
ABSTRACT

This work consists of experimental work for heat exchanger. The approach are made for comparison purpose instead of validation of experimental data. Behaviors of heat exchanger are to be observed through these approaches under two different control systems, open loop and closed loop response. The one concern is the closed loop control system, at which the behaviors are study and clarify. However, for closed loop control system to be established, some data such as PI, and PID values must be calculated from the open loop control system. Then, behaviors are justified through some calculations using established tuning method available in literature such as IMC based PI controller and using Ziegler-Nichols formula based PID controller.

KEYWORDS: control strategies, open loop, closed loop, heat exchanger

INTRODUCTION

A heat exchanger is a device in which energy is transferred from one fluid to another across a solid surface. Heat exchanger analysis and design therefore involve both convection and conduction. Radiative transfer between the exchanger and the environment can usually be neglected unless the exchanger is uninsulated and its external surfaces are very hot [1].

The shell and tube exchanger is by far the most commonly used type of heat transfer equipment used in the chemical plant and allied industries. This is due to the configuration, which gives a large surface area in small volume, a good shape for pressure operation and easily cleaned [2].

Essentially, a shell and tube exchanger consists of a bundle of tubes enclosed in a cylindrical shell. Shell side and tube side fluids are separated by fitting ends of tubes into tubes sheets. Baffles are inserted in the shell side to direct the fluid flow and support the tubes, thus induce higher heat transfer [3]. Then, assembly of baffles and tubes is held by support rods and spacers. Depending on the head arrangement, one or more tube passes may be utilized. Normally, the most fouled fluid will be located on the tube side, to ease the cleaning. Since, the tube bundle can be removed for cleaning purpose[4].

It is mainly used in plant to allow heat exchange between the process fluid and utility fluid. By this, the process fluid can achieve its design outlet temperature [5]. However, in actual operating condition, the outlet temperature will deviate from the expected one due to few factors such as fouling. As a result, particular exchanger performance will deteriorate [6].

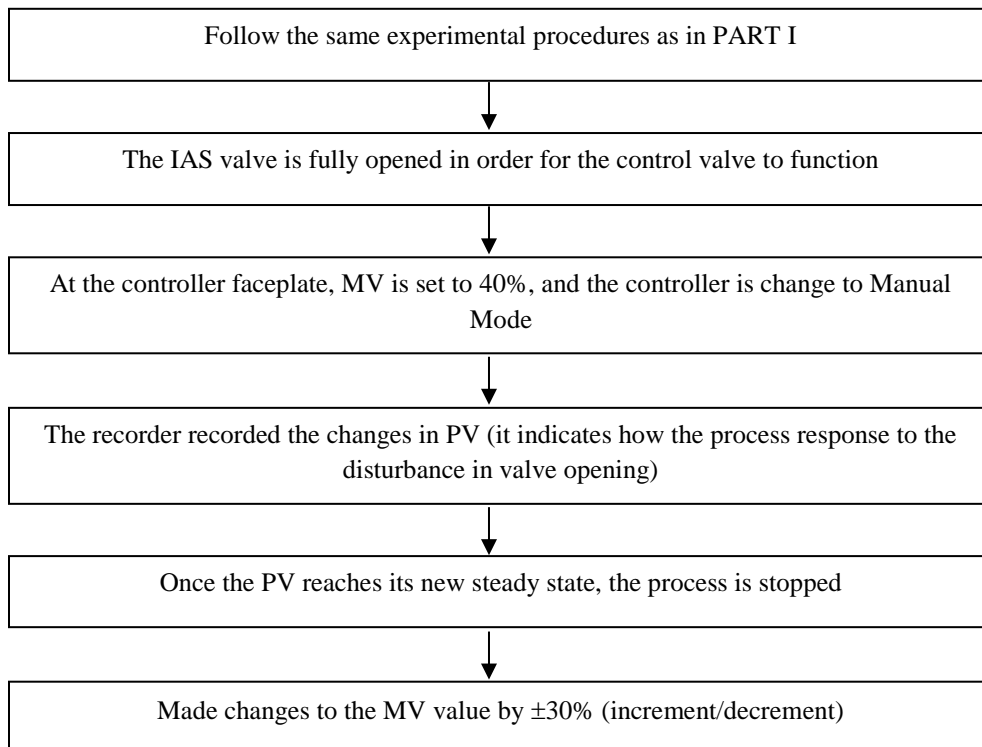
There are three types of fluid flows in heat exchanger, which are co-current flow, counter-current flow and cross flow. Commonly applied is counter-current flow. This type of flow will give better heat transfer between the 2 fluids in tube and shell side since the fluids are flowing in different direction. Thus, give better efficiency of the exchanger [7].

