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Design of Type-2 Fuzzy Logic Controller For Air Heater Temperature Control

Dwi Ana Ratna Wati
Department of Electrical Engineering,
Islamic University of Indonesia,
Yogyakarta, Indonesia
dwi_ana@uii.ac.id

***Abstract*— Air heater temperature control systems generally deal with many uncertainties from their environment as well as uncertainties from the sensor measurement. Type-2 Fuzzy Logic Controller (FLC) has many advantages in handling uncertainties. This research implemented PI-like type-2 FLC for air heater temperature control. The input variables of the type-2 FLC are error and change of error, while its output is change of control signal. The control strategy was mapped into 4 rules in the fuzzy rule base. The experiments was conducted using LabVIEW and NI USB 6009 as acquisition device for controlling the air heater mini plant. The performance of this type-2 FLC was evaluated and compared to type-1 FLC. The experiments were conducted in order to record the step responses, the responses in handling the disturbances, and the responses to set point changes. Based on these experiments, the type-2 FLC performed better step response than type-1 FLC as well as in handling the disturbances and set point changes.**

Keywords— Type-2 Fuzzy Logic Controller; air heater; control

I. INTRODUCTION

Air heater has been applied in many drying processes. It also has been widely used as part of air conditioning systems in subtropical houses. In education, air heater was used as an experiment case of process control because of its simple process and easy to understand [1]. A controller is needed by an air heater to keep the output temperature match to the set point value. The air heater actually has nonlinear characteristics. It also operated in area where there are many disturbances. Many uncertainties from the environment and sensor measurement gave impact on its performance. Consequently, it is needed a controller which able to handle those problems.

Since the first development by Mamdani and Assilian in 1975, Fuzzy Logic Controllers (FLC) have been successfully applied in many real world applications [2] , including cement kiln controller, water treatment system, and automatic train operation control system as well as in home appliances such as washing machine, rice cooker, microwave, and refrigerator. There are two main advantages of FLC over other nonlinear controller. The first is the ability to incorporate the linguistic term of input-output variables by using fuzzy membership function. Second, it can more effectively handle the uncertainties in the input and state measurements [3].

Early, FLC used type-1 fuzzy set in representing the input-output uncertainties. These are uncertainties in the meaning of words in antecedents and consequents of the rules, the histogram value of the consequents extracted from a group of experts, and the noisy data as well as measurements [4]. Type-1 fuzzy sets have limited ability to handle such uncertainties because they applied crisp membership functions. Whereas, type-2 fuzzy sets have the membership grade that are fuzzy [5]. They have the third dimension that add degree of freedom to model the uncertainties [4]. Type-2 FLC applied type-2 fuzzy sets in order to improve its performance in deal with uncertainties. Type-2 FLC had been implemented in mobile robot control system [6] and resulted that it had better performance than type-1 FLC if the noise was available in inputs or outputs. Type-2 PID-like FLC had been applied to control the inverted pendulum and performed significant improvement in handling wide range of system uncertainties [7]. Implementation of type-2 FLC in a complex and nonlinear process has been done in [8] which resulted in proof of its advantages.

This research designed and applied type-2 FLC to control the output temperature of an air heater mini plant which had uncertainties in the data measurement and changing environment. The goal was to achieve the better transient and steady state response characteristics.

II. AN INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER

An interval type-2 FLC with the interval type-2 fuzzy sets is commonly used because its simpler computation than general type-2 FLC [9]. Interval type-2 FLC has many components namely Fuzzifier, Inference Engine, Rule Base, Type-reducer and Defuzzifier [3][9] as in fig. 1. The Fuzzifier is used to calculate the interval type-2 fuzzy sets of the crisp inputs from sensors. Its output is an interval of firing strength of fired rules in the Rule Base. Next, the Inference engine aggregate the output of all fired rules in order to determine its outputs which are type-2 fuzzy sets. There are no different between the rules used in the type-2 FLC and the ones in type-1 FLC, except that the antecedents and/or consequents are interval type-2 fuzzy

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sets. The Type-reducer processes these interval type-2 fuzzy sets, by executing a centroid calculation. The results are type-1 fuzzy sets which are called the type reduced sets. Next, they are defuzzified by computing the average of the type-reduced sets to obtain crisp outputs then are sent to the actuators.

