Study on the Performance of Different Temperature Controllers for Heat Exchanger System

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Abstract

Heat exchangers are widely used in petroleum and chemical industries including petrochemical plants and petroleum refineries. They especially used to control the fluids to the desired range of temperature and pressure. The temperature of outlet fluid of heat exchanger is controlled through the temperature controller circuit which controls the opening and closing of the valves according to the set point temperature. In this paper, the controller circuit is analyzed using the conventional PID controller and compare it with the performance of the developed PID controller. The comparison is carried out for the shortest possible time. In addition, the transient performance and the error criteria of the controllers are analyzed and the best controller is found out. In order to perform this study, the system will be modeled and simulated by using Alternative Transient Program (ATP). The simulation results from the ATP should show the best transient performance of the studied system when different schemes of feedback control systems are applied.

Keywords: Heat exchanger, feedback controller, feed-forward controller, PID controller, Alternative Transient Program (ATP)

1. Introduction

The basic idea of the heat exchanger is that, there is a fluid flows in a pipe and its temperature needs to be controlled at a certain value. This fluid is heated up by a steam that enters the heat exchanger via a controlled valve, where the cooler steam will leave the system from the bottom. So, the fluid in the pipe was heated up based on heat transfer effect. The heat exchanger systems can be classified based on their construction to the following types: double pipe, shell and tube, and coiled. Actually, this paper deals with the shell and tube type. There are several ways for controlling the temperature of the outlet fluid in heat exchanger systems, but most popular one is by using the PID controller for the following reason: "it is more effective and economical compared to other control methods" [1].

2. Studied Heat Exchanger System

The main goal of doing this study is to find out the best performance of the control circuit which is used to control the temperature of the outlet fluid of a shell and tube type of a heat exchanger system at a desired value. Even though, improving the performance of heat exchanger systems using PID is studied, but to the best of our knowledge most of the systems understudy still exhibited high overshoot ratio and long settling time. These unsatisfied values affect the performance of the control circuit and consequently lack their outcome. The first step in this study is to know the transfer function (usually in the S-domain) for each component in the system that will be involved in the control circuit. Based on literature, the block diagram of the heat exchanger system is shown in Figure 2.1.
According to references [2, 4], the S-domain transfer functions of the previous components in the system are defined as:

i. The process: is the object that is needed to be controlled which is the heat exchanger in our case. This component into the control system has a first order or a second order mathematical equation with a delay time as:

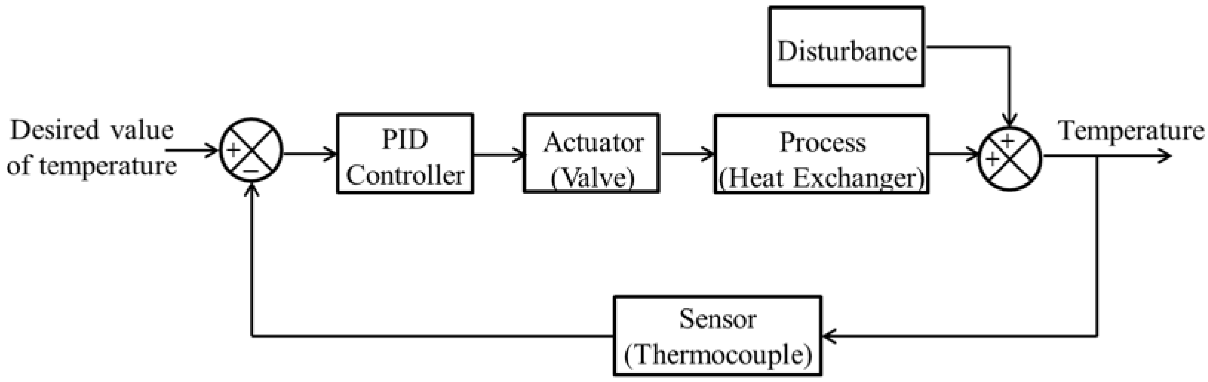

Figure 2.1: Block diagram of heat exchanger system

$$G_p(s) = \frac{50}{1 + 30\,s}\, e^{-\tau s} \quad \text{OR} \quad G_p(s) = \frac{5}{1 + 33\,s + 90\,s^2}\, e^{-\tau s} \tag{2.1}$$

