COMPARISON BETWEEN PI AND FLC CONTROLLER ON WATER TEMPERATURE CONTROL SYSTEM IN A PIREX TANK USING ARDUINO

Nguyen Trong Toan[1], Bui Manh Cuong[2]

[1,2]*Thai Nguyen University of Technology, Thai Nguyen city, Viet Nam*

ABSTRACT

In this work, the water temperature control system in a Pirex tank is designed for teaching purposes. Students can use this system to conduct experiments for subjects in the field of automatic control. Our first task is to build a mathematical model based on physical laws. After the system has been installed completely, the model parameters are identified experimentally based on the unit pulse response. Water temperature control system required to reach the desired temperature set-point in a certain range of time and to avoid overshooting and steady-state error. Therefore, the PID controller and FLC controller are designed and compared each other. Finally, experimental results show that the control system works stably and the settling short time.

Keyword: *Water Temperature Control, Matlab, Fuzzy Logic Control (FLC), Fuzzy Control, PID control.*

---

1. INTRODUCTION

Temperature control is one of the main problems encountered in factory automation and process control. It is also extremely interesting for teaching purposes, because temperature varies very slowly over time and therefore makes it possible to apply different control techniques and assess the effects of the control parameters involved. Water temperature control is one of the most widely used processes in academic laboratories and industries. Students may test out the use of different types of regulators, as are currently employed in industrial applications, and the tests can be performed in highly realistic conditions, as the system is entirely made of industrial quality components.

In this paper, the transfer function model of the system is built through physical laws and verified experimentally, then the PID and FLC controllers are applied.

A way to adjust parameters in PID controller is based on Ziegler–Nichols method [4, 5, 7]. This method uses plant and reference transfer functions to determine the PID parameters. While significant number of works, in industry and academic, has been studied on water Pirex tank temperature control [2, 3, 6], it still continues to elicit interest because of its critical roles in the quality of products and safety. Because of the simplicity of operation and low cost, PID has become one of the best controllers. Therefore, it is interesting to compare those two controller method.

2 TEMPERATURE CONTROL SYSTEM

a) ***Describe the thermal process [2]***

The schematic diagram of the water Pirex tank temperature control system is shown in Fig. 1. The water Pirex tank is heated by a electric heating resistance (R=30Ω, P_{max} = 1,6KW), which is connected to the single-phase AC-AC converter. A sensor module PT100 is used to sense the temperature and provides a corresponding voltage on a simple microcontroller board Arduino Uno which reads the temperature and produces a control signal. The control signal is limited between 0 and 5 V and is used to control the thyristor circuit. The physical size of the Pirex Pirex tank is 1 liter. The heating resistance is fixed inside the Pirex Pirex tank. The aim of this process is to control the water temperature in a Pirex Pirex tank to reach to set-point, and to be kept constant at desired value. Two temperature sensors are used for the measurement of the water temperature inside the Pirex tank increased accuracy. The output of the sensor which is proportional to the temperature is feedback to the controller to stabilize the set value. The water is taken from the general tap water for the experimental building through a centrifugal pump and is introduced into a circuit. During its forced circulation, the water reaches the Pirex Pirex tank, where it can be heated by varying the intensity of the electric current through a resistor. From the Pirex Pirex tank, the water go out. The outgoing flow is equal to the inlet flow. The flow can be adjusted through valve and measured by means of flow-meter. The value of the controlled quantity is acquired through a PT100 sensor.

