International Journal of Aquatic Science
ISSN: 2008-8019
Vol 12, Issue 03, 2021

Cascade Control Based Heat Exchanger Monitoring System

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Abstract. When thermal energy flows between fluids, from a solid surface to a fluid, or between particles, and the flow of that thermal energy occurs at different temperatures, that combination of fluid and thermal energy is known as a heat exchanger. Industrial heating and cooling heat exchangers are commonly employed. Applications in the transportation, building, chemical, and refrigeration industries. For the heat exchanger process the suitable control scheme is provided by implementing the cascade control with optimized PID controller with various optimization techniques such as ZN method, Process Reaction Curve method and Fmincon-GA optimization techniques. The optimization is included to minimize the maximum peak overshoot to less than 5 %, the settling time 10% and nullifying the offset.

Keywords: Heat Exchanger, PID Controller, Cascade Control Scheme, Optimization Techniques.

1. INTRODUCTION

Heat exchangers are among the simplest and most important components in industrial processes. The shell and tube heat exchanger system is the most commonly used type in industries. The primary function of an exchanger is to control the exit temperature of one of the fluids (especially the hot fluid) to remain at a specific temperature. It is nonlinear, varying over time, and time-delayed. The focus is to develop a control model that can accurately control the systems under study while doing so quickly and without incurring oscillation or overshoot. It is necessary to use a controller with the correct behavior to implement this. The controller continuously monitors the controlled process variable (PV), and checks to see if it's accurate or not (SP). Control action is generated based on the difference between the actual and desired values of the process variable known as the error signal, or SP-PV error. Controllability and observability are also included in the various aspects that are concerned. The PID controller is widely used in a number of areas of automatic control.

Though there are a number of high-end PID controllers that are better than existing PID controllers, the simple and well-documented track record of PID controller means that most control problems should use it. When working on a PID controller (PD or PI), practical considerations have to be considered in the development process. These practical concerns, namely measurement noise reduction and tradeoff between robustness and performance, are what is filtering out most of the noise in the measurements.

A large tuning area includes numerous tuning rules, with the goal of developing one rule that can be accurately described through the mathematical model of the system. While using empirical tuning rules, like Ziegler-Nichols, most of the tuning parameters of the PID controller are empirically tuned, but this approach is not appropriate for every kind of process dynamics. Furthermore, some processes, such as dead time, exhibit oscillatory behavior. So, in addition to different conditions and tuning rules for each and every process, there are different sets of conditions and tuning rules for each and every process. Equally large overshoots and unacceptable lags occur in control loops that deal with applications with two or more capacities (e.g., heated jackets). To make things simple, you may wish to think of the solution as having two or more control loops with each having its own input that are cascaded together to form a single regulating device.

An analysis is performed to control a regulatory control process, utilizing various control techniques, such as conventional PID control and cascade control. Different transient criteria and error parameters are used to analyses the controller's set-point tracking and load disturbance rejection features.

Types Of Heat Exchangers

The most common type of heat exchanger uses a separating wall or a wall that experiences a transient transfer of heat. The fluids should never mix or leak in heat exchangers with a heat transfer surface. Exchangers of this type are Ranunculus aspersescus, also known as recuperator, is referred to as direct transfer or simply recuperator. For instance, those in which there are storage and release of thermal energy for intermittent heat exchange between hot and cold fluids an indirect transfer occurs on the exchanger matrix or surface, as well as within the product itself. A classification system was devised to better organize the number of heat exchanger configurations and to assist designers and construction managers. Heat transfer mechanisms: single phase or two phase flow

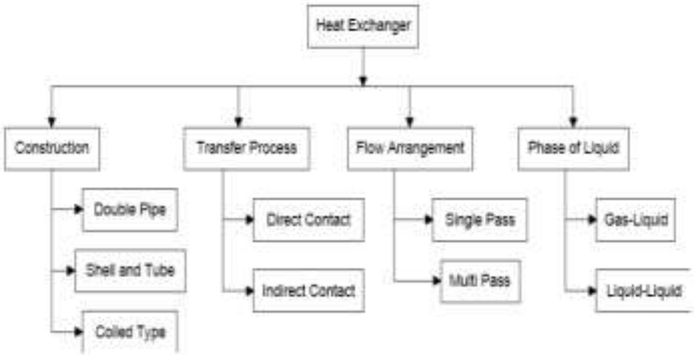

Figure 1 Types of Heat Exchanger

Shell And Tube Heat Exchanger

A figure (see Figure 2) depicts the generic exchanger, which is usually constructed from a bundle of round tubes mounted in a cylindrical shell that is oriented perpendicular to the tube axis. The flow inside the tubes is the same, whether the fluid is moving in one direction or another. This exchanger has tubes (or tube bundle), a shell, front-end head, rear-end head, baffles, and tube sheet as its major components.

