



Article Processing Dates: Received on 2024-10-18, Reviewed on 2024-11-11, Revised on 2024-11-17, Accepted on 2024-11-20 and Available online on 2024-12-30

## Cascade flow rate-temperature control system design based on PID controller using direct synthesis tuning method

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### Abstract

Cascade control is one of the multi-loop control schemes that aim to increase the performance of closed-loop control systems. Temperature control on the outlet of a plate heat exchanger often suffers errors in the control variable and designated set point, so it is necessary to use cascade control in order to stabilize output temperature and reduce the disturbance. The Proportional Integral Derivative (PID) controller in conjunction with the direct synthesis tuning method is used due to ease of implementation and to modify the second-order process model and become the first-order process model, simplifying the model. In cascade control, the flow rate control is designated as the secondary loop, while the temperature control functions as the primary loop. The PID controller model is designed with direct synthesis tuning on the cascade flow rate temperature control, resulting a proportional gain of 2.15%,  $\tau_i$  of 1.976 s, and  $\tau_d$  of 0 seconds on the flow rate control loop. Whereas on the temperature control loop, the proportional gain is 13.23%,  $\tau_i$  is 66.3 s and the  $\tau_d$  is 7 seconds. The transient responses from cascade flow rate temperature control from Simulink are rise time ( $t_r$ ) = 106.7 seconds, settling time ( $t_s$ ) = 183 seconds, and maximum overshoot = 0%. Based on this parameter, the controller generates Process Variable (PV) responses from master control that can reach the Set Point (SP) without overshoot, maintain a steady state, and reduce the disturbance from slave control within 20 seconds of the response increasing from the steady state condition

### Keywords:

Cascade control, disturbance, plate heat exchanger, direct synthesis, PID controller

### 1 Introduction

Cascade control is often used on industrial automation systems, especially on process equipment such as heat exchangers [1], [2], [3], boilers [4],[5], [6] and furnaces [7] on the oil and gas industry. Cascade control is a multi-loop control scheme that aims to increase the performance of closed-loop control systems [8]. This control scheme consists of two loops, which are the secondary loop and the primary loop. The main purpose of cascade control is to reduce the disturbance that comes from the secondary loop before reaching the primary loop [9].

The research of cascade control on the power plant superheater steam system [10] shows that a control system with high performance is important in the power plant, especially in the dynamic process such as steam utilization. Other research on the implementation of cascade control on heat exchangers shows that when the temperature output is not measurable, the cascade

control can improve the performance of the system significantly [6].

Temperature is an important process variable in various industrial applications due to its significant role in heat adsorption [11]. Heat exchange process, especially on the heat exchanger plate requires precise control of the input variable to control the temperature output. But the practice of temperature output control on the heat exchanger plate often suffers from error due to deviation between the manipulated variable and the set point that has been set [12]. Therefore, closed-loop control that can stabilize temperature output and decrease the noise is necessary [7].

The simplest closed-loop control is feedback control, which adjusts the system response, such as rise time, overshoot, settling time, and steady-state error. But the feedback control performance can be not fully optimized due to the disturbance, such as the instability of the hot or cold fluid flow rate that influences manipulated variable value, which will cause variation in the output. Research on the implementation [13] of cascade control to reduce the disturbance on the shell-tube heat exchanger uses the mathematical model of First Order Plus Delay Time (FOPDT) from the plant process and the Ziegler Nichlos tuning method for the PID controller on the secondary-loop to control flow rate. This approach compares the performance of feedback control, single-loop cascade control, and the results from the process plant. MATLAB Simulink simulation of the cascade control shows excellent response, especially on the PI-controller on the secondary loop, with the lowest value of Integral Absolute Error (IAE) of 34.57. The PID parameters on the primary loop, such as  $K_p$ ,  $\tau_i$ , and  $\tau_d$  respectively is 2.85, 53.06, and 13.265. Using those parameters, the lowest IAE value on the primary loop is 601.54 and the fastest rise time is 121.5 seconds. This result indicates that cascade control can reduce disturbance and reach the stable temperature set point, although the flow rate is fluctuating.

The PID controller has been widely used for almost 80 years due to its simple structure that makes the implementation of control simpler [14]. PID linear parameters such as proportional gain ( $K_p$ ), integral time ( $\tau_i$ ), and derivative time ( $\tau_d$ ) have to be adjusted correctly in order to optimize the feedback control system performance [15]. Incorrect settings can reduce the overall performance. Therefore, it is necessary to design a controller that is based on a proper mathematical model because the process control that uses an incorrect model can produce unoptimized results even though the PID parameter has been set properly [16].

The direct synthesis tuning method has been used to increase the performance of cascade control. Research on cascade control for temperature and pressure variables has shown that it will decrease the maximum overshoot of transient response 19.8% to 0.005% [17]. Another research also showed that direct synthesis tuning method on servo tracking improved the stability of the system by decreasing the settling time of the response [18].

Based on the previously said problem, that heat exchanger needs precise control. In order to achieve such precise control, cascade control is needed to control the temperature of fluids by regulating the flow rate of the hot and cold fluids. This research is aimed to shedding light on improvement in using the direct synthesis tuning method cascade flow rate-temperature control system.

### 2 Research Method

#### 2.1 Direct Synthesis Tuning

Controller tuning with the direct synthesis method [19] uses the original model from the plant and the expected model to determine the proportional (P), integral (I), and derivative (D) parameters needed for the controller. This tuning method is one of the PID tuning methods that is used to reach the tracking model function used on the plant. The research method flow is described as Fig. 1.

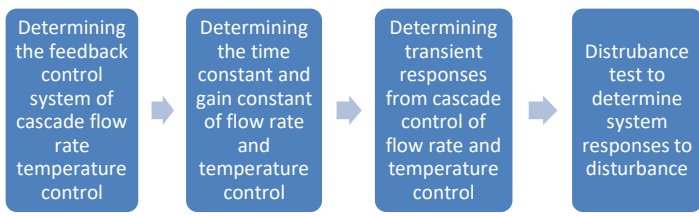


Fig. 1. Research flow of cascade flow rate temperature control.

