performance of the control system were rise time (Tr), time to reach the target (Ts), Error (ΔT). The rise time (Tr) is defined as the time it takes for the control system to reach the specified target temperature. The time to reach the target is called the settling time (Ts), which is the time required by the control system to reach a stable state or a state where the actual temperature is constant. While Error (E) is defined as the difference between the target temperature and the final temperature. An overview of the three variables is presented in Figure 6.

3. Results and Discussion

3.1 Control system functional testing

Functional testing is carried out after the stage of designing the hardware and software of the control system. The control is then integrated into the portable roasting machine. This functional test includes data communication tests between components of the control system, including access of temperature sensor, access of driver, and access to other components involved with the microcontroller. In addition, a functional test of the interface is also carried out which includes the ability of the interface to assist communication between the user and the control unit. After all elements of the control system can interact, the next step is to test the regulatory function, which is done by using the interface for setting
the roast temperature. The functional test results show that the control system device has worked well, able to control the roast temperature.

3.2 Control system performance testing

Performance testing is carried out to assess the performance of the developed control system. As already explained, that in this test, the target temperature is graded. Assessment of control performance includes three variables, namely rise time (Tr), fixing time (Ts), and temperature error (ΔT). In this study, there are seven variations of the fuzzy rules tested, which are used to adjust the roast temperature at the target temperature which is made stratified. In this test, the target temperature is set at 100°C, 150°C, 200°C and 225°C with each duration of 10 minutes. Thus, the control system was tested to achieve variable target temperatures for 40 minutes. The performance of the control system designed for the temperature target varies from the seven variations of the defined fuzzy rules shown in Figure 7.

During testing, a number of data were recorded, especially the actual temperature and time read by the microcontroller. The data is taken with a period of 1 second. The results of the data recording were then analyzed. The analysis includes Tr, Ts, and ΔT for the specified target temperature. The results of the analysis of the Tr parameter are presented in Table 2, while the Ts parameter is presented in Table 3, and the ΔT parameter is presented in Table 4.
| FLC  | Repetition | Target Temperature (°C) | Tr (s) |
|------|------------|--------------------------|--------|
|      |            | 100  | 150  | 200  | 225  |       |
| FLC_1| 1          | 141  | 193  | 141  | 159  | 151.47|
|      | 2          | 137  | 106  | 141  | 159  |        |
|      | 3          | 135  | 204  | 141  | 159  |        |
|      | Average    | 137.67| 167.69| 141.42| 159.10|        |
| FLC_2| 1          | 118  | 106  | 141  | 159  | 136.73|
|      | 2          | 129  | 106  | 141  | 159  |        |
|      | 3          | 174  | 106  | 141  | 159  |        |
|      | Average    | 140.33| 106.07| 141.42| 159.10|        |
| FLC_3| 1          | 160  | 176  | 141  | 159  | 158.88|
|      | 2          | 138  | 176  | 141  | 159  |        |
|      | 3          | 179  | 176  | 141  | 159  |        |
|      | Average    | 159.00| 176.00| 141.42| 159.10|        |
| FLC_4| 1          | 155  | 166  | 141  | 159  | 150.38|
|      | 2          | 121  | 137  | 141  | 159  |        |
|      | 3          | 158  | 166  | 141  | 159  |        |
|      | Average    | 144.67| 156.33| 141.42| 159.10|        |
| FLC_5| 1          | 108  | 127  | 141  | 159  | 138.55|
|      | 2          | 124  | 136  | 141  | 159  |        |
|      | 3          | 125  | 141  | 141  | 159  |        |
|      | Average    | 119.00| 134.67| 141.42| 159.10|        |
| FLC_6| 1          | 122  | 141  | 141  | 159  | 138.63|
|      | 2          | 121  | 138  | 141  | 159  |        |
|      | 3          | 108  | 132  | 141  | 159  |        |
|      | Average    | 117.00| 137.00| 141.42| 159.10|        |
| FLC_7| 1          | 83   | 125  | 168  | 159  | 138.14|
|      | 2          | 119  | 125  | 173  | 159  |        |
|      | 3          | 116  | 130  | 141  | 159  |        |
|      | Average    | 106.00| 126.67| 160.81| 159.10|        |