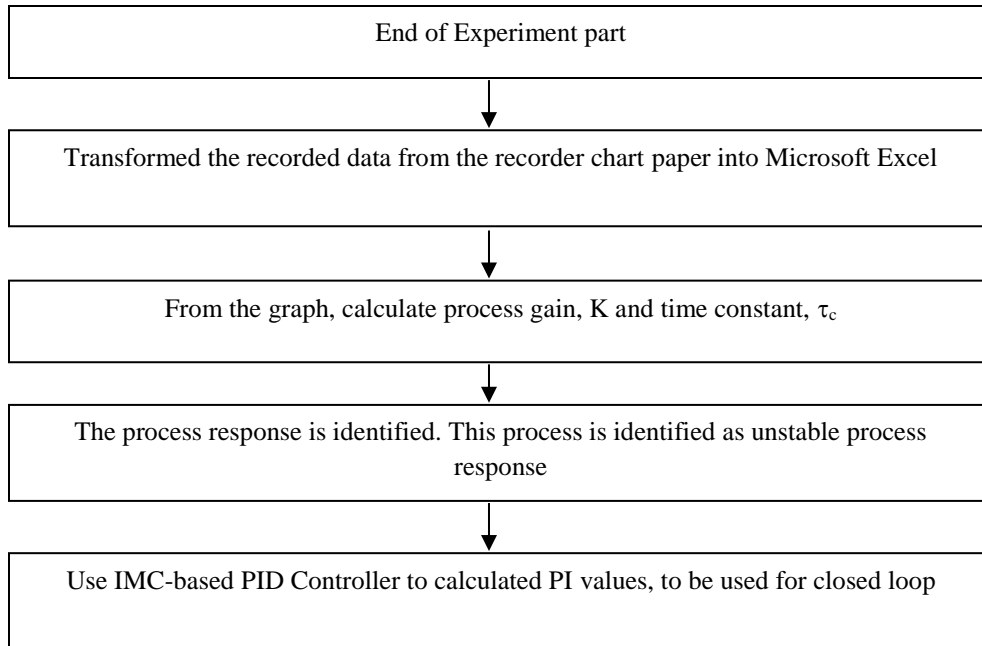
This project consists of two parts, mainly experiments. The two parts are as follow:

- First Part - Experimental Work
Objective(s): To calculate heat exchanger constants such as overall heat transfer coefficient, U , heat capacity for hot water, C_{p_h} and cold water, C_{p_c} at normal operating condition of the heat exchanger
Method: By measuring inlet and outlet temperatures for both streams at various water flow rates
- Second Part – Experimental Work
Divided into another 2 sections:
 - Open Loop
Objective(s): To study how the process response to changes made on the percent of valve opening (MV), which affects the hot water flow rate supplied into the heat exchanger
To calculate process steady state gain, K and time constant, from the graph Then use these values to calculate PI and PID values to be used in the close loop control system
Method: By increasing and decreasing the MV
 - Closed Loop
Objective(s): To study how the process response to the change in Set Point (ΔSP), referring to the outlet temperature of the cold water
To study the heat exchanger behavior by calculating its falling time, settling time and damping factor
To identify the best type of controller in controlling the outlet temperature of product stream
Method: By increasing and decreasing the SP