The first step in this method is to determine the desired output specification by designing the tracking model and using the suitable process plant model for the controller model (Eq. 1 and Eq. 2). By referring to the transfer function from the plant model, the gain is determined by multiplying process gain and control valve gain. If the PID controller that is used on the second-order plant system doesn't implement delay, then the PID parameter can be adjusted according to the plant process to achieve optimized control performance. So, the system block diagram will be similar to the closed-loop system block diagram [20], [21], as shown in Fig. 2.

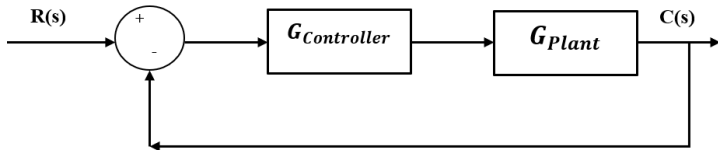


Fig. 2. Plant block diagram using direct synthesis tuning method.

$$G_{Plant}(s) = \frac{K}{\left(\frac{1}{\omega_n^2}\right)s^2 + \left(\frac{2\zeta}{\omega_n}\right)s + 1} \quad (1)$$

$$G_{Controller}(s) = Kp \left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \quad (2)$$

The transfer function of the plant can be written as Eq. 3 and Eq. 4.

$$\frac{C(s)}{R(s)} = \frac{G_{Controller} \times G_{Plant}}{1 + G_{Controller} \times G_{Plant}} \quad (3)$$

$$\frac{C(s)}{R(s)} = \frac{Kp \left(\frac{\tau_i \tau_d s^2 + \tau_i s + 1}{\tau_i s}\right) \left(\frac{K}{\left(\frac{1}{\omega_n^2}\right)s^2 + \left(\frac{2\zeta}{\omega_n}\right)s + 1}\right)}{1 + Kp \left(\frac{\tau_i \tau_d s^2 + \tau_i s + 1}{\tau_i s}\right) \left(\frac{K}{\left(\frac{1}{\omega_n^2}\right)s^2 + \left(\frac{2\zeta}{\omega_n}\right)s + 1}\right)} \quad (4)$$

The principle of the direct synthesis tuning method is to design a PID controller from a second-order plant, resulting in a first-order plant model by using this mathematical model (Eq. 5).

$$\frac{C(s)}{R(s)} = \frac{K^*}{\tau^* s + 1} \quad (5)$$

$K^*$  is the overall gain from the plant, and the  $\tau^*$  is the desired time constant from the system model, which is represented by the first-order system model. In order to generate the first-order model system response, the first-order transfer function is substituted for the second-order closed-loop transfer function (Eq. 6).

$$\frac{K^*}{\tau^* s + 1} = \frac{Kp \left(\frac{\tau_i \tau_d s^2 + \tau_i s + 1}{\tau_i s}\right) \left(\frac{K}{\left(\frac{1}{\omega_n^2}\right)s^2 + \left(\frac{2\zeta}{\omega_n}\right)s + 1}\right)}{1 + Kp \left(\frac{\tau_i \tau_d s^2 + \tau_i s + 1}{\tau_i s}\right) \left(\frac{K}{\left(\frac{1}{\omega_n^2}\right)s^2 + \left(\frac{2\zeta}{\omega_n}\right)s + 1}\right)} \quad (6)$$

From the Eq. 6, can be derived the time integral value ( $\tau_i$ ) and time derivative ( $\tau_d$ ) (Eq. 7- Eq. 9).

$$\tau_i \tau_d = \frac{1}{\omega_n^2} \quad (7)$$

$$\tau_i = \frac{2\zeta}{\omega_n} \quad (8)$$

$$\tau_d = \frac{1}{2 \times \zeta \times \omega_n} \quad (9)$$

If  $K^*$  (gain overall first order) = 1, then Eq. 6 can be further simplified into Eq. 10 and Eq. 11.

$$\frac{K^*}{\tau^* s + 1} = \frac{1}{\frac{\tau_i s}{K_p \cdot K} + 1} \quad (10)$$

$$\tau^* s = \frac{\tau_i s}{K_p \cdot K} \quad (11)$$

On the Eq. 11, the variable  $K_p$  is isolated into its explicit form. Therefore, the value of proportional band ( $K_p$ ) will be Eq. 12.

$$K_p = \frac{\tau_i s}{\tau^* s \cdot K} \quad (12)$$

Desired time constant ( $\tau^*$ ) is determined based on desired settling time ( $\tau_s$ ), which is the time required for the system to reach a certain percentage from its steady state condition. The value of settling time is stated by a  $\pm 5\%$ ,  $\pm 2\%$ , or  $\pm 0.5\%$  range from steady state response (Eq. 13-Eq. 15).

$$\tau_s(\pm 5\%) = 3\tau^* \quad (13)$$

$$\tau_s(\pm 2\%) = 4\tau^* \quad (14)$$

$$\tau_s(\pm 0,5\%) = 5\tau^* \quad (15)$$

## 2.2 Heat Exchanger Design System

This research is focused on the system performance that is generated by a cascade control on the process unit plate heat exchanger and orifice plate flow meter. This unit is used as a process implementation of a cascade flow rate temperature control system. The process of the heat exchanger used in this research can be seen from Fig. 3.

When water from the hot water storage tank is pumped using pump (P1) to the heater, the temperature of the plate heat exchanger outlet on the hot water cycle has to be maintained. The temperature is controlled in cascade by controlling the flow rate that comes to the plate heat exchanger on the cold-water cycle. The flow rate is measured by a Differential Pressure Flow Transmitter (DPT) and the temperature is measured by an RTD Pt100 sensor (TE). RTD sensor measures the process variable (PV) the temperature, then Temperature Transmitter (TT) converts that PV into the standard signal 4-20 mA that will be sent to the temperature controller (TC). In the temperature controller, PV will be compared to Set-Point (SP) and calculated to obtain Manipulated Variable (MV).

