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The Implementation of Cascade Control Strategy for Liquid Temperature Control on Three Tank Systems using PID Controller

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Abstract

Controlling the temperature of the liquid in the tank is most widely used in industrial processes. One of the popular systems in industrial processes is the three-tank system. Controlling the temperature directly using the heater element has the disadvantage of a very long transient response and tends to oscillate when there is a set point change. A cascade control strategy is a form of multilevel control consisting of two layers of control loops that allow controlling the temperature by manipulating the level of the liquid. The PID control can be applied in both control layers. Based on the test results, the steady-state time was 27 seconds; while using the direct control method, the steady-state time was slower by 60 minutes.

Keywords*:* Cascade control, Three tank, PID controller, Temperature, Level

Abstrak

Pengendalian temperature cairan dalam tank paling banyak digunakan dalam proses industri. Salah satu sistem dalam proses industri yang sering digunakan diantaranya sistem three tank. Pada pengendalian temperature secara langsung menggunakan element heater mempunyai kelemahan response transient yang sangat lama serta cenderung terdapat osilasi pada saat terjadi perubahan set point. Strategi cascade control merupakan bentuk kontrol bertingkat yang terdiri dari dua lapis loop control yang memungkinkan dapat mengendalikan temperature melalui manipulasi level dari cairan tersebut. Penggunaan kontrol PID dapat diimplementasikan dalam kedua lapis kontrol tersebut. Bedasarkan hasil pengujian diperoleh waktu steady-state 27 detik, sedangkan menggunakan metode kontrol langsung waktu steady-state lebih lambat sebesar 60 menit.

Kata-kata kunci*: Cascade control, Three tank, Kontroller PID, Suhu, Level*

1. Introduction

Tank systems are widely used in chemical processes in the industry. The system involves several tanks connected by a pipe to perform certain functions. In the tank system, the condition of the liquid contained therein from the level, pressure, temperature, and flow of the connecting pipe must be maintained to carry out these functions [1] [2]. Three Tanks are one of the tank systems that are often widely used in chemical processes. As the name suggests, this system consists of three tanks which are connected through pipes. Based on the principle of Bernoulli's law, this system will affect the level conditions on all tanks causing them to have coupled properties [3] [4].

One of the uses of the three-tank system is to mix liquids of different types and temperatures. In this tank, the temperature of the liquid is maintained at a certain point [5]. So a strategy for controlling the temperature of the liquid in the tank is needed to reach the set point value. The liquid temperature control method that has been widely implemented uses an actuator heater to heat the liquid. When the temperature value meets, the heater will turn off. This method requires a very long steady-state response time to reach the set point [6] [7] . In addition, the actuator will also experience a chattering phenomenon: it will continue to be on and off to maintain the value according to the reference. The use of a heat exchanger actuator can overcome the transient response to be faster by using thermodynamic principles [8] [9] [10]. However, it has a very high price.

In this research, the cascade control method was implemented to control the temperature of the liquid in three tanks using a PID controller. The use of this strategy could overcome the problem of transient response, which tends to be slow in controlling tank temperature.

2. Method

a. Three Tank

As the name suggests, Three Tanks is a system consisting of three tanks that are connected. The fluid properties caused by the gravitational force cause the interaction of level conditions between tanks to affect each other [3] [5]. To avoid this, a valve was installed on the fluid connection of each tank. One of the functions of this system is used to mix liquids of different or the same type and condition. In this research, three tanks were used to control the temperature of the same type of liquid by mixing liquids with different temperature conditions.

The system used in this study is shown in **Figure 1**.