Open Loop Control System

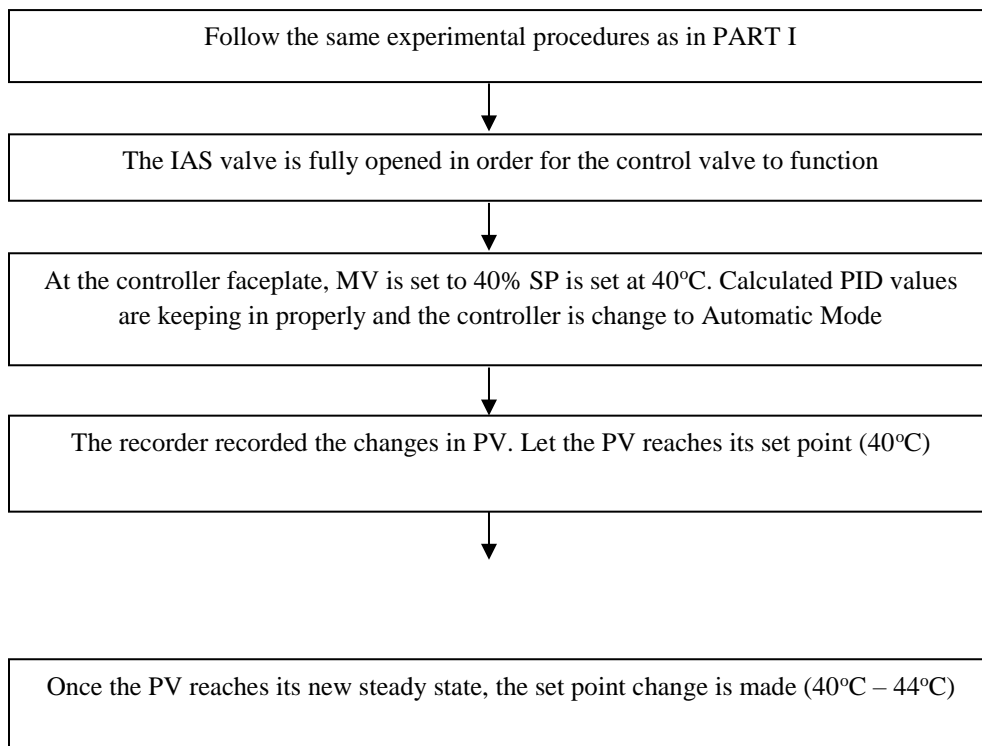
Generally, for the open loop control system, the control valve is leaving in manual mode, which means the control valve will be throttled manually by the operator.