The manipulated variable from the temperature controller will be used as the set point for the Flow Rate Controller (FC). Then, the differential pressure flow transmitter will detect differential pressure as a process variable that is generated by an orifice plate sensor. Differential pressure flow transmitter will linearize measured differential pressure to be flow rate using square root extraction feature from smart transmitters.

Differential pressure will be converted to a standard signal of 4-20 mA by DPT and delivered to the flow rate controller. The flow rate PV will be compared to the set point and be calculated to obtain the manipulated variable. The manipulated variable will be sent to the Flow Rate Control Valve (FCV) to manipulate the cold

water cycle. Therefore, the temperature from plate heat exchanger outlet on the hot water cycle can be maintained at the desired set point. The block diagram of cascade flow rate temperature control that is used in this research is Fig. 4.

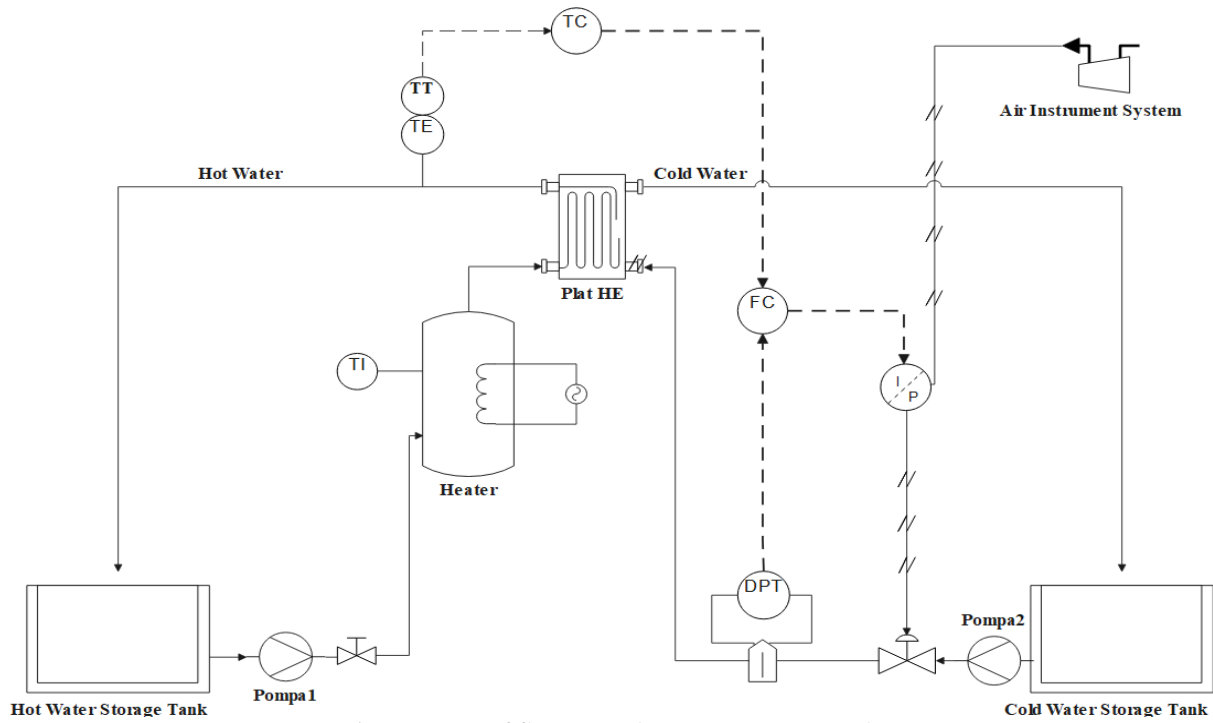


Fig. 3. P&ID of flow cascade temperature control.

### 2.3 Controller Design

The flow rate control loop and temperature control loop is designed as parallel PID controllers to control the system in cascade as shown in Fig. 4. The transfer function of the plant is approached through a bump test experiment that is estimated in the MATLAB system identification. The main focus of the

research is to reach system performance that is able to deliver disturbance rejection [21] that is manually sent to the flow rate control loop. Furthermore, another research goal is to design a control model that is fit to process characteristics using the direct synthesis tuning method.

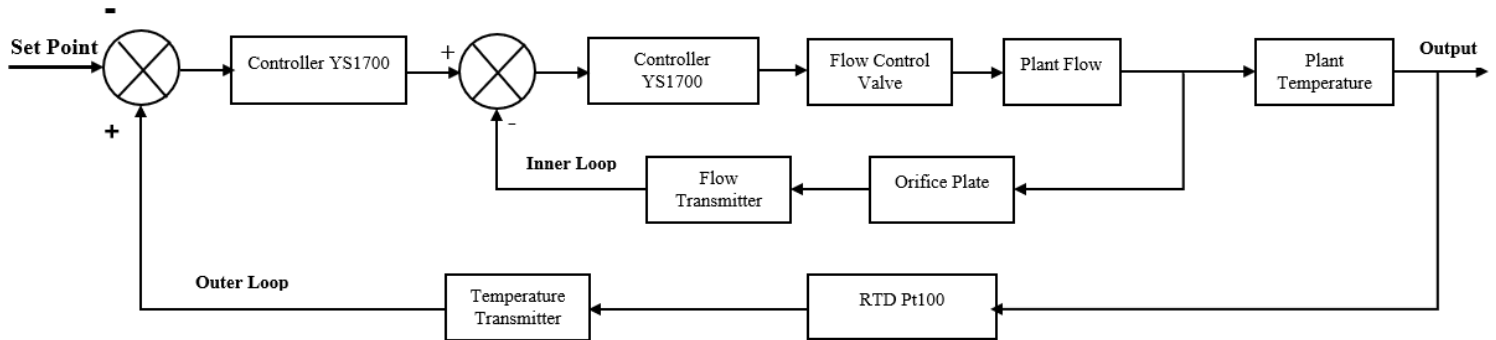


Fig. 4. Block diagram of flow cascade temperature control.