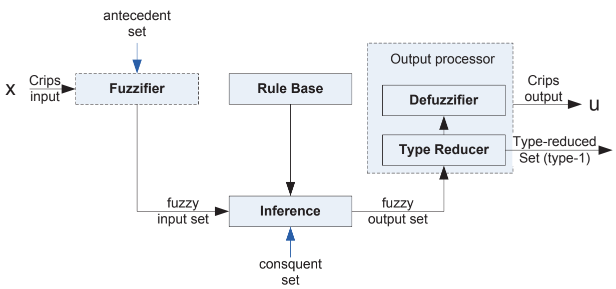

Figure 1. Type-2 FLC [9].

The following is the detail computation of interval type-2 FLC [10]. In this interval type-2 FLC, rule base are defined as:

$$\mathrm{R}^n : \text{IF } x_1 \text{ is } \tilde{X}_1^n \text{ and} \ldots \text{and } x_I \text{ is } \tilde{X}_I^n, \text{THEN } y \text{ is } Y^n \qquad (1)$$

which $n = 1,2,\ldots,N$, $\tilde{X}_i^n (i = 1,\ldots,I)$ are interval type-2 fuzzy sets, while $Y^n = [\underline{y}^n, \overline{y}^n]$ is an interval that is a consequent of type-2 FLC, or called as Takagi-Sugeno-Kang (TSK) model. The computation steps of the interval type-2 FLC with input vector $\mathbf{x}' = (x_1', x_2', \ldots, x_I')$ are as follow.

a. Calculate the membership degree of x_i' on each $\tilde{X}_i^n$, that is $[\mu_{\underline{X}_i^n}(x_i'), \mu_{\overline{X}_i^n}(x_i')]$ where $i = 1,\ldots,I$ and $n = 1,2,\ldots,N$

b. Compute the firing strength interval for n[th] rule as $F^n(\mathbf{x}')$:

$$F^n(\mathbf{x}') = [\mu_{\underline{X}_1^n}(x_1') \times \ldots \times \mu_{\underline{X}_I^n}(x_I'), \mu_{\overline{X}_1^n}(x_1') \times \ldots \times \mu_{\overline{X}_I^n}(x_I')]$$
$$\equiv [\underline{f}^n, \overline{f}^n], \qquad n = 1,2,\ldots,N \qquad (2)$$

Instead of product, the minimum can be used as operator in (2).

c. Perform type-reduction for combining $F^n(\mathbf{x}')$ and its consequent. In this research, center of sets type-reducer (COS) method is used. The details are as follow. Fig. 2 shows the center points, y_l and y_r .

$$Y_{\cos}(x') = \bigcup_{\substack{f^n \in F^n(\mathbf{x}') \\ y^n \in Y^n}} \frac{\sum_{n=1}^{N} f^n y^n}{\sum_{n=1}^{N} f^n} = [y_l, y_r] \qquad (3)$$

which

$$y_l = \min_{k \in [1, N-1]} \frac{\sum_{n=1}^{k} \overline{f}^n \underline{y}^n + \sum_{n=k+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{k} \overline{f}^n + \sum_{n=k+1}^{N} \underline{f}^n}$$
$$\equiv \frac{\sum_{n=1}^{L} \overline{f}^n \underline{y}^n + \sum_{n=L+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{L} \overline{f}^n + \sum_{n=L+1}^{N} \underline{f}^n} \qquad (4)$$

$$y_r = \max_{k \in [1, N-1]} \frac{\sum_{n=1}^{k} \underline{f}^n \overline{y}^n + \sum_{n=k+1}^{N} \overline{f}^n \overline{y}^n}{\sum_{n=1}^{k} \underline{f}^n + \sum_{n=k+1}^{N} \overline{f}^n}$$
$$\equiv \frac{\sum_{n=1}^{R} \underline{f}^n \overline{y}^n + \sum_{n=R+1}^{N} \overline{f}^n \overline{y}^n}{\sum_{n=1}^{R} \underline{f}^n + \sum_{n=R+1}^{N} \overline{f}^n} \qquad (5)$$

which L and R are switch points as in fig. 2, satisfy:

$$\underline{y}^L \le y_l \le \underline{y}^{L+1}$$
$$\overline{y}^R \le y_r \le \overline{y}^{R+1}$$