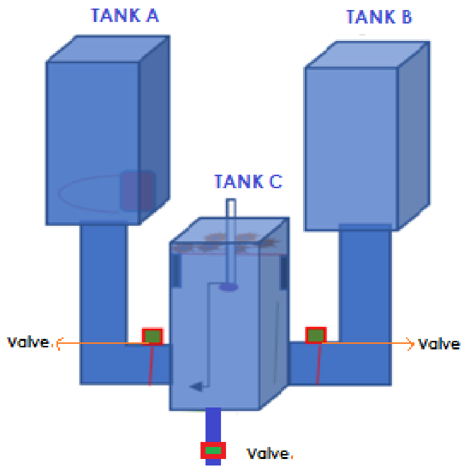

Figure 1. Three Tank

b. Cascade Controller

Cascade control is a control system strategy that has at least two loops, namely, the main control loop and the slave loop. This control is the development of a feedback control system that only controls the results of a process. In the cascade control, there is the addition of two controls that aims to overcome the disturbance that occurs on the manipulated variable side. The first control is an outer loop in the form of the main control system, which is the control goal of the system. The second control is an inner loop in the form of a secondary control system that will process the output signal from the manipulated variable [8] [9] [10]. The block diagram of this system strategy is shown in **Figure 2**.

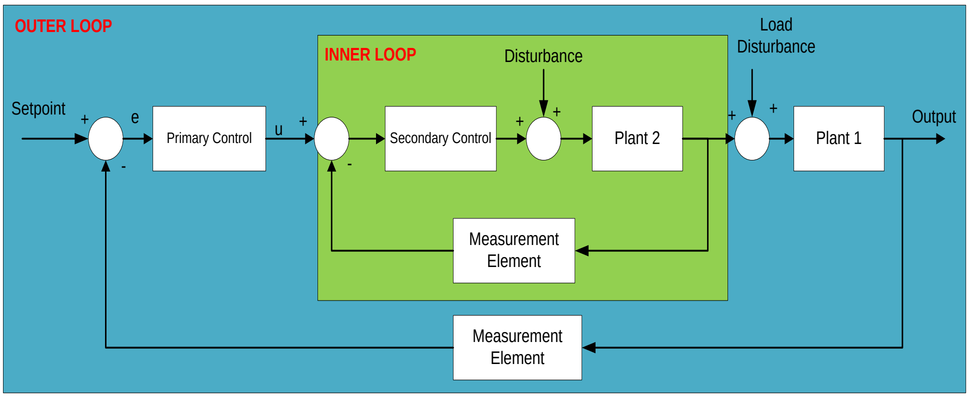

Figure 2. Block Diagram of the Cascade Control

c. PID Controller

PID controller is a conventional control method that is quite simple in design but has a satisfactory performance. Until now, this method has most widely been implemented in control strategies in the industrial world [6] [11]. This controller will process the error signal e into proportional, integral, and derivative. In this controller, some parameters need to be determined to correct the error signal [7]. The parameters are proportional constant Kp, integral constant Ki, and derivative constant Kd. The equations of this controller are as in equation 1.

$$u(t) = Kp\, e(t) + Ki \int_0^t e(t)\, dt + Kd \frac{de(t)}{dt} \quad (1)$$

d. Material

1) Arduino Uno

In this system, as a sensor and actuator output signal processor is Arduino Uno, as shown in Figure 3. Arduino is a Microcontroller formed from hardware and software. Arduino Uno uses the ATmega 328 microcontroller as the main controller. The memory owned by Uno is as follows: Flash Memory of 32KB, SRAM of 2KB, and EEPROM of 1KB. The clock on the Arduino Uno board uses XTAL with a frequency of 16 Mhz in terms of power [11]. The voltage is about 5 volts, so this tool can work with a USB connection. The Uno has 14 digital i/o pins, and the six pins are used for PWM signal operation. The pins are marked with a tilde (~), namely pins 3, 5, 6, 9, 10, and 11. Ardiuno is presented in Figure 3.