#### 2.3.1 Flow Rate Control Loop Design

The bump test for the flow rate process is performed by changing the control valve opening from 0% to 60% for 4 minutes and 35 seconds in manual mode. After that, the response is observed, and the change in differential pressure process variable from the water flow that is through the orifice plate is recorded. The response that is generated by the bump test changes quite a bit but is still near the steady state condition. Gain calculation is done with MATLAB system identification. Data from bump test is inputted to MATLAB, generating a gain plant transfer function without oscillation with a fit estimate of 96.94% (Eq. 16).

$$G_{PlantFlow} = \frac{2.29908}{0.0083598s^2 + 1.9759s + 1} \quad (16)$$

Based on Eq. 7 to Eq. 16, the flow rate plant transfer function is Eq. 17.

$$\tau_i \tau_d = \frac{1}{\omega_n^2} = 0.0083598 \quad (17)$$

Therefore, the Omega<sub>n</sub> (ω<sub>n</sub>) value can be calculated using Eq. 18.

$$\omega_n = \sqrt{\frac{1}{0.0083598}} = 10,78328 \text{ Rad/s} \quad (18)$$

From the Eq. 8, the flow rate plant transfer function can be derived as Eq. 19.

$$\tau_i = \frac{2\zeta}{\omega_n} = 1.9759 \text{ s} \quad (19)$$

$$\tau_d = \frac{0.0083598}{1.9759} = 0.004 \text{ s}$$

Therefore, the zeta ( $\zeta$ ) value can be calculated using Eq. 20.

$$\zeta = \frac{\tau_i \times \omega_n}{2}$$

$$\zeta = \frac{1.9759 \times 10.78328}{2} = 10.65388 \quad (20)$$

The zeta ( $\zeta$ ) and omega ( $\omega_n$ ) values are the pure form of the direct synthesis tuning method that is fit to process characteristics: therefore they can be used to get the values of time integral ( $\tau_i$ ) and time derivative ( $\tau_d$ ). Based on Eq. 8 and Eq. 9, the values of  $\tau_i$  and  $\tau_d$  are Eq. 21 and Eq. 22.

$$\tau_{i \text{ Flow Loop}} = \frac{2 \times 10.65388}{10.78328} = 1.976 \text{ s} \quad (21)$$

$$\tau_{d \text{ Flow Loop}} = \frac{1}{2 \times 10.65 \times 10.78328} = 0.00435 \quad (22)$$

Proportional gain ( $K_p$ ) of the flow rate controller can be calculated based on Eq. 12 with the overall gain flow rate process ( $K$ ) = 2.29908. This value is calculated using Eq. 16. The time constant ( $\tau^*$ ) of the controller is determined by using the settling time ( $t_s$ ) of the system. Based on Eq. 8 and Eq. 9, the values of  $\tau_i$  and  $\tau_d$  for the temperature loop are: is set on  $\pm 0.5\%$  and 2 seconds. Based on Eq. 12 and Eq. 15, the time constant and proportional gain values are responses when reaching a certain percentage from a steady state condition (Eq. 23- Eq. 25).

$$t_s (\pm 0.5\%) = 5\tau^* = 2 \text{ s} \quad (23)$$

$$\tau^* = \frac{2}{5} = 0.4 \text{ s} \quad (24)$$

$$K_{P \text{ Flow Loop}} = \frac{1.9759}{0.4 \times 2.29908} = 2.15 \% \quad (25)$$

Based on the graphic shown on the Fig. 5, using  $K_p$  of 2.15%,  $T_i$  of 1.9759 s and  $T_d$  of 0.004 s, the flow rate control part of cascade control is stable.

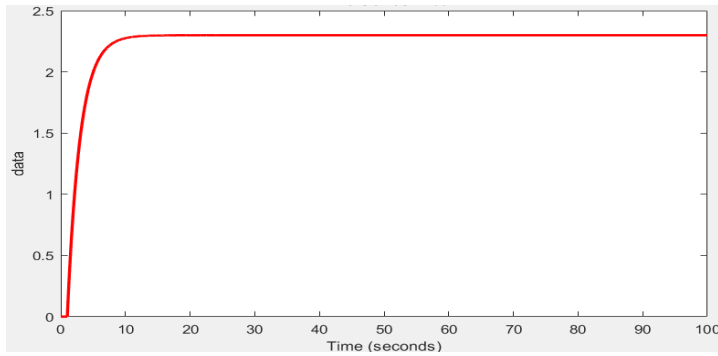


Fig. 5. Flow rate plant model.

### 2.3.2 Temperature Control Loop Design

The bump test for the temperature process is performed when the hot water cycle of the plate heat exchanger reaches  $61^\circ\text{C}$ . Hot water is circulated through the heating process with a power of 300 watts for 35 minutes. After the water reaches  $61^\circ\text{C}$ , the bump test is performed by changing the control valve opening from 0% to 60% for 4 minutes, and 45 seconds in manual mode. The response is observed, and the change in temperature variable on the outlet flow of the plate heat exchanger is recorded. Gain calculation is done with MATLAB system identification. Data from bump test is inputted to MATLAB, generating a gain plant transfer function without delay and oscillation with a fit estimate of 89.66%.

$$G_{\text{PlantFlow}} = \frac{0.10019}{487.855s^2 + 66.29s + 1} \quad (26)$$

Based on Eq. 7 to Eq. 16, the temperature plant transfer function is Eq. 27.

$$\tau_i \tau_d = \frac{1}{\omega_n^2} = 487.855 \quad (27)$$

Therefore, the Omega<sub>n</sub> ( $\omega_n$ ) value can be calculated using Eq. 28.

$$\omega_n = \sqrt{\frac{1}{487.855}} = 0.04528 \text{ Rad/s} \quad (28)$$

From the Eq. 8, the temperature plant transfer function can be derived as Eq. 29.

$$\tau_i = \frac{2\zeta}{\omega_n} = 66.29 \quad (29)$$

Therefore, the zeta ( $\zeta$ ) value can be calculated using Eq. 30.