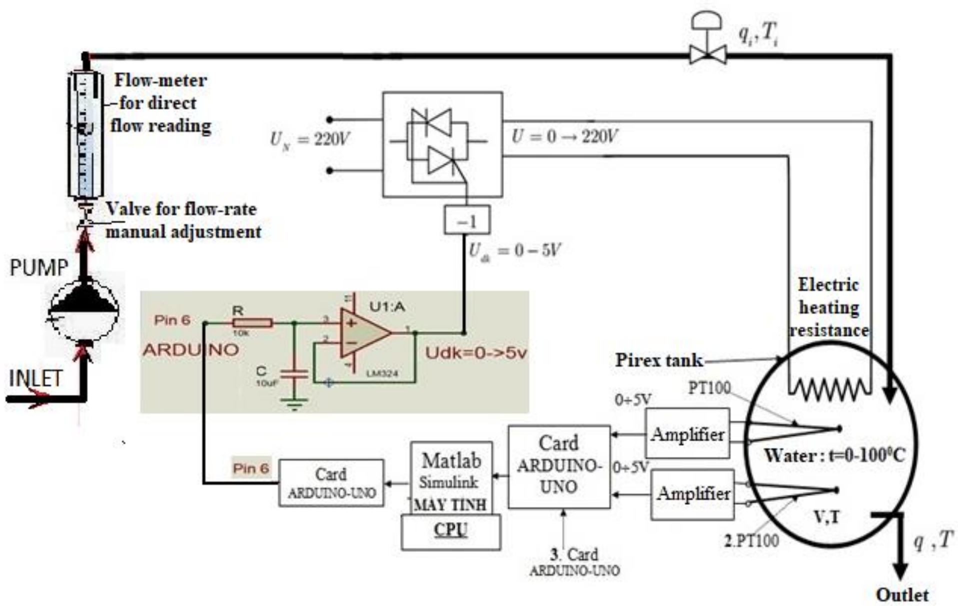

Fig. 1 Water Pirex tank temperature control system

b) Thermal model of the water Pirex tank

To consider the underlying physics of the water Pirex tank, it is assumed that the Pirex tank is at a uniform temperature. Thus, a single temperature is used to describe the temperature of the water inside the Pirex tank and of the outlet water. The outgoing flow is equal to the inlet flow. Based on the equilibrium energy low, the rate of energy entering the system is proportional to exit rate and the energy accumulated in the system. It can be derived the heat transfer equation for the process of transferring heat from the heating resistance wire to water

$$\begin{cases} V\ pC\dfrac{dT}{dt} = qC(T_{in} - T) + Q - Q_{out} \\ Q = \dfrac{U^2}{R} \end{cases} \Rightarrow \begin{cases} V\ pC\dfrac{dT}{dt} = qC\dfrac{(T_{in} - T)}{R_{tt}} + Q - Q_{out} \\ Q = 0.24\dfrac{(44u_{dk})^2}{R} \end{cases} \quad (1)$$

The heat Q_{out} released to the environment:

$$Q_{out} = qC\frac{(T_{in} - T)}{R_{tt}}$$

R_{tt} is called the heat transfer coefficient of glass

The heat Q due to the heating resistance:

$$Q = 0.24\frac{(44u_{dk})^2}{R}$$

Assuming the working point in temperature of the tank to be 60℃, the water temperature entering the tank is 30℃, so we have: $\overline{T} = 60^0C, \overline{T}_{in} = 30^0C$ the initial temperature of water Pirex tank, flow rate at the working point is 10(*l*/h), from the system of differential equations we find, $\overline{Q} = 84cal, \overline{U}_{dk} = 2.71V$, In which the parameters of the model are as follows:

The flow rate q changes from 4 *l*/h to 30 *l*/h, density $\rho = 993.3316 kg/m^3$

Specific heat: $C = 100\ cal/(kg/^\circ C)$

The heat Q_{out} released to the environment: $Q_{tt} = 0.84\ cal/s$

Converting the above differential equation into linearized form around the working point and using the difference variable, we have:

$$\begin{aligned} V\,pC\frac{d(\Delta T+\bar{T})}{dt} &= \frac{(\bar{q}+\Delta q)\,C}{R_{tt}}(\Delta T_{in}+\overline{T_{in}}-\Delta T-\bar{T})+\Delta Q+\bar{Q} \\ &= \frac{\bar{q}C}{R_{tt}}(\Delta T_{in}+\overline{T_{in}}-\Delta T-\bar{T})+\frac{\Delta qC}{R_{tt}}(\Delta T_{in}+\overline{T_{in}}-\Delta T-\bar{T})+\Delta Q+\bar{Q} \\ &= \bar{q}C(\Delta T_{in}-\Delta T)+\underbrace{\bar{q}C(\bar{T}_{in}-\bar{T})+\bar{Q}}_{=0}+\Delta qC(\Delta T_{in}+\overline{T_{in}}-\Delta T-\bar{T})+\Delta Q \\ &= \bar{q}C(\Delta T_i-\Delta T)+\Delta qC(\Delta T_{in}+\overline{T_{in}}-\Delta T-\bar{T})+\Delta Q \\ &= \bar{q}C(\Delta T_{in}-\Delta T)+\underbrace{\Delta qC(\Delta T_i-\Delta T)}_{\approx 0}+\Delta qC(\overline{T_{in}}-\bar{T})+\Delta Q \\ &= \frac{\bar{q}C}{R_{tt}}(\Delta T_{in}-\Delta T)+\frac{\Delta qC}{R_{tt}}(\overline{T_{in}}-\bar{T})+\Delta Q \end{aligned} \quad (2)$$