Where τ = delay time in the process

ii. The actuator: is the component that applies the control action onto the process by increasing or decreasing the amount of the steam to rise or reduce the temperature of the outlet fluid. In our control system, the actuator represents the valve which has a transfer function that can be describes as:

$$G_V(s) = \frac{0.009975}{1 + 3\,s} \tag{2.2}$$

The valve receives its control command from the controller.

iii. The sensor: it measures the varied value of the outlet fluid temperature and sends its measured signal to the comparator. The comparator will compare it with desired value of temperature in order to generate the error signal. The transfer function of the sensor; which is a thermocouple in this case; is given by the following equation:

$$G_s(s) = \frac{0.16}{1 + 10\,s} \tag{2.3}$$

iv. The controller: is a control device that generates the control command based on the error signal from the comparator, and sends its control signal to the valve to apply the suitable control action on the process. There are several types of controllers, but in most of cases of heat exchanger systems, the Proportional-Integral-Derivative (PID) controller is used a lot for such cases. Actually, the parameters of the PID controller are chosen based on the required specifications that are needed to be achieved of the control system of the studied system. According to ref. [5], the general form of the transfer function of the PID controller is defined as:

$$\begin{aligned} G_c(s) &= K_p.\left(1 + \frac{1}{\tau_i\, s} + \tau_d\, s\right) \\ &= \left(K_p + \frac{K_i}{s} + K_d\, s\right) \end{aligned} \tag{2.4}$$

Where:
K_p = The proportional gain
τ_i = The integral time
τ_d = The derivative time
The values of the proportional, integral, and derivative constants (K_p, K_i, $and\ K_d$) are determined using Zeigler-Nichols tuning criteria. The criteria will be introduced in details in the next section.

i. Disturbances: The heat exchanger system can have two types of dynamic disturbances; due to fluctuations in the steam pressure, changes in enthalpy of the steam, or variations in the water pipe; which are flow and temperature. For our studied system, the transfer function of the flow and the temperature disturbances are considered as a first order because the change in the flow rate and temperature are represented as a step, where their functions are defined as:

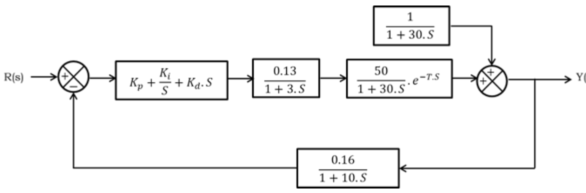

Figure 3.1: Block diagram with transfer function of each component

$$G_{df}\left(s\right)=\frac{1}{1+30\,s}\quad \text{and} \qquad G_{dt}\left(s\right)=\frac{3}{1+30\,s} \tag{2.5}$$

3. Zeigler-Nichols Tuning Criteria

The block diagram in the previous section can be illustrated with showing the S-domain transfer function of each component in the control system as follows:

The closed-loop transfer function without including the controller can be obtained as:

$$G\left(s\right)=\left[G_V\left(s\right)\cdot G_p\left(s\right)+G_d\left(s\right)\right] = \frac{0.49875\left(1+30\,s\right)+\left(1+3\,s\right)\left(1+30\,s\right)}{\left(1+3\cdot s\right)\cdot\left(1+3\cdot s\right)^2}$$

(3.1)

The overall transfer function is

$$\frac{Y\left(s\right)}{R\left(s\right)}=\frac{G\left(s\right)}{1+H\left(s\right)\cdot G\left(s\right)} = \frac{\left[G_V\left(s\right)G_p\left(s\right)+G_d\left(s\right)\right]}{1+G_s(s)\cdot G_V(s)\cdot G_p(s)+G_s(s)G_d(s)}$$

(3.2)

Where the term $\left[1+H\left(s\right)\cdot G\left(s\right)\right]=0$, and it's called the characteristic equation of the feedback control system.