$$\zeta = \frac{66.29 \times 0.04528}{2} = 1.5007 \quad (30)$$

$$\tau_{i \text{ Temperature Loop}} = \frac{2 \times 1.5007}{0.01344} = 66.29 \text{ s} \quad (31)$$

$$\tau_{d \text{ Temperature Loop}} = \frac{1}{2 \times 1.5007 \times 0.04528} = 7.4 \text{ s} \quad (32)$$

Proportional gain ( $K_p$ ) of the temperature controller can be calculated based on Eq. 12 with an overall gain the flow rate process ( $K$ ) = 0.10019. The settling time of flow rate controller is set to  $\pm 0.5\%$  and 2 seconds. Based on Eq. 12 and Eq. 15, the time constant and proportional gain values are Eq. 33-Eq. 35.

$$t_s (\pm 0.5\%) = 5\tau^* = 2 \text{ s} \quad (33)$$

$$\tau^* = \frac{250}{5} = 50 \text{ detik} \quad (34)$$

$$K_{P \text{ Temperature Loop}} = \frac{66.29}{50 \times 0.10019} = 13.233 \% \quad (35)$$

Based on the graphic shown in Fig. 6, using  $K_p$  of 13.23%,  $T_i$  of 66.3 s and  $T_d$  of 7.36 s, the temperature control part of cascade control is stable.

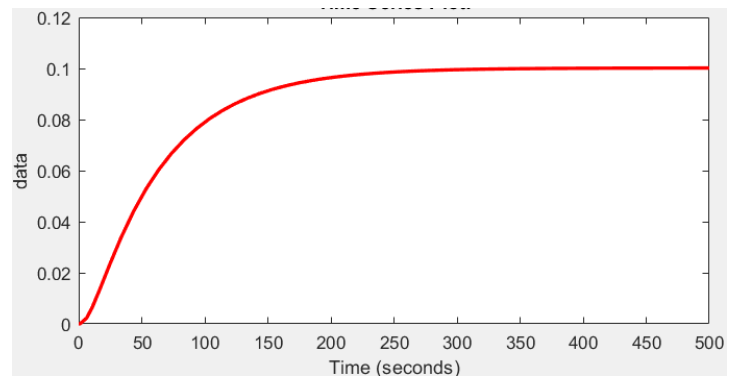


Fig. 6. Temperature plant model.

## 3 Results and Discussion

The effectivity of a PID controller is determined based on the characteristics of second-order process system without delay. The designed controller model is expected to generate a response in first-order characteristics with the desired time constant ( $\tau^*$ ). The PID controller on this model is expected to generate an effective

response when encountering disturbance. Before the controller is implemented in the system, it will be validated through Simulink MATLAB as a preliminary test as shown in Fig. 7. Fig. 7 is the Simulink test used in this study for cascade flow rate temperature

control using a gain constant and time constant used for the temperature and flow rate part (Table 1). The flow of the simulation used on the Simulink is based on the block diagram used in this study as shown in Fig. 4.

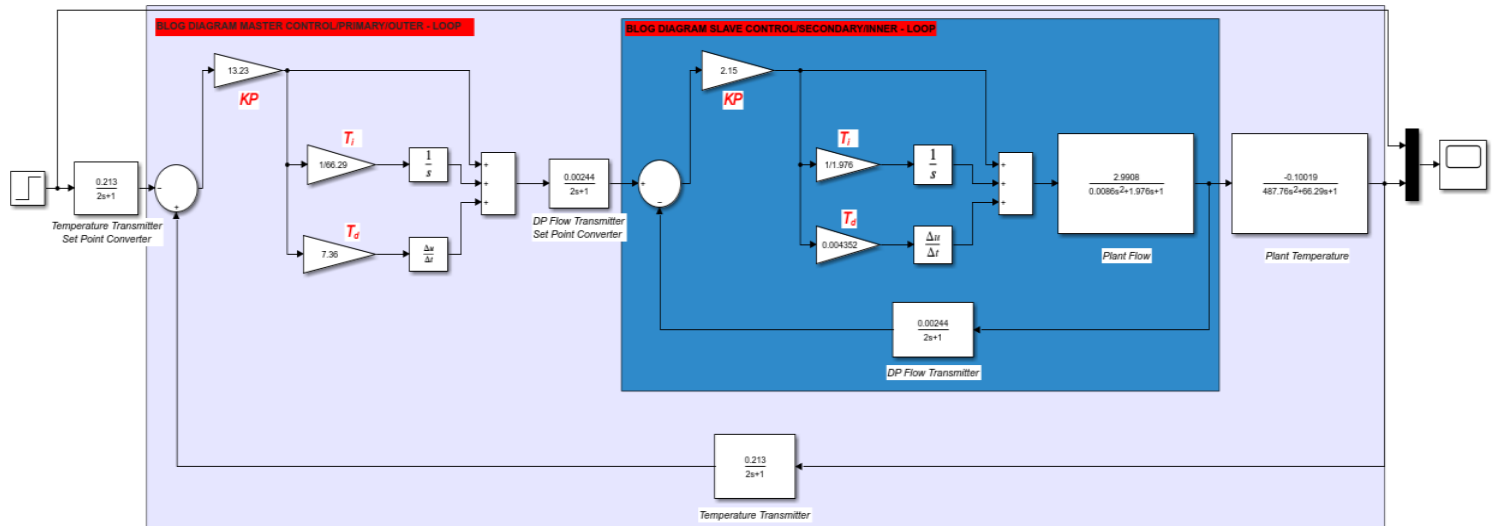


Fig. 7. Simulink diagram of PID controller.

Table 1. Parameter used on the PID-controller

Parameter	Temperature controller	Flow-rate controller
$K_p$	13.23%	2.15%
$T_i$	66.3 (s)	1.976 (s)
$T_d$	7.36 (s)	0.004 $\approx$ 0 (s)

The response from preliminary test of flow-rate cascade flow temperature using Simulink MATLAB as shown in Fig. 8.

Based on the preliminary test result shown in Fig. 8, using parameter from flow rate and temperature control part of cascade control, the control system is stable with no maximum overshoot or steady state error.