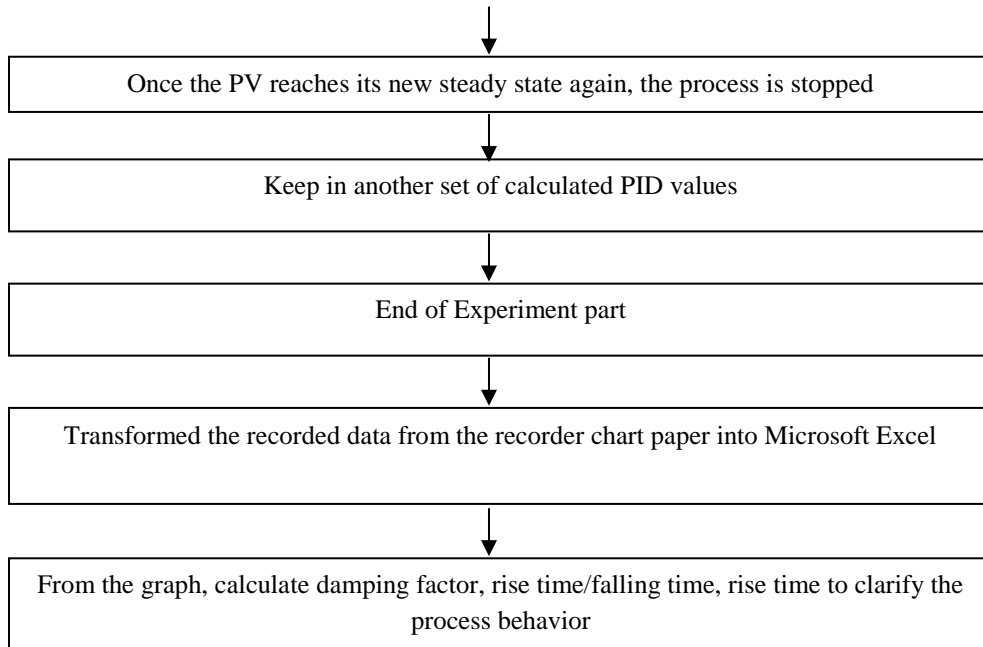




Closed Loop Control System

For the closed loop control system, the process is put under automatic mode. The process response is taken care by the PID controller. In other words, in adjusting the PV in reaching its set point, the valve opening is automatically controlled based on the electrical signal received from the PID controller. For the closed loop, the changes are made solely to the set point value.





RESULTS AND DISCUSSION

Open Loop Control System

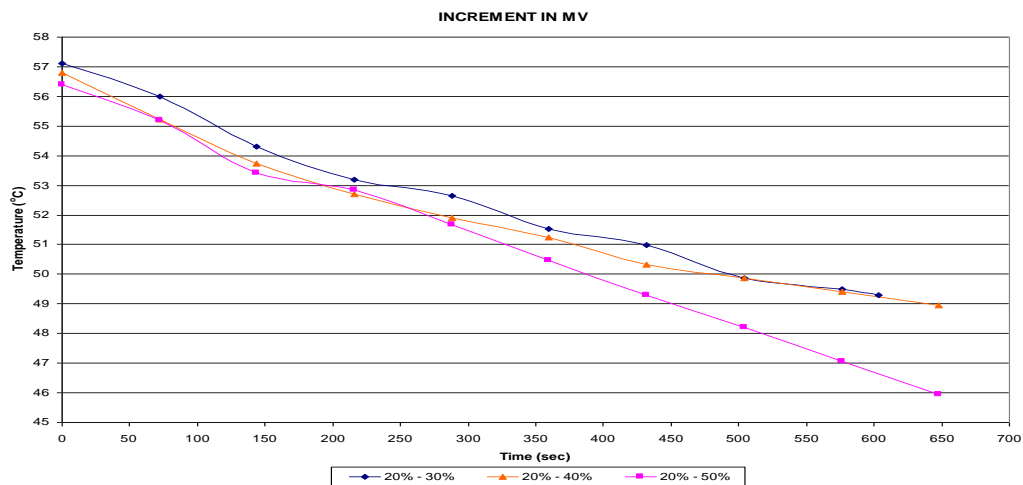


Figure 1 Open Loop – Increment in MV

At a glance to the graph above, it can be said that the process exhibits open loop unstable response. Unstable process response means, the PV is gradually increasing or decreasing due to disturbance made into the system without reaching its set point. As in this case, as the percent of valve opening increases, the temperature of the cold water outlet (SP) decreases gradually without reaching its set point, which is 55°C.

Theoretically, as the percent of the valve opening increases, the hot water flow rate increases. Hence, more heat is transferred from the hot water fluid to the cold-water fluid. This will result in higher outlet temperature of the cold

water. However, in this case, the process exhibits inversely. The temperature of the cold-water outlet decreases as the valve opening increases.

This statement is proven through calculation of process gain, K . Also known as unstable process gain since the process is unstable process and denoted as K_{uns} . The calculated process gain gives negative values for all increment in MV (see Table 1). The values are -0.127, -0.0585 and -0.053 for increment for 10%, 20% and 30% respectively. The negative K values would shows that the increment in MV values is reverse acting. The controller output decreases as the input increases.

For the time constant, the magnitude characterizes the rate of response for a process resulting from an input disturbance. The calculated time constants for increment in MV are about 3-4 minutes. These values are large enough for time constant for a lab scale heat exchanger. This indicates that the process is a slow response. In fact, it is known that the temperature is a slow process response as compared to flow response. Here, it means that small increment in valve opening will directly affect the amount of hot flow rate. However, the temperature will take longer time in order to exhibit this effect.

Next, the PI and PID values are calculated using the K_{uns} and τ_c . Since this process is open-loop unstable response, hence the best method to be applied is IMC-based PID Controller settings.

The results and discussion may be combined into a common section or obtainable separately. They may also be broken into subsets with short, revealing captions.