Figure 3. Arduino Uno

2) Level Sensor

The level sensor serves as a level reference in this tank system. There are various models of level sensors. In the designed system, the level sensor uses the ultrasonic working principle. The workings of ultrasonic sensors for distance measurement use the principle of calculating time from the reflection of ultrasonic waves. Acoustic waves are generated from ultrasonic sensors in frequencies ranging from 20 kHz to 20 MHz. The advantages of JSN-SR04T type ultrasonic sensor is an outdoor tool and has the advantage that sonar is streamed using an external cable and is waterproof, so it is safe to use in extreme or outdoor places. Figure 4 shows the level sensor.

This sensor is equipped with a control module with a blind spot of 23 cm. The IO port TRIG pin uses an ultrasonic sensor type JSN-SR04T at a minimum signal frequency of 5μs; the JSN-SR04T sensor sends a signal with a frequency level of 40 KHz, and then the ultrasonic wave reflection returns and is processed by the module. A signal with a high status then exits the IO pin of the ECHO port. The results of this sensor reading will be processed on the Arduino to determine the amount of liquid level in the tank. Ultrasonic sensor is presented in **Figure 4**.

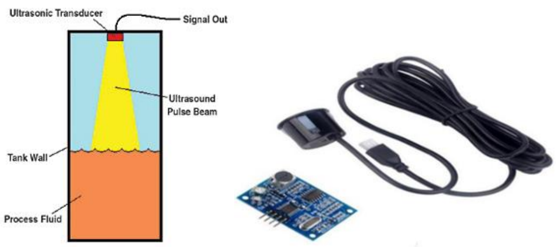

Figure 4. Ultrasonic Sensor

3) Thermocouple

The temperature sensor used in this study is a Thermocouple type K module that can detect temperatures in the range of -270°C – 1350°C. The output voltage issued by this sensor is very small, so it cannot be read by the microcontroller. Therefore, a max6675 signal conditioning circuit is needed as an amplifier of the output and a converter into a digital signal. The output data is 12-bit resolution and can be used for SPI microcontroller communication. The shape of this sensor module is shown in **Figure 5**.

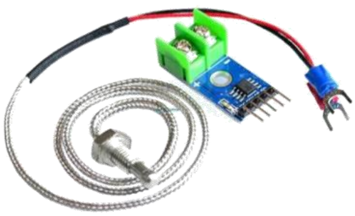

Figure 5. Thermocopel Type K dan max 6675

4) Heater Element

The heating element is an actuator that is used to heat the liquid contained in a container. This component is a metal that generally comes from a brass or copper filament of which ends are connected to a voltage source. The amount of liquid temperature obtained depends on the magnitude of the voltage source and the length of time.

This components shown **in Figure 6**.

Figure 6. Heater Element

5) Servo Valve

This system is a driving actuator that determines the flow of water entering the tank using a servo valve. The servo valve used is a combination of a servo motor coupled to a valve, where the magnitude of the valve opening angle is controlled by a servo motor by providing a PWM signal to the motor. The shape of the motor valve is shown in Figure 7. The valve angle for opening and closing is 0-90 degrees. A Servo motor is a motor that can work in both directions (CW and CCW) where the direction and angle of rotation of the rotor can be adjusted according to the valve with an angle of 90 degrees. How much the valve moves and the servo motor must first be adjusted to determine the angle that will be needed to open or close the liquid entering the tank. Servo motor and valve is presented in **Figure 7**.

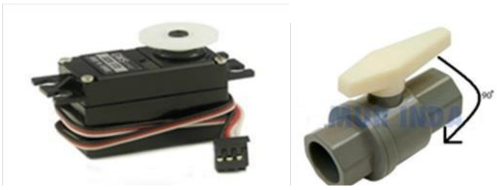

Figure 7. Servo Motor and Valve

6) Block Diagram

The block diagram for the cascade control system in **Figure 8**.