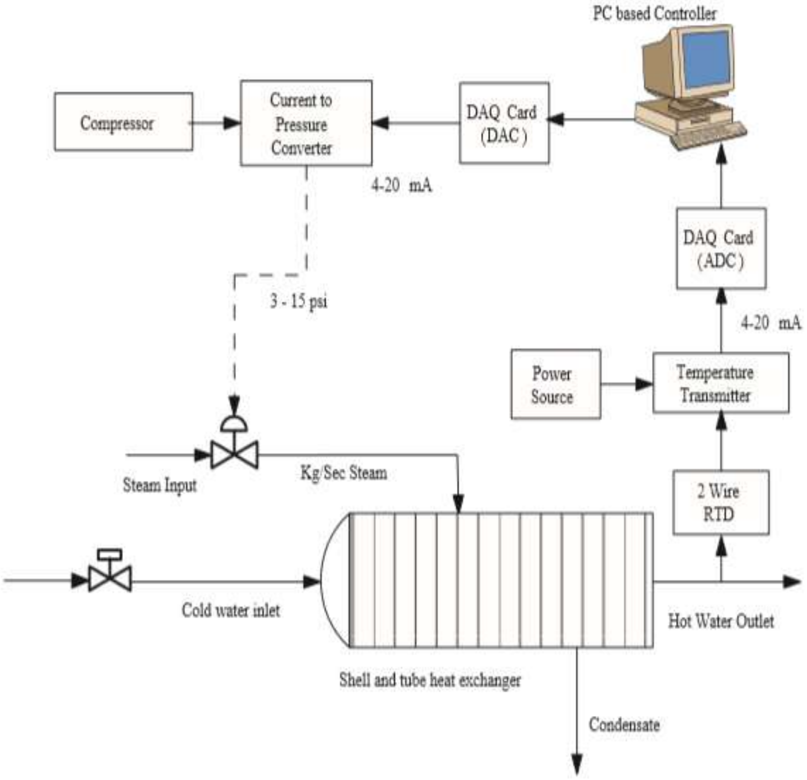

Figure 2 Shell and Tube Heat Exchanger

Process Description

Figure 1.5 illustrates the schematic diagram of shell and tub heat exchanger temperature control. On the shell side of the heat exchanger, cold water is supplied from the overheat tank. Steam is piped from the side of the heat exchanger where the tubes are located. The output temperature of the heat exchanger is measured using a 2-wire RTD, which is connected to the transmitter. A standard 4-20 mA output proportional to the temperature is produced by the 2wire RTD transmitter. Measurement is made much easier thanks to the transmitter. The transmitter unit is provided with a separate power source. This PC-based controller's control circuitry updates the data from the transmitter using a data acquisition (DAQ) device. In the PC-based controller, the error signal is processed and a control signal computed. Another DAQ device receives control signals from the controller and directs the corresponding current to pressure converter. To convert the PC-based controller's current output to a pressure signal, a current to pressure converter is required. A summary of the experimental data is provided below [12–14]. the response of the exchanger is 50°C/kgsec−1 with a time constant of 30 seconds rate of increase in process temperature (with respect to a fixed amount of time) is 3°C/°C Valve flow of 1.6 kg/sec for control valve has a time constant of 3 seconds and a time constant of 10 seconds for the sensor. The experimental data resulting from the linearized mathematical model of the heat exchanger leads to a mathematical model of the heat exchanger.

Figure 3 Systematic Diagram of Temperature Control in Shell and Tube Heat Exchanger

4.1 Disturbance in Heat Exchanger

Load variables, as well as the disturbances, are also referred to as disturbances. These variables are used to control the variables in the form of causing the deviated variables to be out of their set points. In addition to temperature fluctuations outside the heat exchanger, flow rate of the flowing fluid may also change. The intermediate or secondary process output that is being disturbed effects a measurable, direct impact on the primary process output that we are trying to control or the actuator gain is non-linear. Cascade control can help mitigate disturbances in the secondary variable (i.e., secondary variables' response to disturbances) on the primary output (i.e., primary output's response to disturbances). Most of the change in gain occurs as a result of changes in operating point as a result of a change in set point or from sustained disturbances.