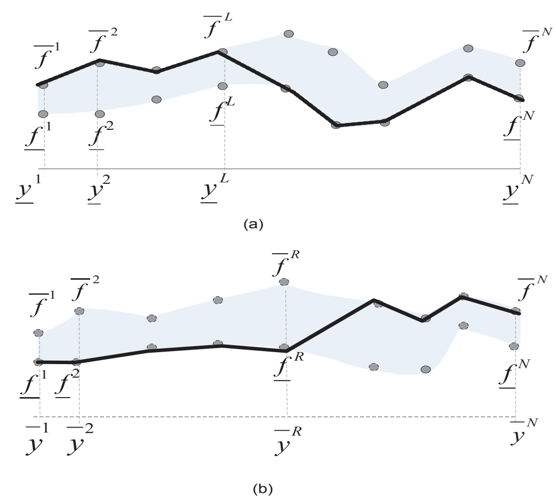

Figure 2. Switch points for computing y_l and y_r [10].

To compute the centroid points y_l and y_r , Enhanced Karnik Mendel Algorithm (EKM) can be applied. The steps are:

Step 1 : set $k = \frac{N}{2.4}$ (the nearest integer to $\frac{N}{2.4}$) and compute:

$$a = \sum_{n=1}^{k} \overline{f}^n \underline{y}^n + \sum_{n=k+1}^{N} \underline{f}^n \underline{y}^n$$

$$b=\sum_{n=1}^{k}\overline{f}^{n}+\sum_{n=k+1}^{N}\underline{f}^{n}$$

$$c'=\frac{a}{b}$$

Step 2 : find $k'\in[1,N-1]$ such that $\underline{y}^{k'}\le c'\le \underline{y}^{k'+1}$.

Step 3 : check if $k'=k$, if yes, STOP and set $c'=y_l$ and L=k. If NO, go to step 4.

Step 4 : compute $s=sign(k'-k)$ and

$$a'=a+s\sum_{n=\min(k,k')+1}^{\max(k,k')}\underline{y}^{n}\left(\overline{f}^{n}-\underline{f}^{n}\right)$$

$$b'=b+s\sum_{n=\min(k,k')+1}^{\max(k,k')}\left(\overline{f}^{n}-\underline{f}^{n}\right)$$

$$c''=\frac{a'}{b'}$$

Step 5 : set $c'=c''$, $a=a'$, $b=b'$ and $k=k'$ and go to step 2.

Below are the steps of Enhanced Karnik Mendel Algorithm for computing y_r :

Step 1 : set $k=\frac{N}{1.7}$ (the nearest integer to $\frac{N}{1.7}$) and compute:

$$a=\sum_{n=1}^{k}\underline{f}^{n}\overline{y}^{n}+\sum_{n=k+1}^{N}\overline{f}^{n}\overline{y}^{n}$$

$$b=\sum_{n=1}^{k}\underline{f}^{n}+\sum_{n=k+1}^{N}\overline{f}^{n}$$

$$c'=\frac{a}{b}$$

Step 2 : find $k'\in[1,N-1]$ such that $\overline{y}^{k'}\le c'\le \overline{y}^{k'+1}$.

Step 3 : check if $k'=k$, if yes, STOP and set $c'=y_r$ and R = k. If NO, go to step 4.

Step 4 : compute $s=sign(k'-k)$ and

$$a'=a-s\sum_{n=\min(k,k')+1}^{\max(k,k')}\overline{y}^{n}\left(\overline{f}^{n}-\underline{f}^{n}\right)$$

$$b'=b-s\sum_{n=\min(k,k')+1}^{\max(k,k')}\left(\overline{f}^{n}-\underline{f}^{n}\right)$$

$$c''=\frac{a'}{b'}$$

Step 4 : set $c'=c''$, $a=a'$, $b=b'$ and $k=k'$ and go to step 2.

d. compute output :

$$y=\frac{y_l+y_r}{2} \tag{6}$$

III. DESIGN OF INTERVAL TYPE-2 FLC FOR AIR HEATER TEMPERATURE CONTROL

The diagram of air heater mini plant is shown by Fig. 3. It consists of heating elements with alternating current (AC) voltage source. It is driven by an actuator which converts DC control signal to an appropriate modulated AC voltage. The fan is used to blow the hot air out of tube. A temperature sensor is attached near the end side of the tube in order to read the output temperature of the air heater. Signal conditioning is needed to change the sensor output as required by the controller. The controlled variable is the output temperature while the manipulated variable is the power of heating element.