Thus

$$VpC\frac{d\Delta T}{dt} = \frac{\bar{q}C}{R_{tt}}(\Delta T_{in}-\Delta T)+\frac{\Delta qC}{R_{tt}}(\overline{T_{in}}-\bar{T})+\Delta Q \quad (3)$$

$$\Delta Q \approx \left(\frac{0.24\times 44^2}{R}\frac{d}{dt}u_{dk}^{\ 2}\Big|_{u_{dk}=\bar{u}_{dk}}\right)\Delta u_{dk} = \left(\frac{0.24\times 44^2}{R}2\bar{u}_{dk}\right)\Delta u_{dk} = 61.875\Delta u_{dk}$$

Converting two linear equations into Laplace operator form we get:

$$VpCs\Delta T(s) = \bar{q}C\left(\Delta T_i(s)-\Delta T(s)\right)+\Delta q(s)\ C(\bar{T}_i-\bar{T})+\Delta Q(s)$$

$$VpCs\Delta T(s)+\bar{q}C\Delta T(s) = \bar{q}C\Delta T_i(s)+\Delta q(s)C(\bar{T}_i-\bar{T})+\Delta Q(s)$$

$$\left(V\ pCs+\bar{q}C\right)\Delta T(s) = \bar{q}C\Delta T_i(s)+\Delta q(s)C(\bar{T}_i-\bar{T})+\Delta Q(s)$$

$$k_{Ti}=1, k_q=(\bar{T}_i-\bar{T})/\bar{q},\ k_Q=1/\left(C\bar{q}\right), \tau = V\ p/\bar{q}$$

$$\Delta T(s) = \frac{K_{T_i}}{\tau s+1}\ \Delta T_i(s)+\frac{K_q}{\tau s+1}\Delta q(s)+\frac{K_Q}{\tau s+1}\Delta Q(s)$$

$$K_{T_i}=1, K_q=1.0714\times 10^4, K_Q=0.3571, \tau=298.6913$$

$$\begin{cases}\Delta T(s) = \dfrac{1}{298.6913s+1}\Delta T_i(s)-\dfrac{1.0714\times 10^4}{298.6913s+1}\Delta q(s)+\dfrac{0.3571}{298.6913s+1}\Delta Q(s) \\ \Delta Q = 61.875\Delta u_{dk}\end{cases}$$

$$\begin{cases}\Delta T(s) = \dfrac{0.3571}{298.6913s+1}\Delta Q(s) \\ \Delta Q = 61.875\Delta u_{dk}\end{cases} \quad (4)$$

c) Parameter identification of the system by experiment

In this experiment, we will derive a model for the thermal dynamics of the water Pirex tank based on the step response data recorded. That is, we will fit a model to the data without any consideration of the underlying physics of the system. Therefore, we will fit a transfer function to the data of the form shown below. In order to identify the parameter of the system, a step response is obtained as shown in Fig. 2, where the type of input is step function with amplitude of 80% of the power and the sampling time is $T_s = 1s$ and flow rate is 12l/h.

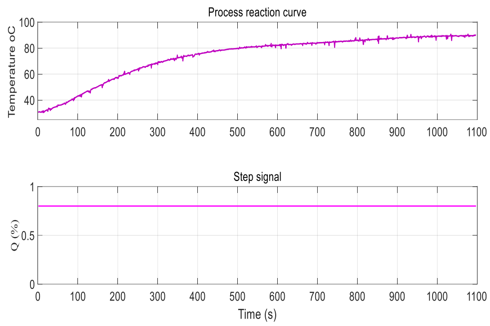

Fig -2: Step response of the water Pirex tank

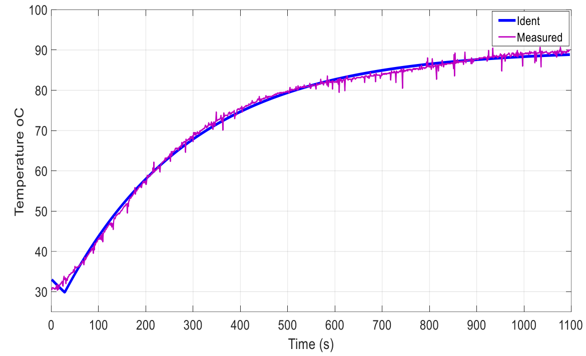

Fig -3: Best Fits 94.51%

From inspection of the given step response data, the ambient temperature (initial water temperature) appear to be approximately 32 degrees C, while the steady-state water temperature appears to be about 88 degrees C. Based on the step response and using System Identification Toolbox in Matlab, the process model is obtained as follows:

$$G(s) = \frac{K}{Ts+1}e^{-\tau s}\ \frac{22,1}{298,6913s+1}e^{-30s} \tag{5}$$

Where K is the static transfer coefficient, τ is the delayed time (s), T is the time constant of system (s).