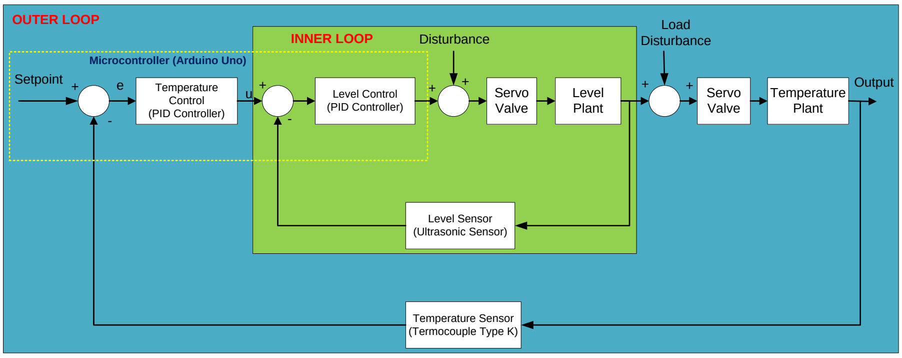

Figure 8. Block Diagram Control

Block diagram system is presented in Figure 9.

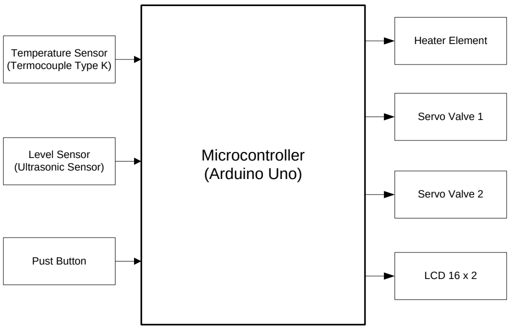

Figure 9. Block Diagram System

3. Results and Discussion

The Three Tank system used consists of three glass tanks, each measuring 10 x 15 x 70 cm. Tank 1 is a heating tank with a heater, tank 2 is a mixing tank with a temperature sensor and a level sensor, and tank 3 is a tank with water at room temperature. Between tank 1 and tank 2, and tank 2 and tank 3 is a water channel in the form of a pipe of which the amount of flow is controlled by a servo valve actuator. The shape of the system is as shown in Figure 10.