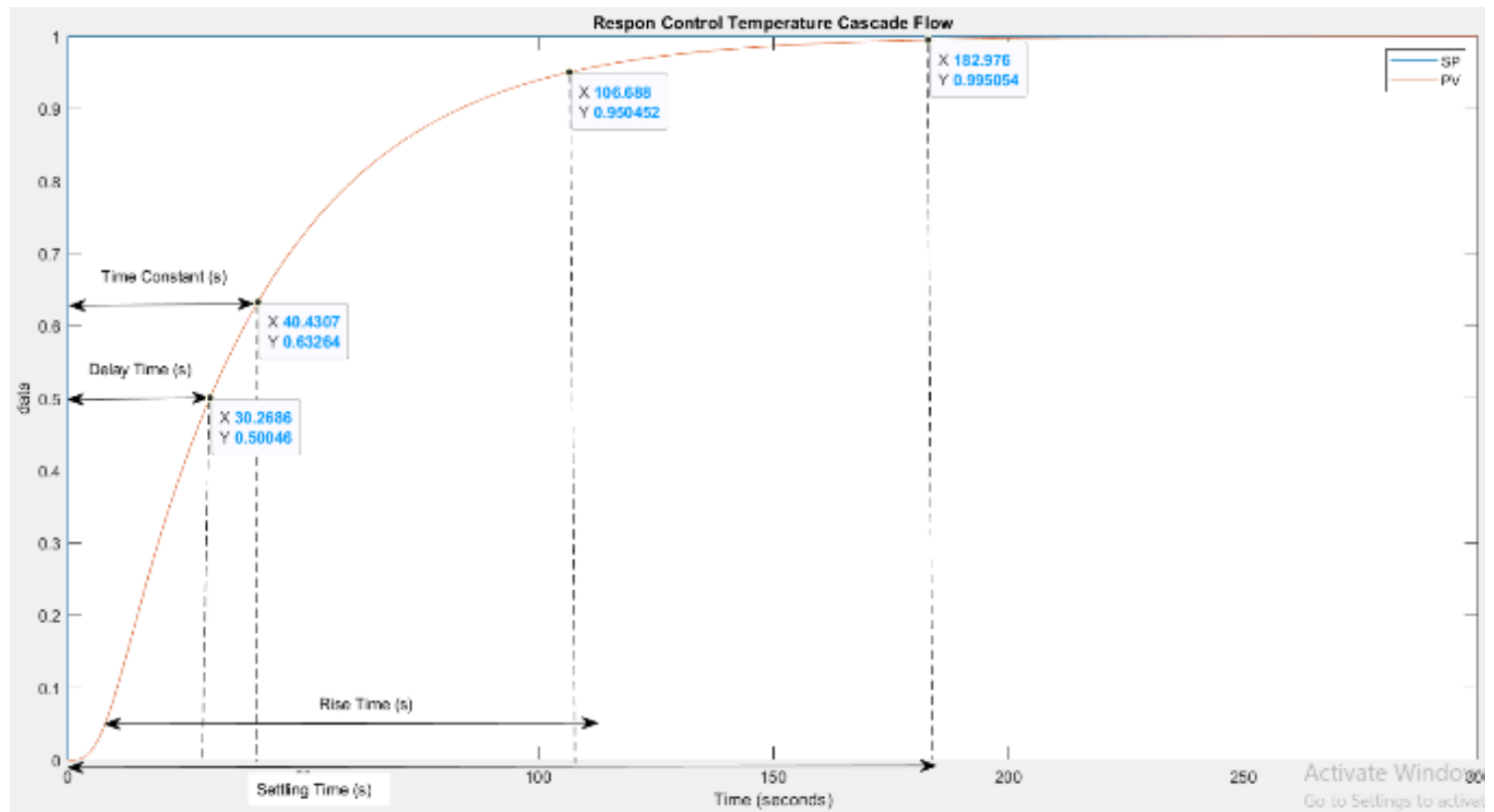


Fig. 8. Transient response of PID controller.

Table 2. Transient response characteristic of PID-controller

Response specification	Value
Time constant (s)	40.43
Settling time, $t_s$ (s)	183
Delay time, $t_d$ (s)	30.27
Rise time, $t_r$ (s)	106.7
Over shoot maximum (%)	0
Error steady state (%)	0

Testing of the direct synthesis tuned-PID controller is done on 60°C hot water flow. There is a rise in water temperature due to continuous heating that is circulated from the heater to the plate heat exchanger. Output temperature from the hot water cycle is the master/outer control loop that is controlled through the cold water cycle, which is also controlled as the slave/inner control loop. The initial condition for the cold water cycle that is pumped to the plate heat exchanger is 15°C. The cold-water function is to

become a cooling agent for the heat exchange process between hot water flow and cold-water flow on the heat exchanger. The testing of the PID controller is done three times: 60°C to set point 55°C, 55°C to set point 50°C and 50°C to set point 45°C, disturbance testing at stable condition 45°C.

### 3.1 60°C to Set Point 55°C

The testing of the PID controller for 60°C to set point 55°C is shown in Fig. 9. Transient response of PID controller from 60°C to SP 55°C: loop master and loop cascade.