3. DESIGN OF THE TEMPERATURE CONTROL SYSTEM

3.1 *PI Controller Design*

$$\begin{cases} \Delta T(s) = \dfrac{1}{298.6913s+1}\Delta T_i(s) - \dfrac{1.0714\times 10^4}{298.6913s+1}\Delta q(s) + \dfrac{0.3571}{298.6913s+1}\Delta Q(s) \\ \Delta Q = 61.875\Delta U_{dk} \end{cases} \tag{6}$$

PI controller continuously calculates an error *e(t)* as the difference between a desired set point and measured process variable and applies a correction based on proportional and derivative terms.

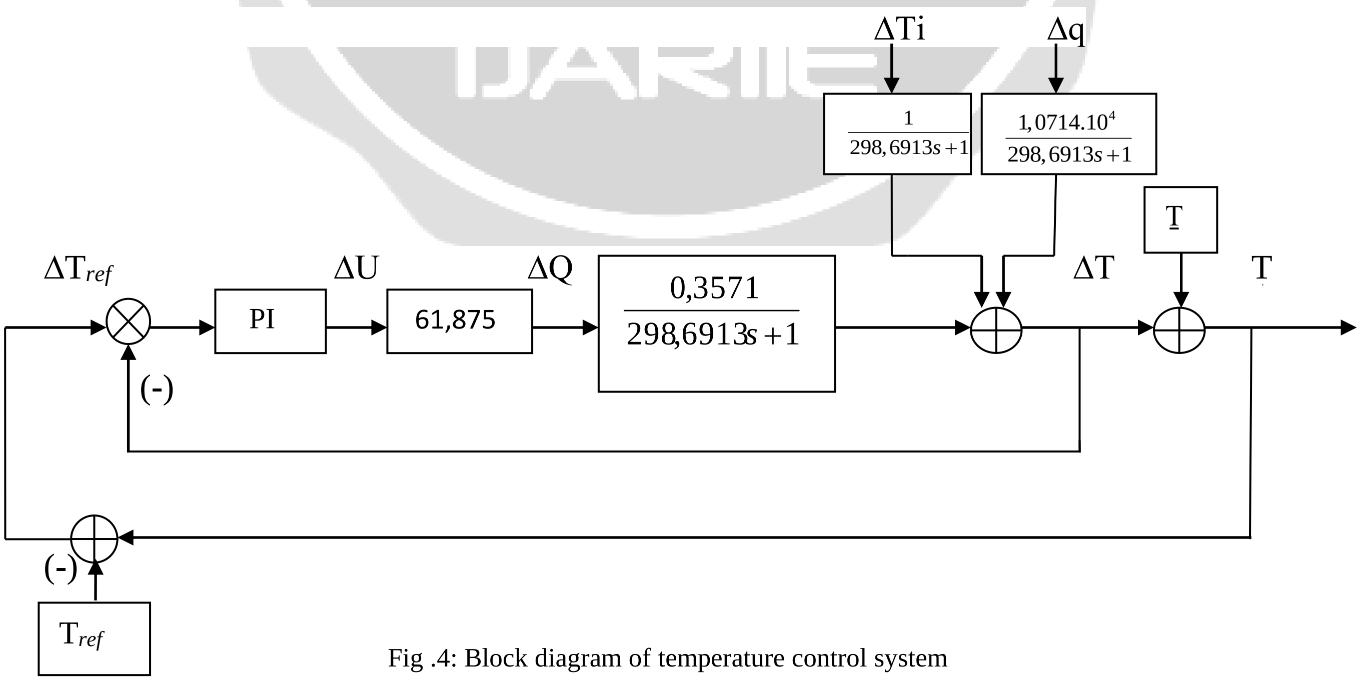

Fig .4: Block diagram of temperature control system

Since mathematical model of the plant can be derived, then it is possible to apply various design techniques for determining parameters of the controller that will meet the transient and steady-state specifications of the systems.

$$G_{plant}(s) = \frac{61,875.0,3571}{298,6913s+1} = \frac{22,1}{298,6913s+1} \quad (7)$$

Chose a reference model:

$$G_{ref}(s) = \frac{1}{298,6913s+1}; \qquad G_{close}(s) = \frac{G_{ctrl}(s)G_p(s)}{1+G_{ctrl}(s)G_p(s)} \quad (8)$$

$$G_{close}(s) = \frac{G_{ctrl}(s)G_p(s)}{1+G_{ctrl}(s)G_p(s)}$$

PI controller has the form:

$$G_{close}(s) = G_{ref}(s) \Rightarrow G_{ctrl}(s) = \frac{1}{G_p(s)}\frac{G_{ref}(s)}{1-G_{ref}(s)}$$

$$G_{ctrl}(s) = \frac{298,6913s+1}{22,1}\frac{1}{298,6913s+1} / (1-\frac{1}{298,6913s+1}) = \frac{298,6913s+1}{6601s} = 0,045+\frac{1}{6601s} \quad (9)$$