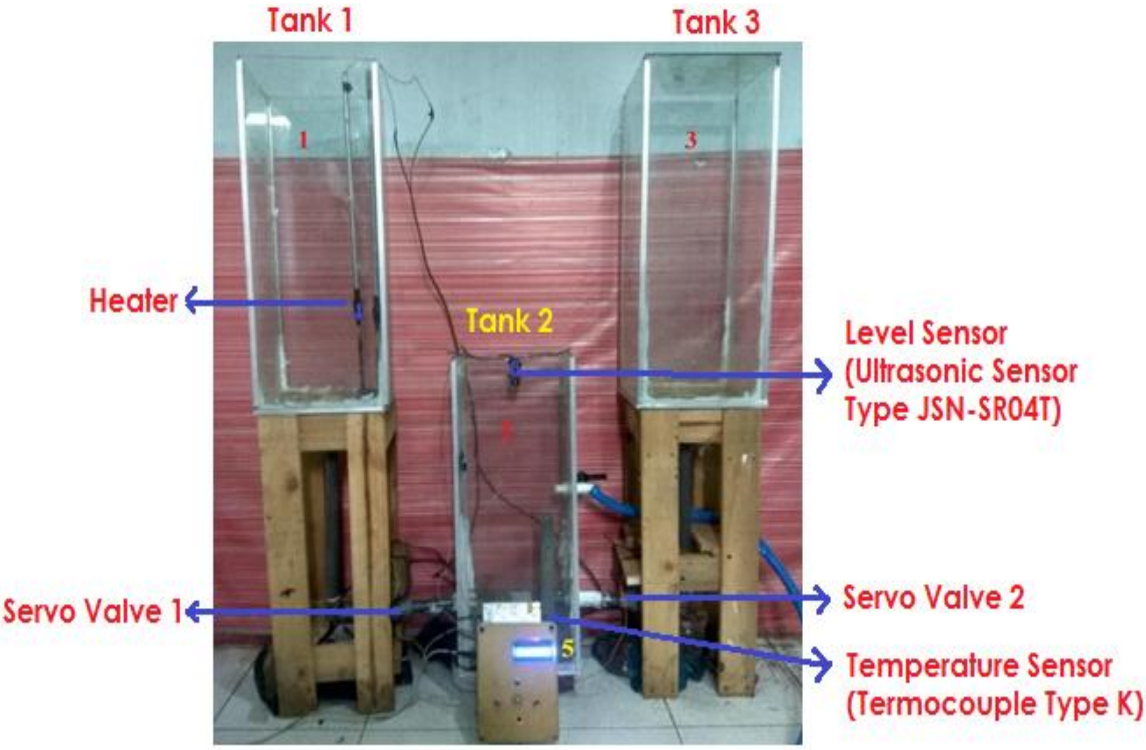

Figure 10. The Three Tank System

a. Result of Level Sensor and Temperature Test

In order to ensure the measure from the level and temperature sensors used, the sensor was tested and then calibrated so it can measure according to its real value. In the level sensor testing, it was done by filling tank 2 to a certain height level by varying the servo valve opening. The readings from the sensor were then validated manually using a ruler. Based on the test, the error value of the difference in measurement was 9. 38%. Next, the calibration process was carried out by making a linear line based on the original measurement results from the level sensor. The linear equation $y = -0{,}0011x^2 + 1{,}1494x - 0{,}6289$ was carried out, where x is the reading of the microcontroller ADC and y is the output level of the calibration results. Based on the test after calibration, it can improve the level sensor readings with the error value of the difference being 0.92%. The test results are as shown in Table 1.

Table 1. Result of Level Sensor Test

No	Manual Level Measurement (cm)	Sensor Measurement Before Calibration		Sensor Measurement After Calibration	
		Level (cm)	Error %	Level (cm)	Error %
1	0	0.08	8.6	0	0
2	2	1.91	9.23	2	0
3	6	5.91	8.63	5.85	2.5
4	10	9.91	9.03	9.97	0.7
5	13	12.91	8.45	12.91	0.69
6	17	16.91	9	17.14	0.82
7	20	19.90	9.52	20	0
8	23	22.9	10	23.5	2.17
9	27	26.89	10.45	27.2	0.74
10	30	29.89	10.88	30.5	1.66
Means Error		9.38		0.92	

Testing the temperature sensor was carried out on tank 2 by providing hot liquid from tank 1. The results of the sensor reading were then validated using a manual temperature measuring instrument using a thermometer. Based on the experimental results, the error value of the measurement difference is quite small, at 2.02%. However, the results were then calibrated based on the original measurement results from the temperature sensor; a linear equation $y = 0{,}0023x^2 + 0{,}6985x + 7{,}6476$ was obtained. Based on the calibration results, it can reduce the temperature sensor difference error to 0.97%.

The test results are presented in **Table 2**.

Table 2. Result of Temperature Sensor Test

No	Thermometer Measurement (° C)	Sensor Measurement Before Calibration		Sensor Measurement After Calibration	
		Temperature (° C)	Error %	Temperature (° C)	Error %
1	28	27	3.5	27.99	0.8
2	37	37.35	0.94	36.98	2.2
3	41	41.75	1.82	40.98	2.5
4	50	51.75	3.50	49.99	1.1
5	58	60	3.44	58.00	0
6	63	66.5	3.90	62.98	1.6
7	70	72.25	0.35	70.00	0
8	80	81.75	2.18	80.00	0.3
9	90	90.25	0.27	89.99	0.6
10	100	100.25	0.25	99.99	0.6
	Means Error		2.02		0.97

b. Result of Open Loop Level and Temperature Plant

The initial stage of the required cascade control design is to know the characteristics of the two plants contained in the inner loop and outer loop. In the inner loop, the plant functioned as the level control, and in the outer loop, the plant functioned as the temperature control. To get the characteristics of each plant, the open-loop system was tested. The plant-level test was carried out by providing a set point of 25 cm for the liquid level which was carried out five times. The test data are as shown in Figure 11. Based on the test results, the plant has the characteristics of an order 1 system with a steady-state error of 8% and a steady-state time between 8–10 seconds for all tests. Result of open loop level plant is presented in **Figure 11**.