To improve dynamic performance of the studied system, a PID controller is added in the control circuit of the system. The parameters of the PID controller need to be determined using Ziegler-Nichols tuning method. Since the transfer function of the plant of our system is known, then by applying a step function input; on the set point of the control system; and putting integral time (τ_i) to be large enough and derivative time (τ_d) to be too small. After that, increase the value of the proportional gain (Kp) of the PID controller till the output response of the system is oscillated sustainably, as shown in Figure 3.2.

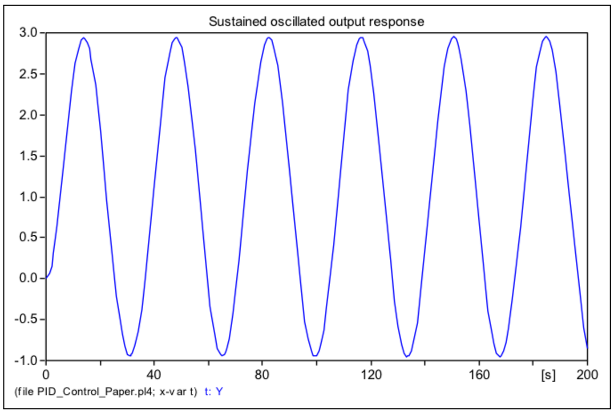

Figure 3.2: Oscillated output response of the system

The oscillated value of the Kp is called the critical gain value (K_{cr}), and the periodic time (T_{cr}) of the oscillated output response also needs to be determined. Now, based on these two values of K_{cr} and T_{cr}, the values of the PID controller parameters can be specified using the following formulas of the Ziegler-Nichols tuning criteria:

$$K_p=0.6\,K_{cr},\ \tau_i=0.5\,T_{cr},\ and\ \tau_d=0.125\,T_{cr}$$

The dynamic performance of feedback control systems are evaluated based on the following dynamic parameters:

i. Rise time (t_r): which is the required time of the output response to reach to about 90% of its final value.

ii. Peak overshoot (M_p) is the instantaneous maximum value of the output response and it can be calculated mathematically by using the following formula:

$$M_p\% = \frac{Y\left(t_p\right)-Y\left(t_s\right)}{Y\left(t_s\right)}\times 100 \tag{3.3}$$

iii. Peak time (t_p) is the measured time at the instant when the value of the output response is located at its maximum overshoot value.

iv. Settling time (t_s) which is the required time of the output response to reach its final value with allowed error percentage of $\pm 2\%$.

4. Simulation Results and Discussion

Our studied system is simulated using a powerful transient program called ATP/EMTP. This software has TACS (Transient Analysis of Control Systems) modeling for implementing control circuits. The TACS has some built-in control devices, such as transfer function $G(s)$, transport delay, summing point, TACS source which used for input(s), TACS prob for measuring or monitoring the controlled signals and output(s). Figure 4.1 shows our simulated heat exchanger system; with its feedback PID controller; in the ATP environment. We assume that, at the steady state, all temperatures and flow rates of the cold and hot fluids in the heat exchanger do not change. Based on this assumption, the transfer function of the process is modeled to be first order with dead time [6].

When the PID controller is not involved in the control circuit of the simulated system, the resultant parameters of the output transient response are: $t_r = 47.111\,s$, $M_p = No\ Overshoot$, $t_p = Not\ Applicable$, and $t_s = 114.67\,s$. Now, by adding the PID controller into the circuit, the obtained values of the parameters are improved to be: $t_r = 4.228\,s$, $M_p = 39.54\%$, $t_p = 15.828\,s$, and $t_s = 82.222\,s$. Figures 4.2 and 4.3 show the ATP simulation results of the transient response of the output without and with including the feedback PID controller into the control circuit, respectively.