Table 1. Calculation of Unstable Process Gain, K_{uns} and Controller Time Constant, τ_c for increment in MV

Description	Increment		
	20% - 30%	20% - 40%	20% - 50%
change in MV (ΔMV)	0.1	0.2	0.3
slope of the graph (ΔPV)	-0.0127	-0.0117	-0.0159
$K_{uns} = K$	-0.1270	-0.0585	-0.0530
ΔSP (diff in temp.)	7.80	7.86	10.45
Lowest SP	49.30	48.94	45.95
Lowest SP + 0.632* ΔSP	54.23	53.91	52.55
Controller Time Constant, τ_c	180	162	230

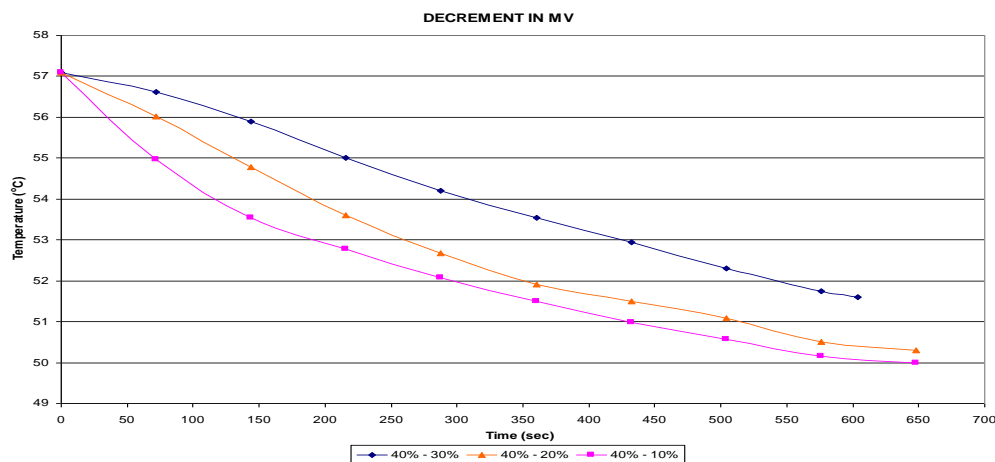


Figure 2 Open Loop – Decrement in MV

Generally, the decrement in MV does not deviate much from the increment in MV in terms of the interpretation to the process behavior. As for decrement in MV, it also gives unstable process response at which the temperature drops gradually without achieving its set point, which is 55°C.

The calculated time constants for decrement in MV also in the range of 3-4 minutes that is large enough for a lab scale heat exchanger. This gives a slow response process. Once again, it is justified that temperature is a slow response process since it changed slowly within a large period.

The difference is the decrement in MV results in direct acting process. At which the controller output decreases with decreases in input. This is theoretically approved, based on the sign of the calculated K_{uns} all decrement in MV gives positive sign in Table 2.

Next, the PI and PID values are calculated using the K_{uns} and τ_c . Since this process is open-loop unstable response, hence the best method to be applied is IMC-based PID Controller settings. The calculated PI and PID values are available in Table 3.

Table 2 Calculation of Unstable Process Gain, K_{uns} and Controller Time Constant, τ_c for decrement in MV

Description	Decrement		
	40% - 30%	40% - 20%	40% - 10%
change in MV (ΔMV)	-0.1	-0.2	-0.3
slope of the graph (ΔPV)	-0.0095	-0.0106	-0.0100
$K_{uns} = K$	0.0950	0.0530	0.0333
ΔSP (diff in temp.)	5.50	6.80	7.10
Lowest SP	51.60	50.30	50.00
Lowest SP + 0.632* ΔSP	55.08	54.60	54.49

Controller Time Constant, τ_c	215	167	111
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Table 3 Calculated PID Values using IMC-based PID Controller Tuning Method