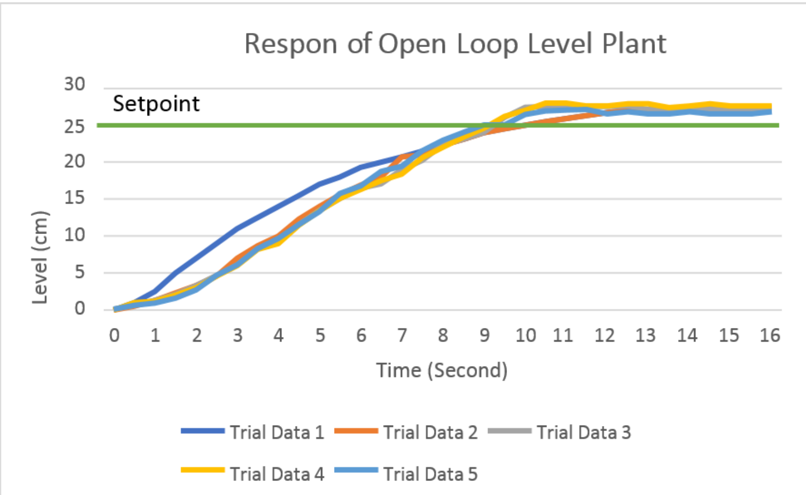

Figure 11. Result of Open Loop Level Plant

The plant temperature test was carried out by giving a set point of 45 ˚C with a liquid temperature of 33 ˚C for five times, as shown in Figure 12. These tests revealed that the plant temperature had the characteristics of an order 2 system by having a maximum overshoot of all test data of 18–25%, where the highest value was in the test data 1. The plant will also continue to oscillate to maintain the reference value with a steady-state error value of – 4 – 29%. Result of open loop temperature plant is presented in **Figure 12**.

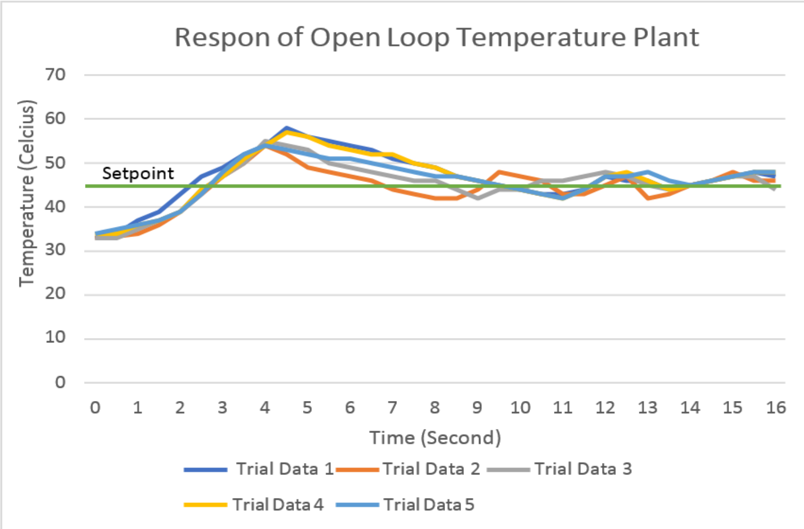

Figure 12. Result of Open Loop Temperature Plant

The results of the test for the two plants were then identified using the least square method using the Matlab identification toolbox for analysis and looking for controller parameters in compiling a cascade control strategy using a PID Controller. The structure of the desired plant model resembles a second-order system with a polynomial form for the two plants. Based on the identification results, the transfer function plant level and temperature plant models are obtained, as shown in **Table 3**.