3.2 Fuzzy Controller

There are two inputs and single output will be designed in FLC system. The inputs is the error and the change of error while the output is the change in control signal. The main idea is highlighted in Figure 9. The FLC system will be implemented on water Pirex tank system through Fig 9. This system will be design using MATLAB fuzzy tools using FIS (Fuzzy Inference System). The design on the MATLAB itself is using the FLC (Fuzzy Logic Controller) to exert a block diagram based on the problem.

There are 7 variables on e membership function, the membership functions of e are shown at fig. 6.. The membership function of de is shown at fig.7. The membership function of u is shown at fig. 8. In this case the interval of u is 0 to 5. . The inference engines that are used are; Maxmin (Mamdani) method and centre of gravity technique for defuzzification.

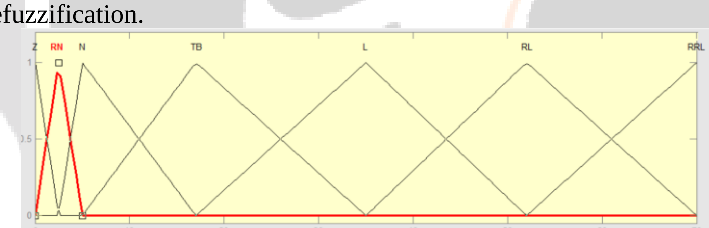

Fig.5: Membership functions of e

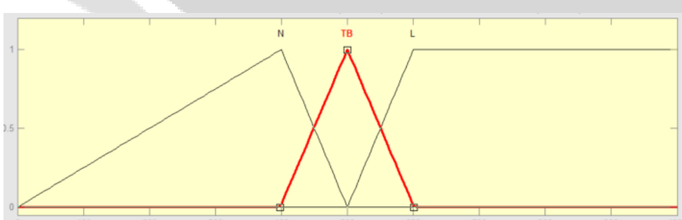

Fig.6: Membership functions of *de*

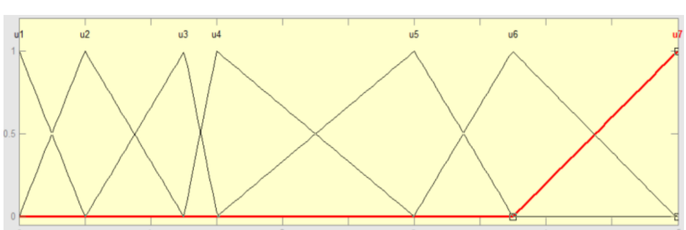

Fig.7: Membership functions of u_{dk}

DE \ E	Z	RN	N	TB	L	RL	RRL
L	U3	U4	U5	U6	U7	U7	U7
TB	U2	U3	U4	U5	U6	U7	U7
N	U1	U2	U3	U4	U5	U6	U7

Fig.8: Rules Matrix

4. EXPERIMENTAL RESULTS

A PID control strategy, based on a deduced model, is proposed for implementing a thermal process currently employed in industrial applications, and the tests can be performed in highly realistic conditions. The designed system consists of a Pirex tank, made of glass, a 30 Ω resistance, two temperature sensor PT100, an Arduino Uno-R3, a triac 40A and 220 V–50 Hz power supply.