2. MATHEMATICAL MODEL

A proper mathematical model of the process is required to develop a controller. Industrial systems, especially those related to manufacturing, are often non-linear in nature, and approximated as FOPTD or SOPTD models. A FOPTD model can be expressed in the generic form of this:

$$G_p(s) = \frac{K_p e^{-t_d s}}{\tau s + 1}$$

The general form of SOPTD model can be expressed as

$$G_p(s) = \frac{K_p e^{-t_d s}}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

There are two process are considered the primary process transfer function is given below in the equation

$$Gp\ (s) = 50 / (30s + 1)$$

The transfer function of secondary process is second order process shown below

$$G(s) = 5/ (90s^2 + 33s + 1)$$

Cascade Controller

We have one handled variable and more than one measurement in the cascade control configuration. It is obvious that we can only control one output with a single manipulation. A cascade control system can typically outperform a traditional single-measurement controller when numerous sensors are available for measuring conditions in a regulated process. Because the overshoot and unacceptable lag are unavoidable, it is nearly impossible to manage heated clothing items such as jackets with a single control loop. When you have two or more control loops connected in series, the resulting single regulating device is a cascade of control loops.

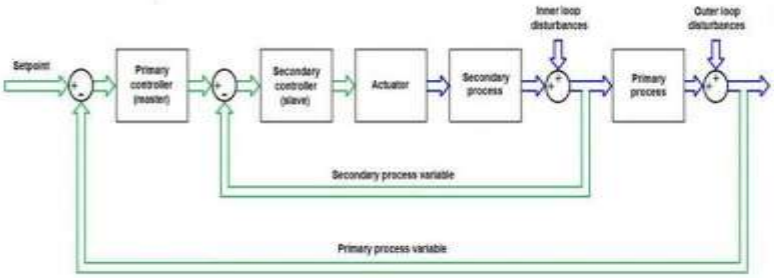

Figure 4 Block Diagram of the Cascade Controller

Inner and outer loops comprised of the secondary controller and the primary controller are depicted by the block diagram geometry. The internal loop operates similarly to a conventional feedback control system, consisting of a set point, a process variable, and an actua-tor that acts on the process. The outer loop does the same thing as the inner loop, except that its actuator is the whole inner loop.

Tuning Methods Of Pid Controller

The tuning of the PID controller takes place before it is put to work. Designers offer the predefined default values for P, I, and D terms, which in some cases contribute to control instability and sluggish behavior. Although PID tuning has numerous approaches for obtaining different tuning results, it is important for the operator to focus on determining proportional, integral, and derivative gains. You will find these listed below.

Two PID Controllers are in the cascade control scheme, one in the inner loop and other in the outer loop, both controllers are optimized by various methods as given below.

- Process Reaction Curve Technique
- Zeigler-Nichols Method
- Fmincon - Genetic Algorithm Hybrid

7.1 Process Reaction Curve Technique

Open-loop tuning is used. When a step input is applied to the system, it creates a response. We will need to manually apply some control output to the system, and we will have to log the response curve throughout this initial stage. In 1953, Cohen and Coon proposed a first-order + time-delay process model based on their work. An empirically derived set of tuning settings yielded a ¼-decay response with a closed-loop circuit. This methodology uses a dead end circuit where the closed loop is cut between the controller and the final control element. This process undergoes a radical shift, where a major step change is introduced into the final control element, and the response of the process variable is observed. This response is "S" in shape, and this process reaction curve is called an S-shaped response. Process Reaction Curve (PRC) or Open Loop Transient reaction are terms that describe this approach. Transfer function obtained for air flow temperature control process is,

$$G_{PRC}(s) = \frac{\overline{y_m(s)}}{\overline{c}(s)} \cong \frac{Ke^{-t_d s}}{\tau s + 1}$$

Where,

$K = \text{Static gain}$, $t_d = \text{dead time}$ and $\tau = \text{time constant}$