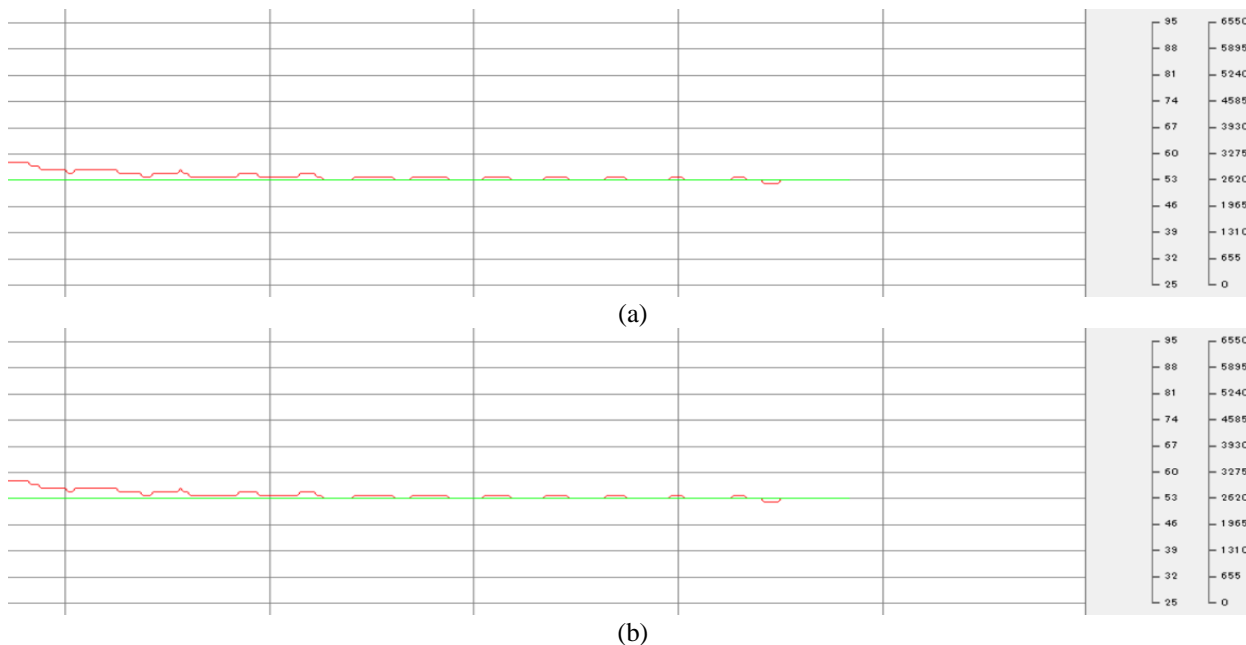


Fig. 9. Transient response of PID controller from 60°C to SP 55°C (a) loop master (b) loop cascade.

### 3.2 55°C to Set Point 50°C and 50°C to Set Point 45°C

From the result of three gradual decreases on set-point testing, the PID controller model shows a transient response that can reach set-point value when there is a temperature change, as shown in Fig. 10. This response is based on manipulated variable response that works on a correction value or error that is calculated by PID

controller. Therefore, PID controller will continuously send correction value signal to the control valve as the final element. As shown by characteristic response comparison from three set-point testing, PID controller performance is more efficient with faster response at lower temperature. More details on the test are shown in Table 3.

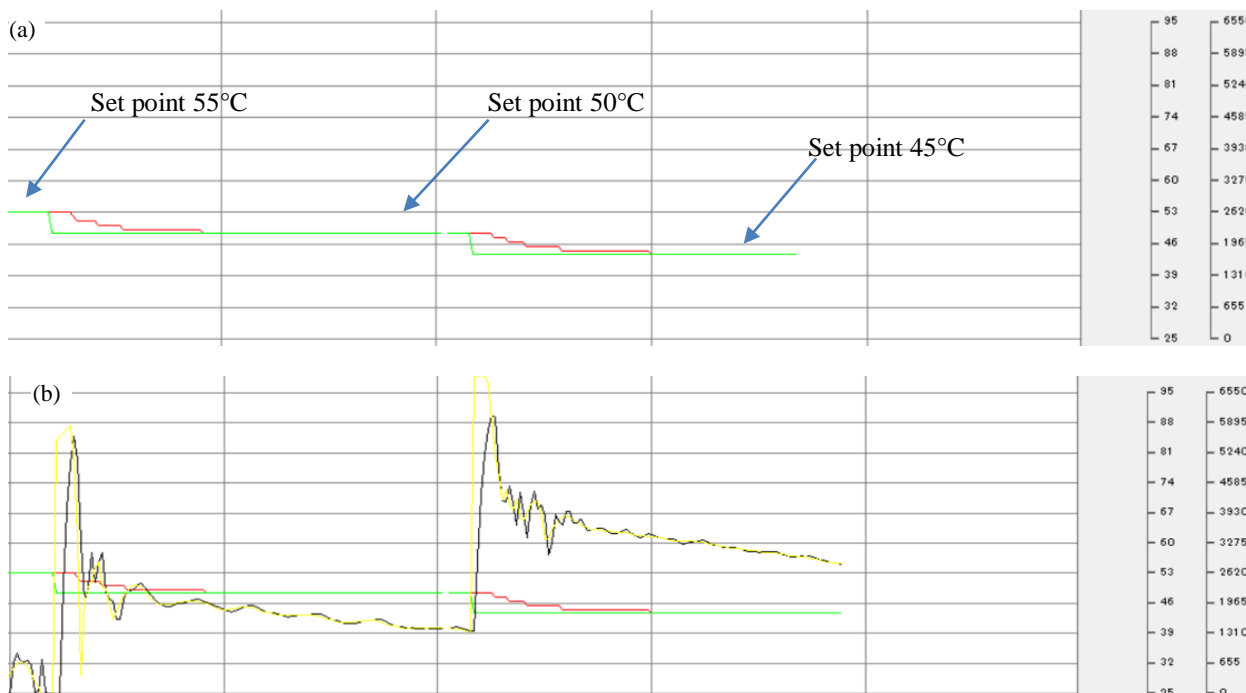


Fig. 10. Transient response of PID controller of SP 50°C and SP 45°C (a) loop master (b) loop cascade.

Table 3. Characteristic response comparison between set point

Response specification	Value		
	60°C to SP 55°C	SP 55°C to SP 50°C	SP 50°C ke SP 45°C
Time constant (s)	43	12	15
Settling time, $t_s$ (s)	172	31	40
Delay time, $t_d$ (s)	32	8	10
Over shoot maximum (%)	0	0	0
Error steady state (%)	0	0	0

Transient response that is generated by the PID controller has not shown any significant overshoot and steady-state error. At the first testing of temperature decrease from 60°C to set point 55°C, temperature response reaches the steady state condition as fast as 172 seconds. However, not long after reaching steady state condition, the temperature will increase again to continuous heat exchange. This increase is immediately responded to by the flow rate control loop (slave control), which will execute a change to return the temperature from the temperature control loop (master control) to its steady state condition. Slave control will continuously give a response to return the master control to a steady-state condition.