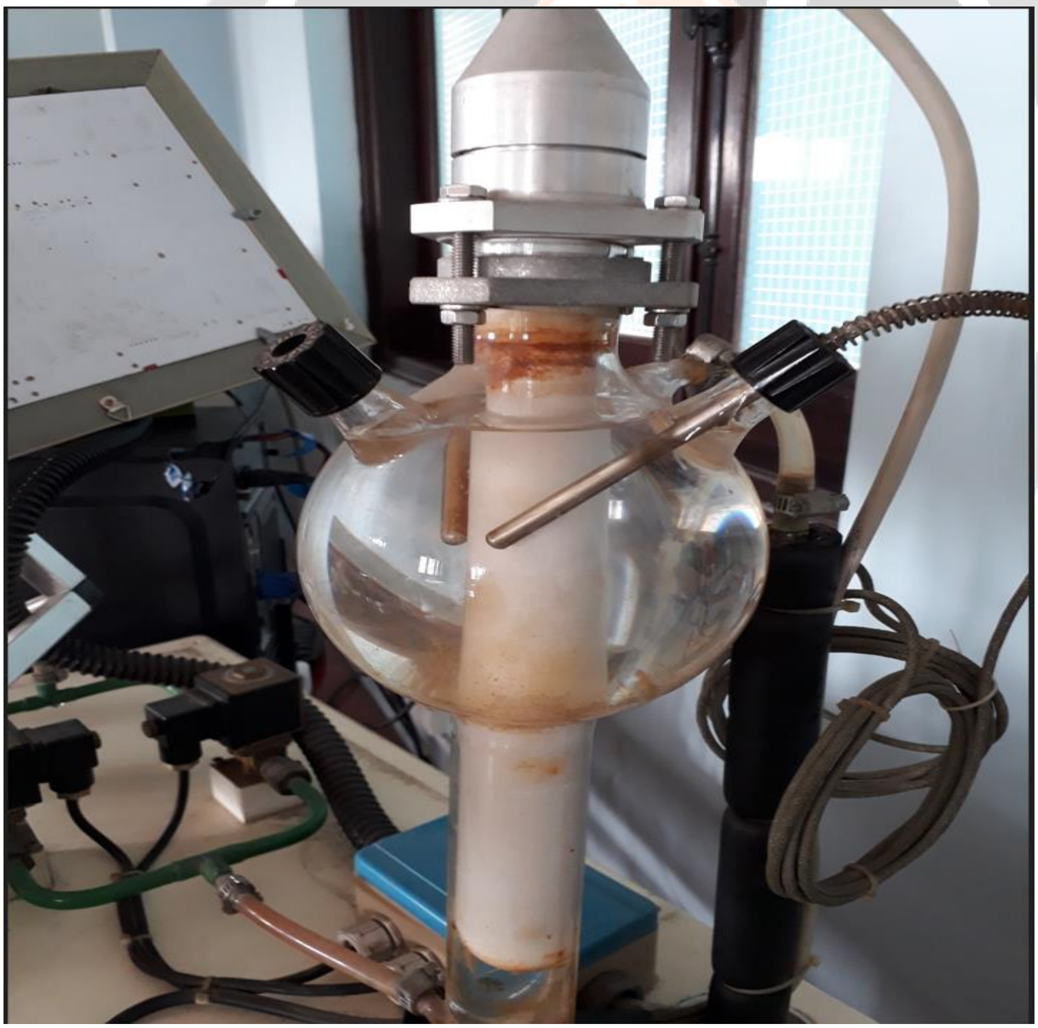

Fig.9: Schematic of water Pirex tank control system

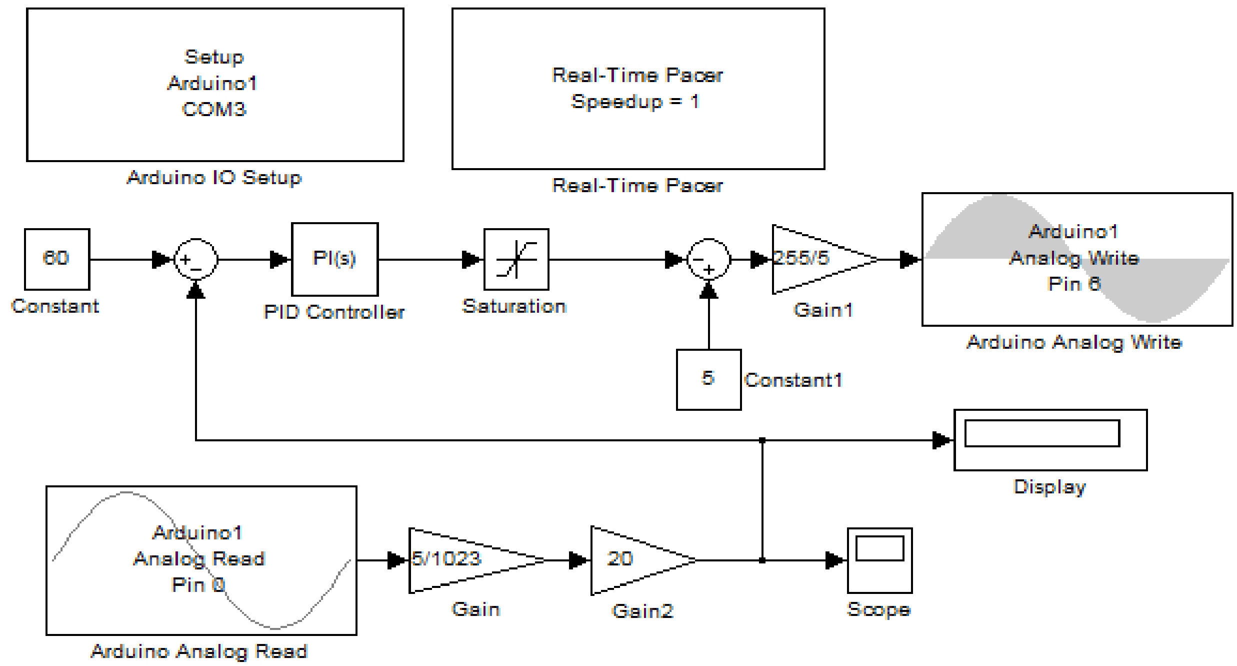

Fig .10: Actual control diagram of PI controller

The test circuit uses a small power Triac with incandescent lamp while running with 1600w load will use Triac 40A. Arduino is used to control a Triac's gate in the phase angle control circuit using Arduino.