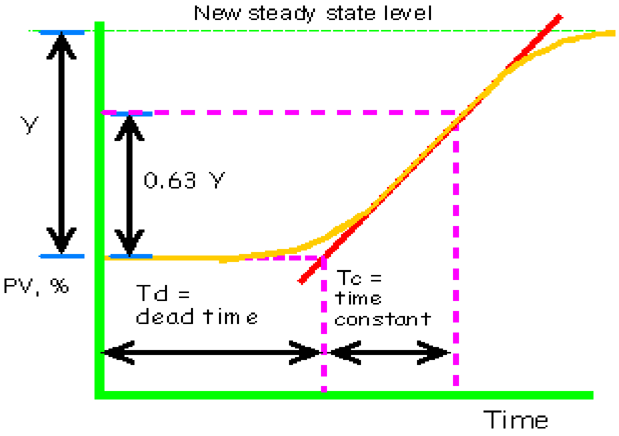

Figure 5 Process Reaction Curve

Table 1. Process Reaction Curve Technique.

Controller Type	**K_p**	**K_i**	**K_d**
P	T/L	-	-
PI	0.9 T/L	L/0.3	-
PID	1.2 T/L	2 L	L

7.2 Zeigler-Nichols Method

In order to tune the PID controller, Zeigler-Nichols introduced closed-loop approaches. Damped oscillation and continuous cycling are the two options available to you. The two procedures have the same steps, but different oscillation behaviors. First, we must set the Proportional controller constant, 'K_p 'to a particular value. After that, we have to supply' K_i 'and 'K_d 'with zero values.

Table 2. Zeigler-Nichols Method

Controller Type	**K_p**		**K_i**	**K_d**
P	0.5 Ku		-	-
PI	0.45 Ku		1.2 Kp/Pu	-
PID	0.6 Ku		2 Kp/Pu	Kp Pu /8

7.2 Fmincon - Genetic Algorithm Hybrid

GA is a heuristic quest set of rules which favours natural stimulation since people with more powerful capabilities are able to battle and are more likely to die in a rival environment, regardless of odds. Unfortunately, some situations have occurred in which the weaker participants struggled and succeeded. We check these incidents to satisfy expectations.

The flowchart demonstrates how the GA optimises the PID controller, starting with the initial population setting, a random sample is chosen with the limits and the fitness function evaluation is done with the ISE and IAE, depending on the values the process is repeated to find whether the target sample values are met or not.

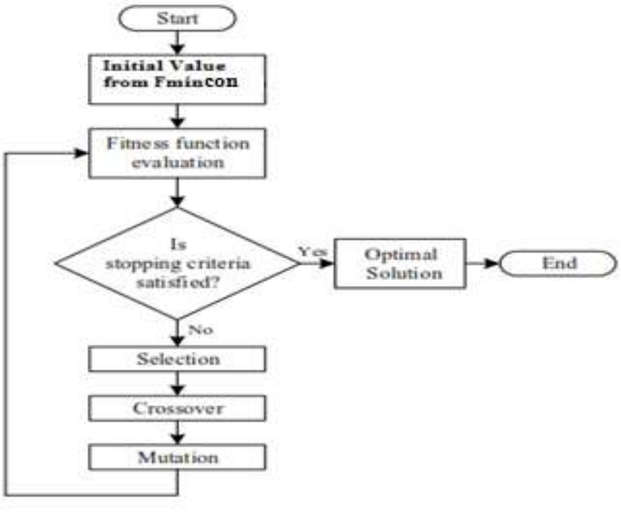

Figure 6 Flow chart of Fmincon – GA for Temperature

Table 2. Fmincon – GA for Temperature.

Parameters in Fminsearch –GA Optimization	**Options**
Population Type	Double Vector
Population size	50
Fitness Scaling Function	Rank
Crossover Fraction	0.8
Crossover Function	Single Point
Mutation Function	Constraint Dependent
Migration Fraction	0.2
Migration	Both (Forward / Reverse)
Ending Criterion	100
Plot Function	Best Fitness
Hybrid Function	Fmincon

System Description Of Cascade Controller

Any action that involves a measurable secondary variable that has an effect on the primary controlled variable can benefit from cascade control. When the inner loop process has dynamics comparable to or slower than those of the primary process, tuning processes must be adjusted to achieve cascade control's objectives.Figure 7 Cascade control of effluent temperature via steam flow control Secondary control loops centred on secondary process measurements are used to manage the influence of disturbances on the primary process output. Additionally, the sensitivity of the main process is decreased. When picking which procedure to utilise, fluctuations in the effluent temperature play a role. The cascade control of effluent temperature with steam flow control is illustrated in figure 7.