CASE	CHANGE IN MV (\square MV)	K_c	τ_I	τ_D	PB	K_c/τ_I
M ($Ke^{-\theta s/s}$)	40% - 30%	8.6808E-02	448.3158	-	1152	0.00223
	40% - 20%	1.9441E-01	351.2830	-	514	0.00285
	40% - 10%	4.3242E-01	240.1600	-	231	0.00416
	20% - 30%	7.6024E-02	377.4331	-	1315	0.00265
	20% - 40%	1.8076E-01	341.3299	-	553	0.00293
	20% - 50%	1.4680E-01	477.4465	-	681	0.00209
N ($Ke^{-\theta s/s}$)	40% - 30%	0.0939	448.3158	8.8193	1065	0.00223
	40% - 20%	0.2148	351.2830	8.7694	465	0.00285
	40% - 10%	0.4997	240.1600	8.6627	200	0.00416
	20% - 30%	0.0834	377.4331	8.7854	1198	0.00265
	20% - 40%	0.2003	341.3299	8.7627	499	0.00293
	20% - 50%	0.1581	477.4465	8.8303	633	0.00209

Closed Loop Control System

Using the calculated PI and PID values from the open loop part, the process behavior for the heat exchanger is then examined under the closed loop control system. First, the process response is evaluated for PI-Controller.

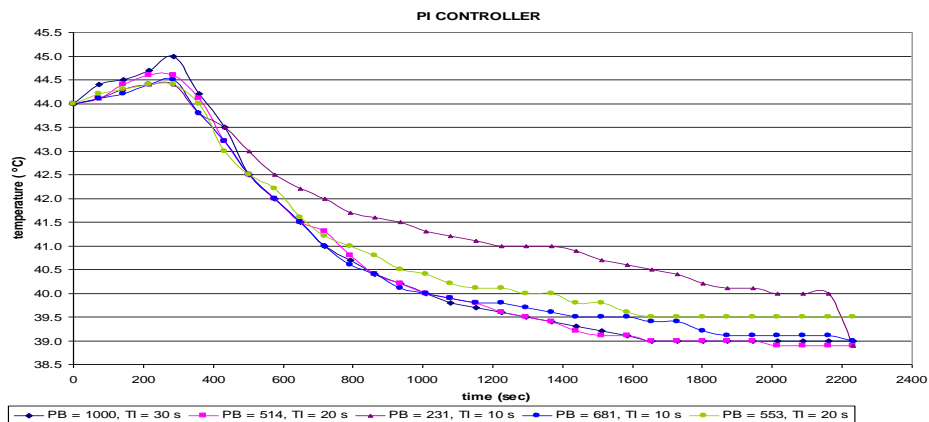


Figure 3 Closed Loop – PI-Controller

This is the graph obtained from the experimental work. It shows how the process response if PI Controller is integrated with the system. From this graph, the heat exchanger behavior is evaluated based on three factors, which are, damping factors, settling time, and rise time.

From the graph it can be seen that the process is initially overshoot in the range of 44.5°C to 45°C, then it keep decreasing away from its set point, which now is 44°C. The overshoot exhibits a criterion of underdamped response. This is proven through calculations that imply the Smith's method. Most of the calculated damping factor is below 1.0. The damping factor below 1.0 signifies an underdamped response. The maximum offset value is 5°C, which means the process settles at 5°C away from set point value, which is 44°C.

The rise time and settling time can be identified directly from the graph. The rise time is the time for the process output to first reach the new steady state value. However, in this case, there is a falling time instead of rise time. The temperature falls from about 45°C to 44°C and this took about 5 minutes. The settling time is the time required for the process output to reach and remain inside a band whose width is equal to ±5% of the total change in y-axis for 95% response time. Here, the settling time is about 30 minutes, which is a long period. From this part, it can be said that process is a very slow response, since it takes much time for the process to settle down after an exertion of changes onto the process.

The graph also shows that the closed loop control system of this heat exchanger is an integrator dynamics. It acts like a ramp input. The process is changing gradually with a roughly constant slope.

The above graph was plotted using a very high PB value and results with very large settling time. This is because; PB is inversely proportional to controller gain.

$$PB = \frac{100\%}{K_c} \quad (1)$$

Low controller gain value indicates high time constant. High time constant means the process is having a slow response.