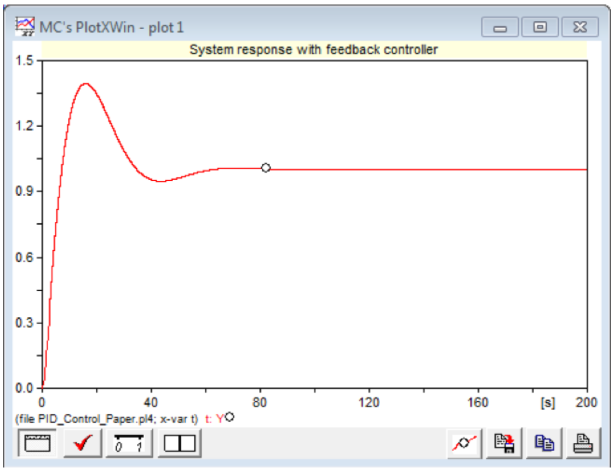

Figure 4.3: The system response when feedback controller is added

For better dynamic performance of our heat exchanger system, the feed-forward control model is introduced in the system. The S-domain transfer function of the feed-forward controller can be obtained as follows:

$$G_{CFF}(s) = -\frac{G_d(s)}{G_p(s)} = \frac{-\left[18\,s^2 + 6.6\,s + 0.2\right]}{(1 + 30\,s)\cdot(1 + \lambda\,s)} \tag{4.1}$$

Where λ = The filter parameter, and its value somewhere between zero and unity[3].

In fact, the main drawback of the feedback PID control system is that it acts after the disturbance of the heat exchanger system distorts the control signal of the controlled object. In most of cases in control systems, the disturbance signal can be predicted or estimated, so the controlled input signal of the plant can be corrected; by adding a feed-forward transfer function in the forward path of the plant; before the disturbance input deviates the output control signal of the system. Figures 4.4 and 4.5 illustrate the block diagram of the feedback control of the heat exchanger system with included feed-forward control and the improved simulation result of this block diagram, respectively.

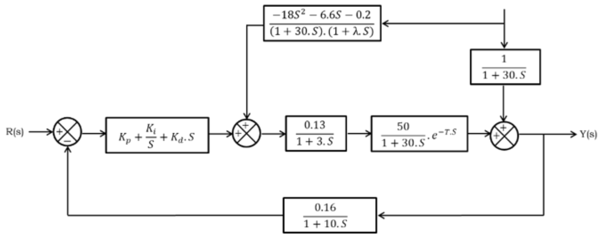

Figure 4.4: Block diagram with feedback plus feed-forward control

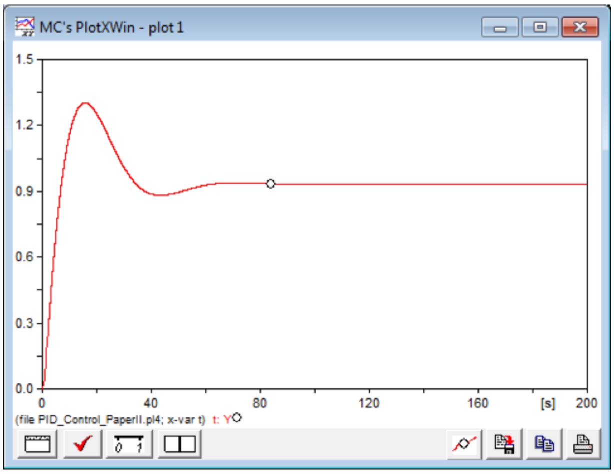

Figure 4.5: Response of system when feed-forward controller is included

Where, the resultant values of the transient performance of the output response of the system are: $t_r = 6.711\,s$, $M_p = 30.1\%$, $t_p = 15.618\,s$, and $t_s = 84\,s$. Table 1 summarizes the obtained values from the ATP simulation results of the transient parameters of the output response of the studied heat exchanger