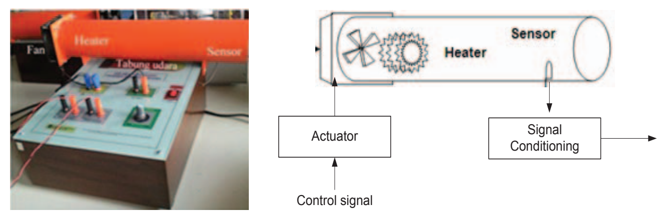

Figure 3. Air Heater miniplant.

This research designed PI-like interval type-2 FLC to control the output temperature of the air heater mini plant. The interval type-2 FLC was implemented in closed loop control configuration as shown in fig. 4. The input variables are error, $e(k)$ and change of error, $\Delta e(k)$. Error is the difference between set point (r(k)) and the present value (y(k)) that is output temperature as in (7). While, the change of error is increment value of error as in (8). The output of interval type-2 FLC is the change of control signal, $\Delta u(k)$, while the control signal, $u(k)$, is calculated using (9).

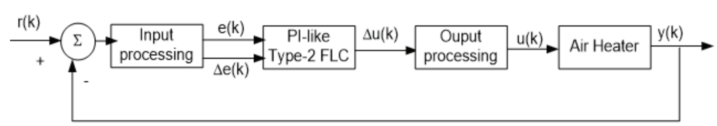

Figure 4. Close loop control of Air Heater miniplant.

$$e(k)=r(k)-y(k) \tag{7}$$

$$\Delta e(k)=e(k)-e(k-1) \tag{8}$$

$$u(k)=u(k-1)+\Delta u(k) \tag{9}$$

The linguistic value of all input variables are divided into two fuzzy values as Negative (N) and Positive (P). Fig. 5 shows the plot of interval type-2 fuzzy membership functions for error $e(k)$, while fig. 6 shows the interval type-2 fuzzy membership functions for change of error $\Delta e(k)$. Both of these figures show that their range are in [-1,1]. So, the normalization procedure is needed for error and change of error before processed by these membership functions.

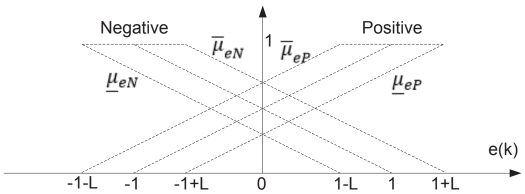

Figure 5. Error Membership function.

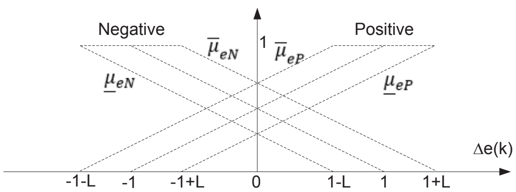

Figure 6. Change of error membership function.

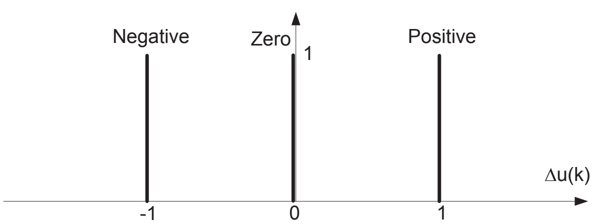

Figure 7. Singleton Fuzzy sets of change of control signal

The consequent part of the rules base, which are the changes of control signal, $\Delta u(k)$, are singleton fuzzy sets as shown in fig. 7 and can be written as in (10).

$$Y^n = \underline{y}^n = \overline{y}^n \tag{10}$$

which are take the following values; Negative (N) = -1 , Z = 0 , and Positive (P) = 1. Because the output variable of this type-2 FLC is change of output, it is called incremental mode control. The rules base was developed based on [2] which stated that for set point control problem, four rules could cover all possible control needs of it. Table I summarizes the rule bases of the type-2 FLC as air heater temperature control.