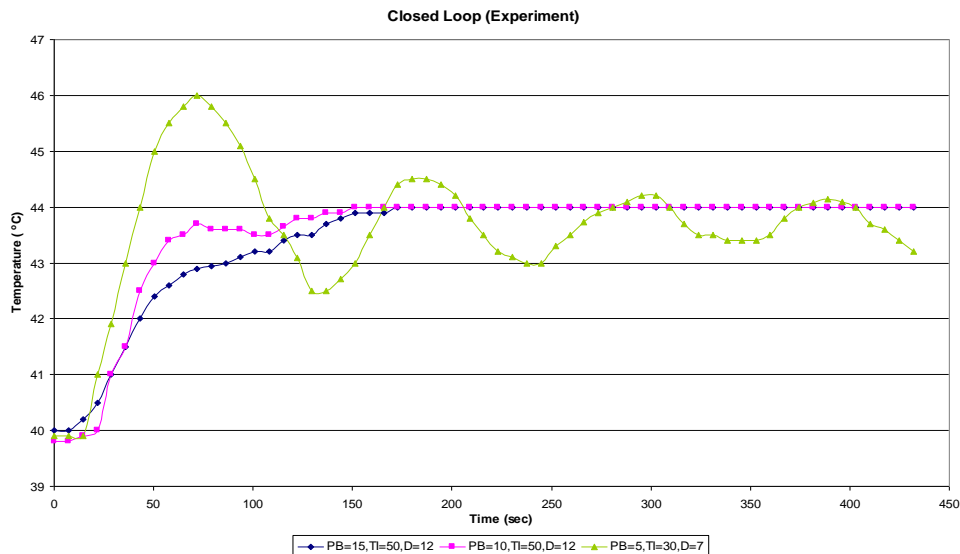


Figure 4 Closed Loop – PID-Controller

Observation made from the above PI-Controller results, it shows that high PB values give a very slow response. It took much time for the process to reach its new steady state level. Hence, for following closed loop, for PID testing, the calculated values are replaced with another set of PID values. This time, the PB introduced is much smaller compared to previous PB values.

As for the first trial, the PID values are PB = 15%, TI = 50 sec, TD = 12 sec. the second trial PID values with PB = 10%, TI = 50 sec, and TD = 12 sec. From the two sets of PID values, it can be seen that the response is less oscillatory in other words; it is more damped. This is shown in the graph above, as indicated by the blue and red line. Both reach its set point or steady state level after 3 min. However, the set of PID values using PB = 10, is more damped. More damped is also known as an overdamped response, which means slower response in moving upon its SP.

The difference between this result as compared to the PI-Controller is that at this point, the PV is moving towards the SP and remains at the steady state level with less oscillatory in the beginning. Whereas, for the first part, the PV gives slightly overshoot, then it falls down, away from the SP.

Hence, it is clarified that the process must be controlled at low PV values. However, there is no uniform oscillation exist. The PB as well as the natural period of oscillation, T_n is jotted down. Then, the approximate PID values are established from the PB and natural period of oscillation using Ziegler-Nichols formula.

$$K_c = (1.66)/ PB\%, \quad TI \text{ sec} = 0.5(T_n), \quad TD \text{ sec} = 0.125(T_n) \quad (2)$$

Using the PB = 3% and $T_n = 60$, the following set of PID values are obtained.

$$PB\% = 5\% \quad TI \text{ sec} = 30 \text{ sec}, \quad TD \text{ sec} = 7.5 \quad (3)$$

Using this set of values, the process response overshoots slightly in the beginning, after changed of set point. Then it oscillates about the same range of oscillation period. This indicates that the process is settling down and reaching the new steady state level. It settles at 280 sec, about 5 minutes.

For the green line, the rise time is at 40 sec, indicating the time for the process output to reach its new steady state value. Then it overshoots to 46°C at 75 sec. Presence of overshoot shows that the process is an underdamped response.

CONCLUSION

From the experimental part, it is concluded that the heat exchanger behaves like an integrator dynamics. It represents an unstable process response, which acts similar to ramp input. Any disturbance or set point changed detected in the process will result in gradually decreased or increases of process variable moving towards the set point or away from the set point. Increment in MV gives a reverse acting process response while decrement in MV gives a direct acting process response.

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