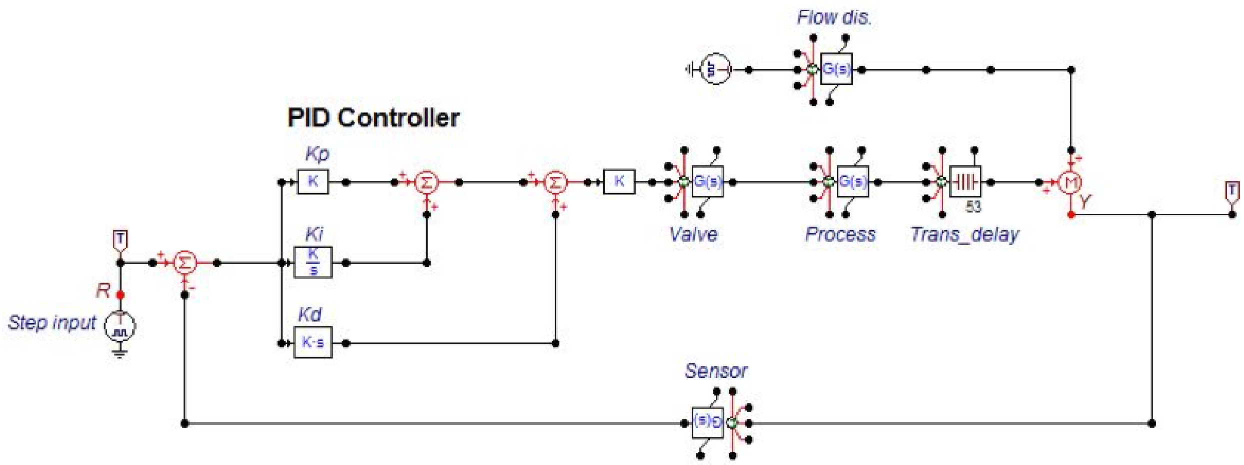

Figure 4.1: Control circuit with feedback PID controller in ATP

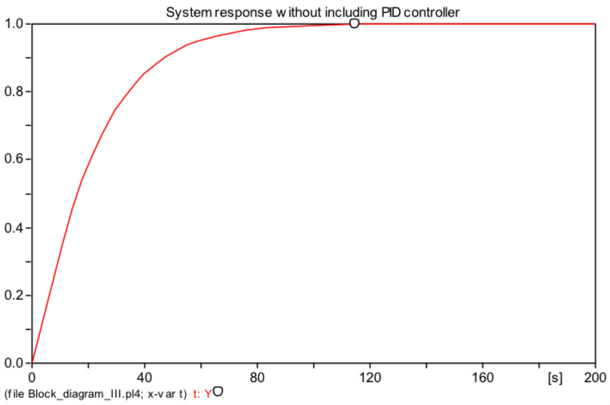

Figure 4.2: The system response without including the feedback controller

system, and table 2 gives the specified tuned parameters of the PID controller, respectively.

Table 4.1: Transient parameters of system output response

Case	$t_r(s)$	$M_p(\%)$	$t_p(s)$	$t_s(s)$
Without PID Controller ×× ×× ××	47.111	Not registered	N/A	114.67
With PID Controller ×× ×× ××	6.228	39.54	15.828	82.222
With Feed forward ×× ×× ××	6.711	30.1	15.618	84

Table 4.2: Obtained parameters of feedback controller

Case	K_{cr}	$T_{cr}(s)$	K_p	$\tau_i(s)$	$\tau_d(s)$
Value	23.8	34.167	14.28	17.083	4.271

5. Conclusion

This paper deals with studying the dynamic performance of a heat exchanger system when the feedback PID controller and the feedback with feed-forward controller are added into its control circuit. The studied system has been modeled and simulated using the ATP/EMTP software with the aid of its TACS Devices. Based on the ATP simulation results in table 1, we accomplish that adding feed-forward control in the forward path of the control system plant will improve the system dynamic performance. Where, the system response speeds up when the PID controller is involved but with higher overshoot. To reduce the resultant overshoot from the feedback PID controller, a feed-forward controller has been added into the system. The feedback plus feed-forward control improved most of the transient parameters unlike the settling time, where the improvement was a little bit fair. In our future paper for continued work on this study, different control approaches; such as fuzzy logic and neural networks or combination between them; will be addressed and compared with the results of this paper for better controlling of the outlet fluid temperature of heat exchanger systems.

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