TABLE I. TABLE OF RULES BASE

Δu(k)		**e(k)**	
		Negative	**Positive**
Δe(k)	**Negative**	Negative	Zero
	Positive	Zero	Positive

IV. RESULT AND ANALYSIS

The design of interval type-2 FLC was implemented using LabVIEW as programming tool and system monitoring. NI USB 6009 was used as data acquisition board to read the sensor information from and send the control signal to the air heater mini plant. Fig. 8 shows the hardware implementation of type-2 FLC as air heater temperature control.

To evaluate the performance of the type-2 FLC, we compare to the type-1 FLC with the same rules base and output membership functions. The input membership functions of the type-1 FLC are the center line of the ones in the interval type-2 FLC. Fig. 9 and 10 show the step responses of type-1 and type-2 FLC when the set point is 50°C, while the sample time is 0.1 s and 0.5 s respectively. Table II presents the characteristic values of these response. These give the proof that the type-2 FLC has smaller settling time as well as overshoot. Fig. 11 and 12 present the responses when the set point is change from 50°C to 30°C. Both figures show that type-2 FLC has better response than type-1 FLC.

Fig. 13 shows the responses of type-1 and type-2 FLC to the disturbances which are introduced in the steady state of 40°C set point. This graphs show that type-2 FLC has smaller oscillation around the steady condition and was able to handle the disturbance better than type-1 FLC, while keeping the response in the set point. The response of both FLC in the set point changes is shown by fig. 14, which presents that type-2 FLC has better response than type-1 FLC in handling the set point changes.

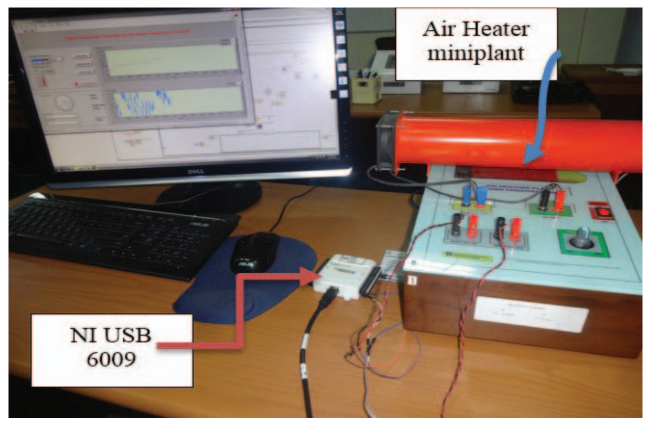

Figure 8. Hardware implementation

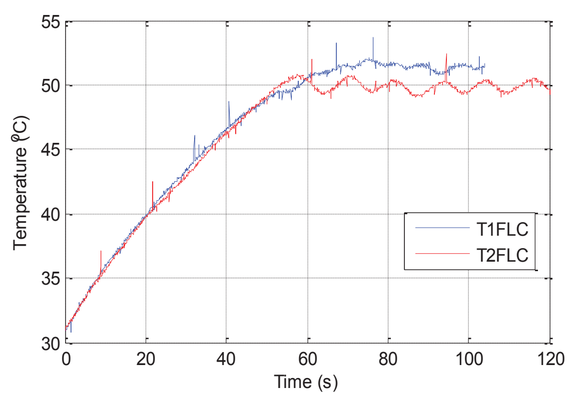

Figure 9. Step response with 50°C set point and 0.1 s sample time

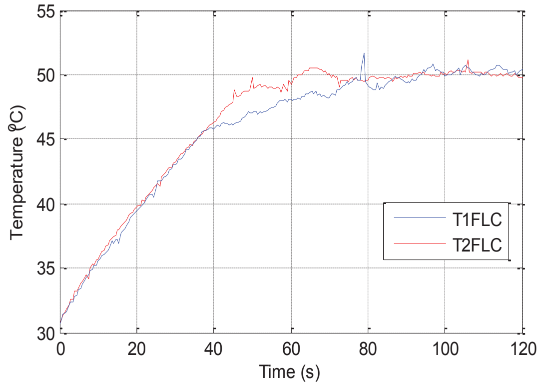

Figure 10. Step response with 50ºC set point and 0.5 s sample time

TABLE II. STEP RESPONSE CHARACTERISTICS

Step response characteristics	Sampling time = 0.1 s		Sampling time = 0.5 s	
	T1FLC	T2FLC	T1FLC	T2FLC
Rise time (s)	37.1974	42.4733	54.6748	41.4853
Settling time (s)	-	121.4148	121.4564	106.4221
Overshoot (%)	7.3518	4.7518	3.3650	2.2318