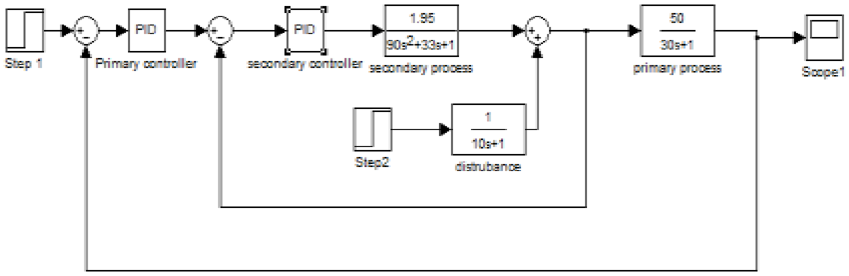

Figure 7 System Model of Cascade Controller

3. RESULT

We employ the open loop test to compute the mathematical model, and then fine-tune model parameters via genetic algorithm. Various strategies such as Process reaction curve method, Z-N method and Fmincon-Genetic algorithm, optimization algorithms are used to modify the PID controller parameters using the Integral Absolute Error criteria in order to optimize the closed loop process. The response behavior of the closed-loop control system in the pictures is illustrated and compared the performance based on the different optimization techniques using time domain specification value such as Maximum Peak Overshoot Mp%, Rise Time ‘Sec’, Settling Time ‘Sec’and Offset.

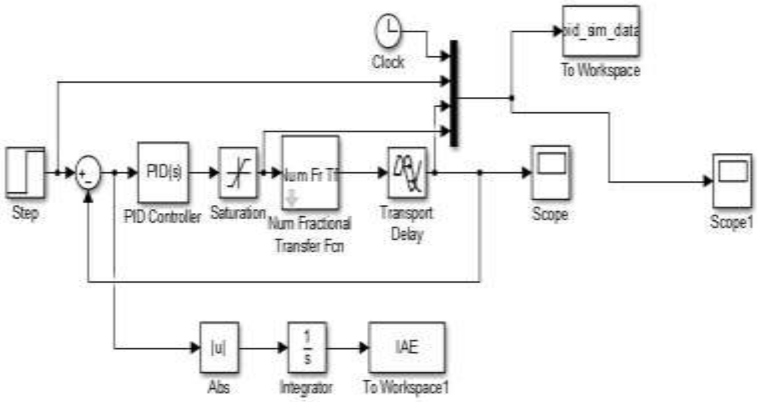

Figure 8 Response of Heat Exchanger Process with Process Reaction Curve Method for IO-PID Controller for Set Point Tracking

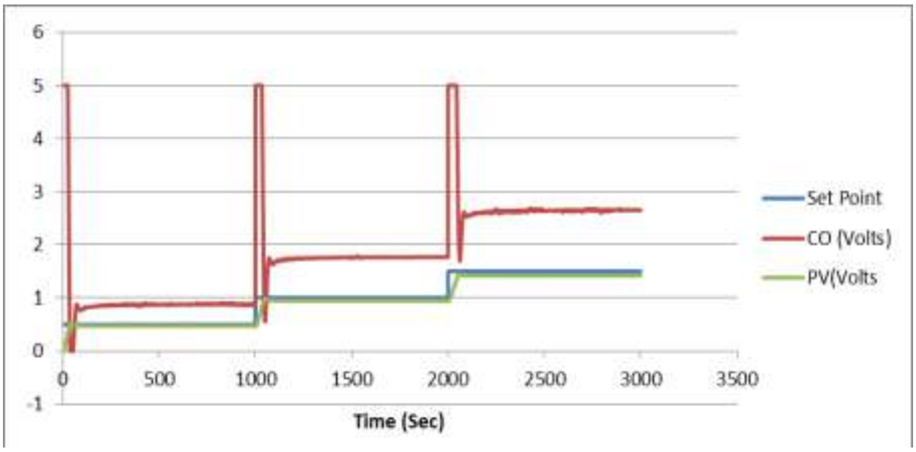

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Figure 9 Response of Heat Exchanger Process with Process Reaction Curve Method for IO-PID Controller for Set Point Tracking