Table 3. Result of Identification Plant

No	Plant	Transfer Function
1	Level	$\frac{0.1519s + 0.06735}{s^2 + 0.4002s + 0.06311}$
2	Temperature	$\frac{-0.2125s + 0.3033}{s^2 + 0.2692s + 0.2895}$

b. Result of System Test

1) System Test Without Cascade Control Strategy

This test was conducted to determine the response of the temperature control results manually without using a cascade control strategy by providing a set point of 45 °C. This test was carried out by heating the liquid in tank 2 using the heater until the temperature reached the reference value. The test results in Figure 13 show that the response has an overshoot of 4%. The steady-state plant time was also very long, up to 60 minutes, then the system will oscillate to maintain the reference temperature. Response of temperature control without cascade control is presented in **Figure 13**.

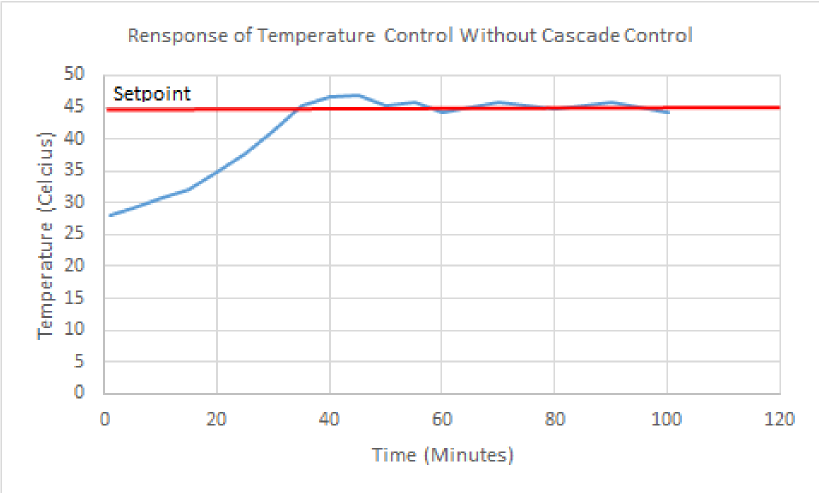

Figure 13. Response of Temperature Control without Cascade Control

2) System Test with Cascade Control Strategy

In the previous section, the modeling carried out for plant level and plant temperature is discussed. Furthermore, a simulation was carried out using Matlab to find the PID controller parameter values that then was used to control the plant in the inner loop and outer loop. The simulation design is shown in **Figure 14**.