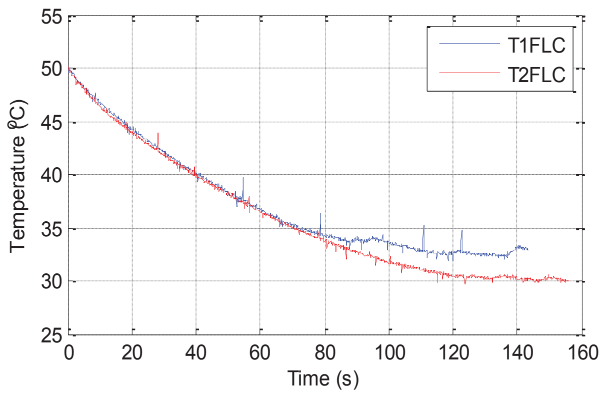

Figure 11. Step response with 50ºC initial condition, 30ºC set point and 0.1 s sample time

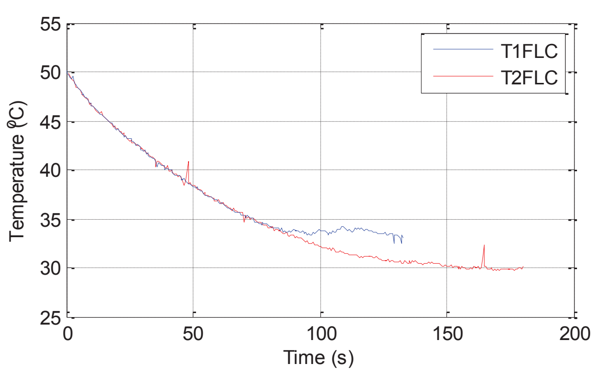

Figure 12. Step response with 50ºC initial condition, 30ºC set point and 0.5 s sample time

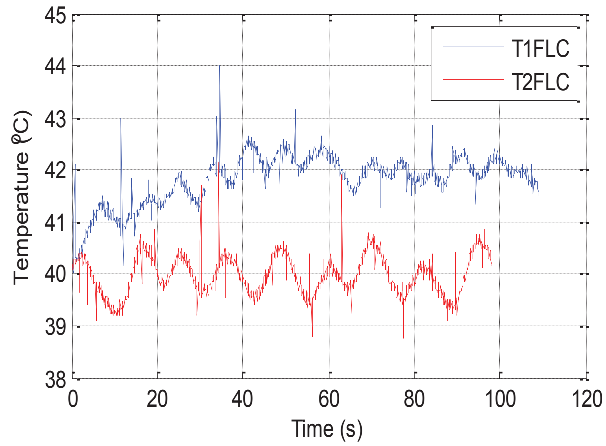

Figure 13. Response with disturbance, 40ºC set point and 0.1 s sample time

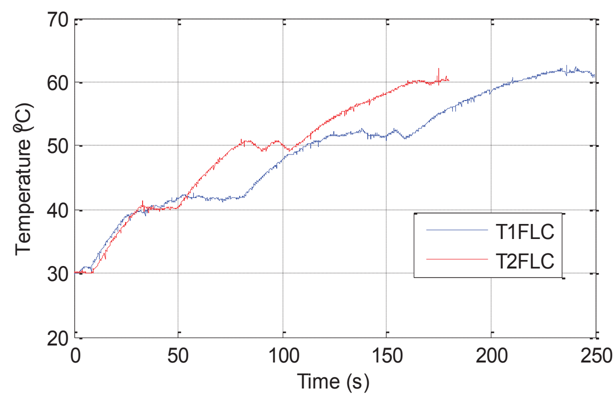

Figure 14. Response with set point change and 0.1 s sample time

V. CONCLUSION

This research has implemented an interval type-2 FLC to control the output temperature of air heater mini plant. This is applied using LabVIEW and NI USB 6009 data acquisition. It controlled the temperature of air heater in closed loop control configuration with the input variables were error and change of error, while the output was change of control. The rules base consists only four rules which are able to cover the set point control problem. Based on the experiment results, interval type-2 FLC has better performance than the type-1 FLC. It has faster settling time of step response with smaller overshoot, better disturbance handling, as well as handling the set point changing or operation condition of the air heater.

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