4.2 Bộ điều khiển mờ

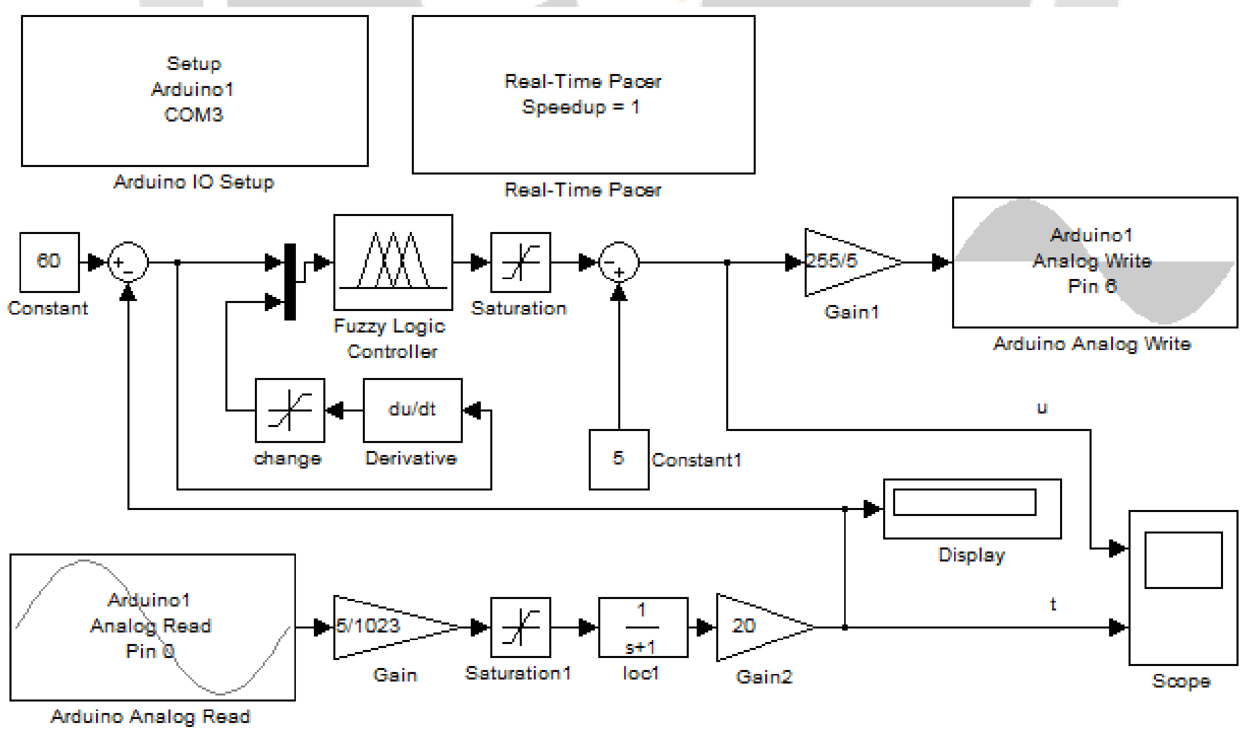

Fig .11: Fuzzy Controller Block Diagram

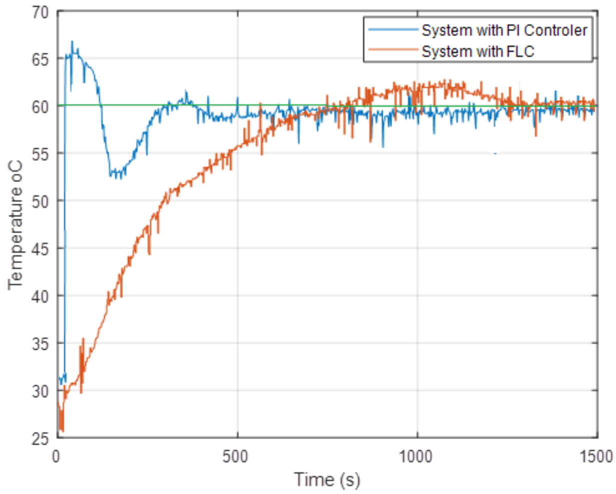

Fig -12: Waveform when setpoint 60 ºC

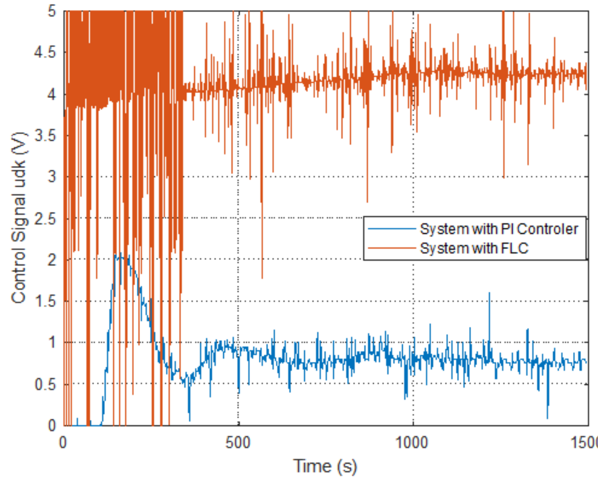

Fig -13: Waveform of control signal u_{dk}

Fig. 12 shows that without any disturbance the PI controller can generate water temperature stable at 60ºC, while The FLC can generate water temperature stable at 59.8 ºC. Thus, it was concluded that PI controller can generates more accurate water temperature than FLC. However when the system get a disturbance, FLC can handle it better than PI controller.

5. CONCLUSIONS

In conclusion, this paper successfully elaborates the designing of two controllers. we designed and implemented an efficient temperature controlling system with an Arduino board.

The main contributions of this paper are deriving the mathematical model of the system, simulate the system with Matlab Simulink and applied different control strategies to the system such as PI controller and FLC controller to control the temperature in the tank. In the couple tank system, the most required criterion is that the system has a small or no overshoot and zero steady state error. PI controller is simple to design and easy to calculate the controller parameters using reference model method, while in the FLC the stability of the closed-loop system and the convergence of the adaptation error are assured. The simulation result presented the conventional PI controller improved in the steady state region, while the FLC improved in the transient and steady state regions of the response. Hence it can be concluded that FLC yields better result than PI controller.