| FLC  | Repetition | Target Temperature (°C) | Ts (s) |
|------|------------|--------------------------|--------|
|      |            | 100  | 150  | 200  | 225  |       |
| FLC_1| 1          | 247  | 293  | 324  | 201  | 269.50|
|      | 2          | 185  | 333  | 216  | 103  |        |
|      | 3          | 418  | 256  | 357  | 301  |        |
|      | Average    | 283.33| 294.00| 299.00| 201.67|        |
| FLC_2| 1          | 306  | 383  | 272  | 220  | 274.42|
|      | 2          | 185  | 333  | 216  | 103  |        |
|      | 3          | 434  | 360  | 302  | 179  |        |
|      | Average    | 308.33| 358.67| 263.33| 167.33|        |
| FLC_3| 1          | 323  | 312  | 289  | 302  | 318.25|
|      | 2          | 427  | 270  | 345  | 228  |        |
| FLC | Repetition | Target Temperature (°C) | ΔT (°C) |
|-----|------------|--------------------------|---------|
|     |            | 100 | 150 | 200 | 225 | |
| FLC_1 | 1 | 0.62 | 2.78 | 3.66 | 4.21 | 2.69 |
|       | 2 | 0.73 | 2.46 | 3.36 | 4.11 | |
|       | 3 | 0.68 | 1.30 | 4.17 | 4.25 | |
|       | Average | 0.68 | 2.18 | 3.73 | 4.19 | |
| FLC_2 | 1 | 3.17 | 3.51 | 4.10 | 4.38 | |
|       | 2 | 2.65 | 3.44 | 4.04 | 4.38 | 3.74 |
|       | 3 | 2.90 | 3.49 | 4.60 | 4.17 | |
|       | Average | 2.91 | 3.48 | 4.25 | 4.31 | |
| FLC_3 | 1 | 2.75 | 3.29 | 3.39 | 3.36 | |
|       | 2 | 2.39 | 3.34 | 3.30 | 3.27 | 3.21 |
|       | 3 | 3.09 | 3.48 | 3.49 | 3.37 | |
|       | Average | 2.74 | 3.37 | 3.39 | 3.33 | |
| FLC_4 | 1 | 1.13 | 1.78 | 2.25 | 2.40 | 2.02 |
|       | 2 | 1.27 | 1.88 | 2.57 | 2.69 | |
|       | 3 | 1.50 | 1.90 | 2.34 | 2.48 | |
|       | Average | 1.30 | 1.85 | 2.39 | 2.52 | |
| FLC_5 | 1 | 1.06 | 0.62 | 1.67 | 1.88 | 1.30 |
|       | 2 | 1.31 | 0.70 | 1.63 | 1.88 | |
|       | 3 | 0.70 | 0.75 | 1.56 | 1.84 | |
|       | Average | 1.02 | 0.69 | 1.62 | 1.87 | |
| FLC_6 | 1 | 7.34 | 0.81 | 3.56 | 4.12 | 3.86 |
|       | 2 | 7.18 | 0.43 | 3.33 | 4.10 | |
Based on the results of the tests that have been carried out, overall the FLC control designed has good performance, is able to follow various target temperatures, and is able to maintain the operating temperature at the set target temperature. However, from the FLC variations tested, all variations showed different performance. Judging from the parameters $T_r$, FLC_5, FLC_6, and FLC_7 showed the best performance because they were able to reach the target temperature with the shortest time duration. Meanwhile, when viewed from the $T_s$ parameter, FLC_4 shows the best performance with a determination time of 247.25 s. When viewed from the parameter $\Delta T$, the FLC_5 control shows the best performance with the mean error for the four variations of the target temperature of 1.30 ℃. Thus, overall, it can be concluded that the FLC_5 design shows the best performance with $T_r$ of 138.55 s, $T_s$ of 274.75 s, and an error of 1.30 ℃.

### 3.3 Testing Control Systems for Coffee Roasting

After the performance test has been completed, the next stage is testing the control system in real applications. For this purpose, the roaster that has been combined with the FLC_5 control system is then tested for roasting coffee. At this roasting, the roasting temperature that is the target of the control system is set at 225 ℃. Roasting starts when the roasting temperature (heating chamber temperature) has reached the target temperature, the ingredients in the form of coffee beans are put in the roaster. During the roasting process, heating room temperature and roasting room temperature are observed periodically with a period of 1 s. The results of observations of heating room temperature data and roasting room temperature are presented in Figure 8. Based on this figure it can be concluded that the control system has worked well and is able to maintain the heating room temperature at the set target temperature. During the roasting process, the roasting room temperature profile shows a pattern of temperature reduction at the beginning of the roasting process because of the entry of low-temperature ingredients into the roasting room. Over time, the roast room temperature, which indicates the coffee bean temperature, will increase until it reaches the target temperature and the roasting process is complete when the roast degree has been reached.

![Figure 8. Performance of the FLC applied on the portable roaster for real coffee roasting](image)

### 4. Conclusion

Research on designing of temperature control based on fuzzy logic has been carried out and implemented in a laboratory-scale of portable roaster. The fuzzy logic control is designed with input of
error and change of error, each of which is divided into 5 membership functions and providing an output signal used to regulate the heater element. The fuzzy logic control has been tested with varied temperature target. The result shows that the control is able to follow a determined temperature setting target. The fuzzy logic control has been tested for real application of the roaster for roasting process of coffee bean, and it is able to regulate the roasting temperature needed for the roasting.

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Reference
[1] Sri Mulato, Edi Suharyanto, and Kaswanto, Products Development of Coffee. Indonesian Coffee and Cocoa Research Institute, Jl. PB. Sudirman No. 90, Jember 68118 - Indonesia, 2010.
[2] H.-S. Chung, D.-H. Kim, K.-S. Youn, J.-B. Lee, and K.-D. Moon, “Optimization of roasting conditions according to antioxidant activity and sensory quality of coffee brews,” Food Sci. Biotechnol., vol. 22, no. 1, pp. 23–29, Feb. 2013, doi: 10.1007/s10068-013-0004-1.
[3] O. Gonzalez-Rios et al., “Impact of ‘ecological’ post-harvest processing on coffee aroma: II. Roasted coffee,” J. Food Compos. Anal., vol. 20, no. 3, pp. 297–307, May 2007, doi: 10.1016/j.jfca.2006.12.004.
[4] H.-D. Belitz, W. Grosch, and P. Schieberle, Food Chemistry. Springer Science & Business Media, 2009.
[5] A. Illy and R. Viani, Eds., Espresso Coffee: The Science of Quality, 2nd edition. Amsterdam ; Boston: Academic Press, 2005.
[6] Radi, B. Purwantana, R. P. Alamsyah, and H. D. Prawira, “Design of Portable Coffee Roaster for Home Industry,” IOP Conf. Ser. Earth Environ. Sci., vol. 327, p. 012019, Oct. 2019, doi: 10.1088/1755-1315/327/1/012019.
[7] Danny, “How to roast cocoa beans,” Chocolate Phayanak. https://chocolatephayanak.com/unkategorisier/ how-to-roast-cocoa-beans/ (accessed Dec. 23, 2020).