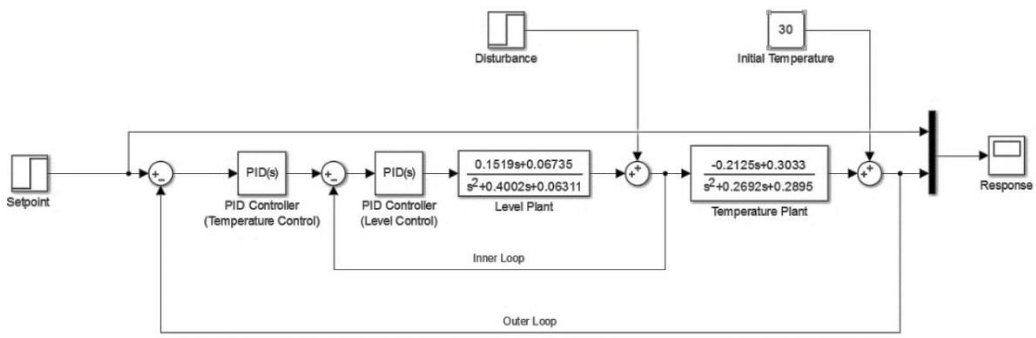

Figure 14. Simulation of Block Diagram Cascade Control

In designing the PID controller, the trial-and-error method was used until the controller parameter values were obtained with the output response results that had a good performance. Based on the results of the design using the simulation, it was obtained that the PID controller parameter had the best performance results, where for the plant level (inner loop), Kp = 1, Ki = 0.0004, Kd = - 11.484; and for the temperature plant (outer loop), Kp = 0.00001, Ki = 0.067, and Kd = 6. These parameters are then implemented in the Microcontroller program. Based on the results of the test implementation by providing a setpoint temperature in the form of a regulator (fixed) 45 ˚C, it shows that the transient response criteria will experience an overshoot of 1.6% with a time constant value of 16.43 seconds, rise time 36.1 seconds, settling time 49.29 seconds, time delay 11.38 seconds. and steady-state error 1.6%. These results indicate that using a cascade control strategy in controlling temperature has a faster time to steady-state values according to the reference. The results of this experiment can be seen in **Figure 15**.

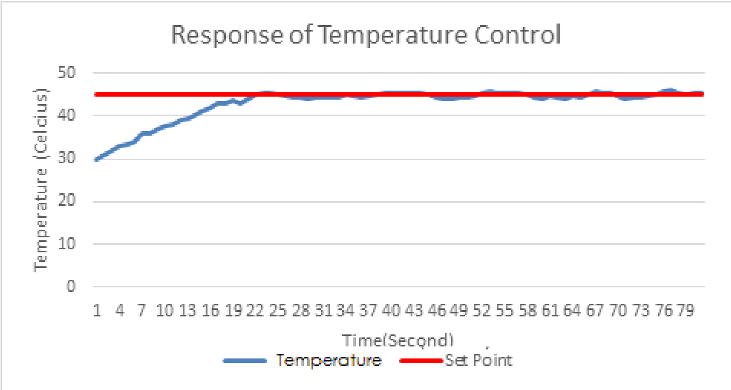

Figure 15. Response of Cascade Control with Regulator Set point

In the next test, tracking was carried out by changing the set point temperature periodically from 45 ˚C, 55 ˚C, and 65 ˚C. The aim was to test the system with dynamic reference changes. Based on the test results, it is uncovered that at the initial set point of 45 ˚C, the system had the criteria for a transient response as before. When there is a change in the set point to 55 ˚C and 65 ˚C, the response did not experience a significant change. **Figure 16** is presented about response of cascade control with tracking set point.

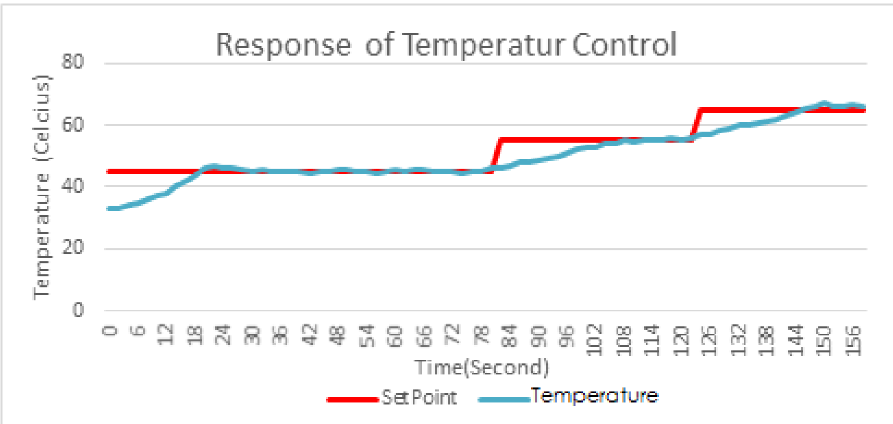

Figure 16. Response of Cascade Control with Tracking Set point

4. Conclusion

Based on the results of the tests that have been carried out, it is unveiled that the use of the cascade control strategy in temperature control in the Three Tank system can accelerate the transient response compared to the direct control method. With a fixed setpoint and tracking, the steady-state time was 27 seconds, while using the direct control method, the steady-state time was slower by 60 minutes.

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