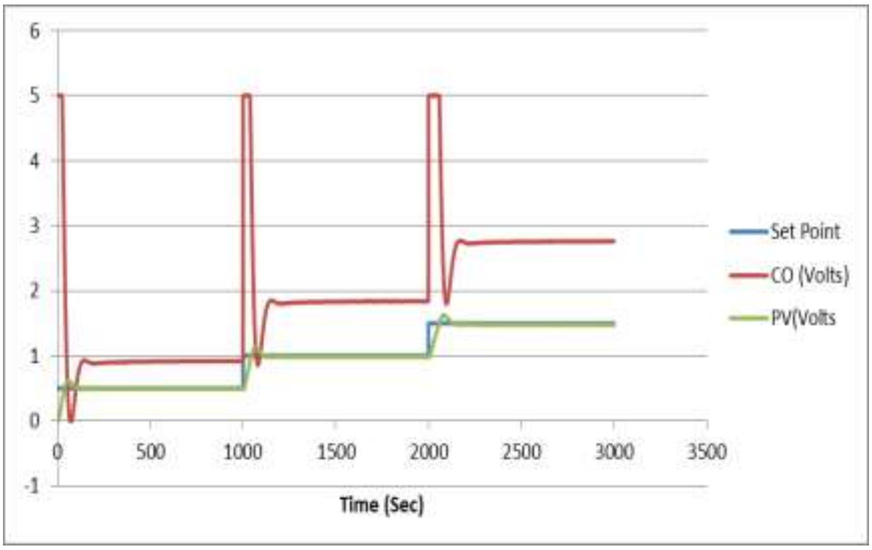

Figure 10 Response of Heat Exchanger Process with ZN Method for IO-PID Controller for Set Point Tracking

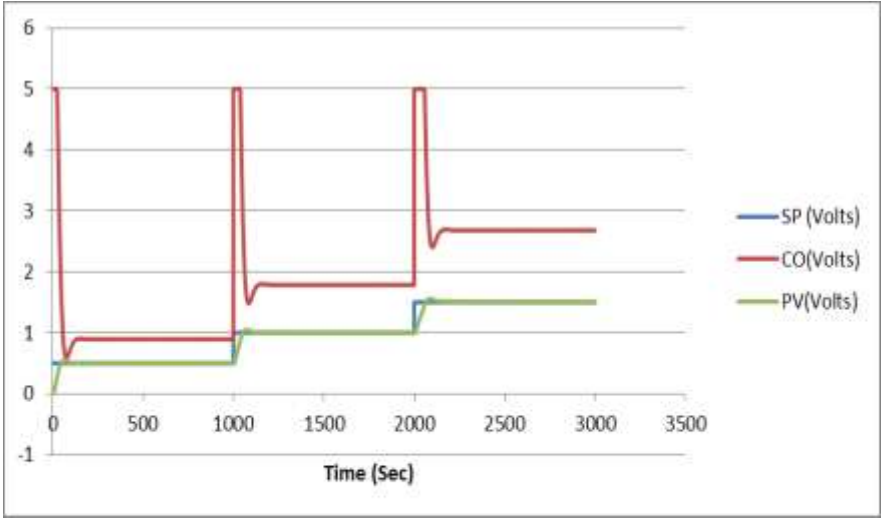

Figure 11 Response of Heat Exchanger Process with **F_{min}-GA** Method for PID Controller for Set Point Tracking

Table 3 Time Domain Specifications for Heat Exchanger for Different optimization Techniques

Optimization Techniques	**Maximum Peak Overshoot Mp%**	**Rise Time ‘Sec’**	**Settling Time ‘Sec’**	**Offset**
ZN	20%	39	183	0.0065
Cohen Coon	3%	29	21	0.00014
Fmin-Genetic Algorithm (Fmin-GA)	0%	15	15	0.000016

4. CONCLUSION

Conventional PID controller response is used as a baseline to build a shell and tube heat exchanger temperature control that uses a cascade controller. The controller's analysis is handled in MATLAB, and the PID controller's tuning is performed using SIMULINK. This experiment demonstrates that cascade controller response is better than PID controller because it has reduced steady state error, faster reaction, and a lower system overshoot. Since the cascade controller is able to respond dynamically and more precisely than a static controller, it also has steadier error characteristics. The system was able to meet the demands of the shell and tube heat exchanger's temperature control system.

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