From Fig. 9(a), it is shown that the master loop will truly reach steady state condition at 255 seconds. This shows that slave control works optimally to keep temperature loop control at the set point or steady state. As for temperature decrease testing at set points 50°C and 45°C, the characteristic response of the testing is faster than set point 55°C. This is due to it is being easier to decrease temperature at lower temperatures than higher temperatures because of lower energy requirements from the water.

Similar results were also studied on the research of cascade control on heat exchangers. The transient responses of those cascade controls are compared to analyze each of the controls strong points and points to improve.

Both studies used cascade control with temperature and flow rate parameters to be controlled. They are also using Simulink as a part of a method to generate the transient response of the control system. The research conducted on the FOPDT model of heat exchanger use Ziegler-Nichols tuning method. From Table 4, it is shown that the cascade control of temperature and flow rate will have faster rise time and settling time using the direct synthesis tuning method. Also, the maximum overshoot is zero percent compared to the Ziegler-Nichols one which has an 11.34% maximum overshoot. This result shows that using direct synthesis as a tuning method for cascade temperature flow rate control will have a better transient response compared to Ziegler-Nichols tuning method.

Table 4. Transient responses measure

Response specification	Deni et al (Simulink)	Tridianto et al (PID Simulink) [13]
Time constant (s)	40.43	-
Settling time, $t_s$ (s)	183	468
Delay time, $t_d$ (s)	30.27	-
Rise time, $t_r$ (s)	106.7	121.5
Over shoot maximum (%)	0	11.34
Error steady state (%)	0	

### 3.3 Disturbance Testing at Stable Condition Set Point 45°C

The actual condition from cascade flow rate temperature control can be influenced by disturbances that will change response from stable condition at set point to prolonged steady state error. Disturbance testing is done to evaluate flow rate control loop performance whenever facing response change at master control from its steady state condition. The disturbance given on the testing is reducing hand valve opening from its full open condition to a specific condition targeted to the flow rate control loop (slave control).

The disturbance testing on the slave control loop is important to observe whether the master control can return to its steady state condition after the slave control is disturbed. The return of master control response depends on slave control performance at responding to disturbances received. The response of master control after a given disturbance at slave control is shown in Fig. 11.

The disturbance testing is done at a stable condition of set point 45°C. After the opening of the hand valve is reduced, there

is a pressure drop at the cold-water cycle. The black line is the flow rate response after being given the disturbance. After the slave control is given a disturbance, the temperature response on the master control deviates upwards immediately from its steady state condition as shown on a red line at Fig. 11. However, at slave control, there is a disturbance rejection as a response from slave control. This is proven by the increase of flow rate process variable set point; therefore, slave control will send a correction signal to the final element. Thus, it will increase the opening of the manipulated variable, and the flow rate at the cold-water cycle will reach the flow rate set point as a response of slave control to reject disturbance. Temperature control response after its deviation from steady state due to disturbance will immediately return to its steady state condition in 20seconds.

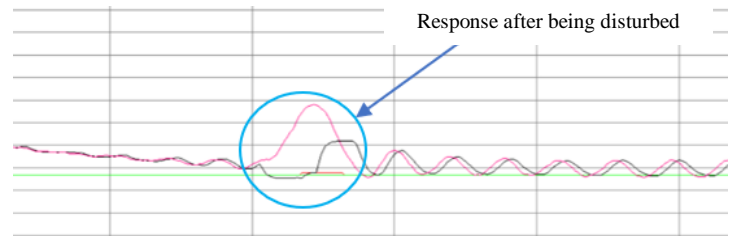


Fig. 11. Response chart after disturbance testing.

## 4 Conclusion

The procedure of cascade flow rate temperature control starts from a bump test on flow rate and temperature process on manual mode. The input signal is given in the form of a manipulated variable opening change. Then, output response from the process variable is recorded and estimated to get the transfer function through MATLAB System Identification. The transfer function then be used as gain plant for each of the processes. Next, the tuning calculation is done using the synthesis method. The tuning calculation generates parameters that will be used on PID controller, such as proportional gain ( $K_p$ ), time integral ( $\tau_i$ ), and time derivative ( $\tau_d$ ).

The PID controller model on the cascade flow rate temperature control uses parameters such as proportional gain ( $K_p$ ) = 2.15%, time integral ( $\tau_i$ ) = 1,976 seconds, and time derivative ( $\tau_d$ ) = 0 seconds on the flow rate control loop. On the temperature control loop, the parameters used are propotional gain ( $K_p$ ) = 13.23%, time integral ( $\tau_i$ ) = 66.3 seconds, and time derivative ( $\tau_d$ ) = 7 seconds. The transient responses from cascade flow rate temperature control from Simulink are rise time ( $t_r$ ) = 106.7 seconds, settling time ( $t_s$ ) = 183 seconds, and maximum overshoot = 0%

The PID controller is tested three times to study the response of the controller when the set point is changed. In a temperature range of 60°C to 45°C, the PID controller will give a faster response in the specific range of 55°C to 50°C. Direct synthesis tuning method usage on cascade flow rate temperature control gets better transient response compared to the Ziegler-Nichols tuning method with better rise time, settling time, and maximum overshoot.

The controller will generate a process variable response from master control that can reach the set point without overshoot and error steady state. Moreover, the PID controller model can overcome the disturbance that is given to slave control quickly. Then after the slave control is disturbed, the master control can quickly return to steady state condition as fast as 20 seconds after the disturbance is given. Slave control can directly overcome the disturbance by raising the set point quickly and then reaching the set point that is corrected by the correction signal from the manipulated variable on the flow rate process.

Future studies can use other parameters for heat exchangers, such as pressure, to control temperature and its effect on the turbulency of the flow. Also, the tuning for the cascade control

can use modern tuning, such as fuzzy logic and neural networks to study the effect of artificial intelligence on cascade control.

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