ACKNOWLEDGEMENT

The work described in this paper was supported by Thai Nguyen University of Technology (http://www.tnut.edu.vn).

6. REFERENCES

[1]. Nguyen Trong Toan, Nguyen Nam Trung, “Auto-tuning controllers of a class of plants using gradient descent algorithm” *International Journal of Engineering and Applied Sciences (IJEAS) ISSN: 2394-3661, Volume-6, Issue-6, June 2019.*

[2]. Mai Trung Thai, Nguyen Trong Toan, Nguyen Nam Trung, "Design the Temperature Controller Application for Heat Transfer System in the Laboratory," *SSRG International Journal of Electrical and Electronics Engineering*, vol. 8, no. 6, pp. 23-27, 2021.

[3]. Verma, O. P., R. Singla and R. Kumar (2012). "Intelligent Temperature Controller for Water Pirex tank System." *World Academy of Science, Engineering and Technology, International Journal of Computer, Information, Systems and Control Engineering 6(9).*

[4]. Hang, C.C., Astrom, K.I., Ho, W.K, "Refinements of the Ziegler–Nichols tuning formula", *IEE Proc. D, Control Theory Appl., 1991, 138, (2), pp. 111–118.*

[5]. Ziegler, J.G., Nichols, N.B, "Optimum settings for automatic controllers", *Trans. ASME, 1942, 64, pp. 759–768.*

[6]. G. G and K. E, A comparison of Fuzzy Logic and PID Controller for a single-axis tracking system, Springer Open J. Renew. Wind. Water, Sol., 2016.
[7]. Ang, K.H. and Chong, G.C.Y. and Li, Y. (2005) PID control system analysis, design, and technology. *IEEE Transactions on Control Systems Technology 13(4):pp. 559-576.*
[8]. Bui Manh Cuong, Nguyen Trong Toan, Ansys software application to build transformer model and use mechanical vibration signal to diagnose fault, IJARIIE-ISSN(O)-2395-4396, Vol-10 Issue-3 2024.