Controller Design for Temperature Control of Heat Exchanger System: Simulation Studies

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Abstract: This paper analyzes the performance of different controllers such as feedback, feedback plus feed-forward and internal model controller to regulate the temperature of outlet fluid of a shell and tube heat exchanger to a certain reference value. The transient performance and the error criteria of the controllers are analyzed and the best controller is found out. From the simulation results, it is found out that the internal model control outperforms feedback PID and feedback plus feed-forward controller.

Key–Words: Feedback controller, Feedback plus feed-forward controller, internal model controller

1 Introduction

Design of controller for any regulatory or servo problem is one of the challenging tasks due to many aspects. To design a controller, an accurate mathematical model is required which can be obtained either from first principle model or from black box system identification experiment [1]. A controller has two distinct objectives such as set-point tracking and load disturbance rejection. Set-point tracking is a major issue in servo control whereas the main focus area of regulatory control is load disturbance rejection and to maintain steady state conditions. Apart from the mathematical model of the process the system designer has to consider various other aspects like process uncertainty, measurement noise, and robustness of system while developing a controller. Skogestad [2] reported that, control of a process can be classified as either smooth control or tight control. Tight control technique gives a fastest way of control which will result in an acceptable robustness where as smooth control gives the slowest possible control which produces a good disturbance rejection property.

Proportional-Integral-Derivative (PID) controller, the most commonly used controller finds wide spread applications in various areas of automatic control. Though there are several high end controllers superior to existing PID and its variants, the simplicity and proven track record of PID controller makes it an obvious choice for most of the control problems. While developing a PID type controller (PI or PD) different practical consideration has to taken care off. These practical concerns are filtering of measurement noise [3] and tradeoff between robustness and performance [4]. Tuning of PID controller is a wide area of research [5] with many tuning rules where the main objective is to formulate such a tuning rule which can be characterized from the mathematical model of the system. The three parameters of PID controller are mostly tuned by empirical tuning rules like Ziegler-Nichols but this method is not always suitable for every kind of process dynamics [6]. The process has also its own dynamics such as some process have long dead time, some process have oscillatory behavior and some other process can be unstable. So there are different set of conditions and different set of tuning rules for each and every process dynamics. Many model based controller techniques such as internal model based control [7, 8], dynamic matrix control [7, 8] are used in conjunction with PID controller to improve the dynamic response of the process. Apart from the conventional techniques of controller tuning there are many soft computing based intelligent tuning rules. Fuzzy control [9] is gaining fast acceptance in control domain due to its superior performance. Many researcher have worked towards optimizing the tuning parameters using different optimization techniques like evolutionary optimization technique [10] and swarm optimization techniques [11].

In this paper, the performance of different control techniques such as feedback PID, feedback plus feedforward control and internal model control are analyzed to control a regulatory control process. Set-point tracking and load disturbance rejection feature of the controller are analyzed using different transient criteria and error parameters.

Apart from introductory section, this paper has four different sections. In section 2, system configuration is introduced and mathematical model of the system is obtained. In section 3, different control configurations like (feedback PID, feedback plus feed-forward control and internal model control) is discussed. Section 4, provides simulation results for different control techniques and the best controller design technique is identified from the transient response performance and error criteria. Section 5 concludes the paper.

2 Heat Exchanger System

Heat exchanger transfers heat between two fluids without mixing them up. The dynamics of heat exchanger depends on many factors like temperature difference, heat transfer area, flow rate of fluids, flow patterns. Heat exchanger finds wide spread applications in different industries such as petroleum, food, petrochemical, power generation, nuclear, space craft etc. The basic principle of heat exchanger is shown in Fig. 1.

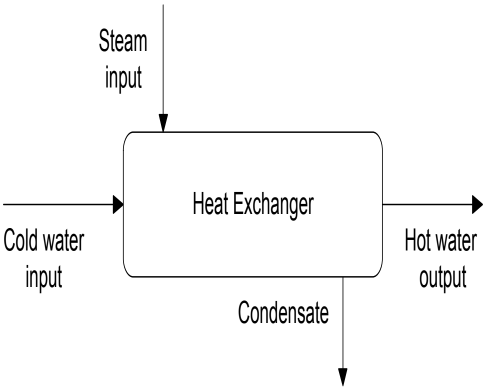

Figure 1: Principle of heat exchanger

There are various types of heat exchanger which are categorized with respect to construction, transfer process, flow and phase. A brief classification of heat exchanger is shown in Fig. 2.

Shell and tube heat exchanger probably is the most common type of heat exchangers applicable for wide range of operating temperature and pressure. It has larger ratio of heat transfer surface to volume than double-pipe heat exchangers, and it is easy to manufacture in a large variety of size and configuration. Shell and tube heat exchanger can operate at high pressures, and its construction facilitates disassembly for periodic maintenance and cleaning. A shell-and-tube heat exchanger is an extension of the double-pipe configuration. Instead of a single pipe within a larger pipe, a shell-and-tube heat exchanger consists of a bundle of pipes or tubes enclosed within a cylindrical shell. In shell and tube heat exchanger one fluid flows through the tubes, and a second fluid flows within the space between the tubes and the shell.

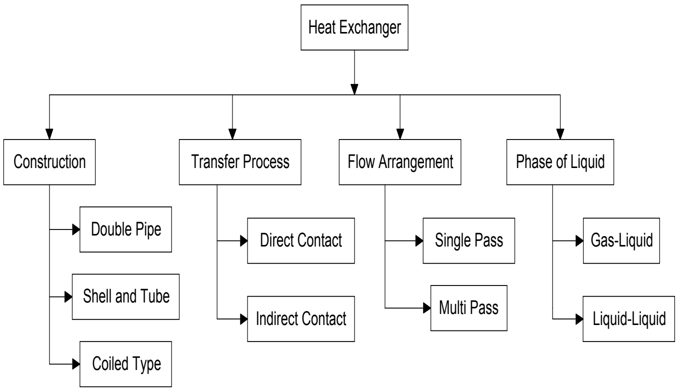

Figure 2: Classification of heat exchanger

2.1 System Description

The schematic diagram of temperature control of a shell and tub heat exchanger is shown in Fig. 3. Input cold water is supplied from the overheat tank to the shell side of the heat exchanger. Steam is supplied to the tube side of the heat exchanger. A 2-wire RTD is used to measure the output temperature of the heat exchanger and is connected to the transmitter. The 2-wire RTD transmitter produces a standard 4-20 mA output which is proportional to the temperature. The transmitter helps to reduce the noise in measurement. A separate power source is supplied to the transmitter unit. The data from the transmitter is updated in the PC based controller using a data acquisition (DAQ) device. The PC based controller processes the error signal and computes the appropriate control signal. The controller unit sends the corresponding control signal to current to pressure converter via another DAQ device. The current to pressure converter converts the current output of PC based controller to appropriate pressure signal so that the steam valve can be actuated in a proper manner. The experimental data available for the heat exchanger system is summarized below [12–14].

Exchanger response to steam flow gain is $50^{\circ}C/kg\sec^{-1}$, time constant is 30 sec, Exchanger response to variation of process fluid flow gain $1^{\circ}C/kg\sec^{-1}$, Exchanger response to variation of process temperature gain $3^{\circ}C/^{\circ}C$, capacity of control

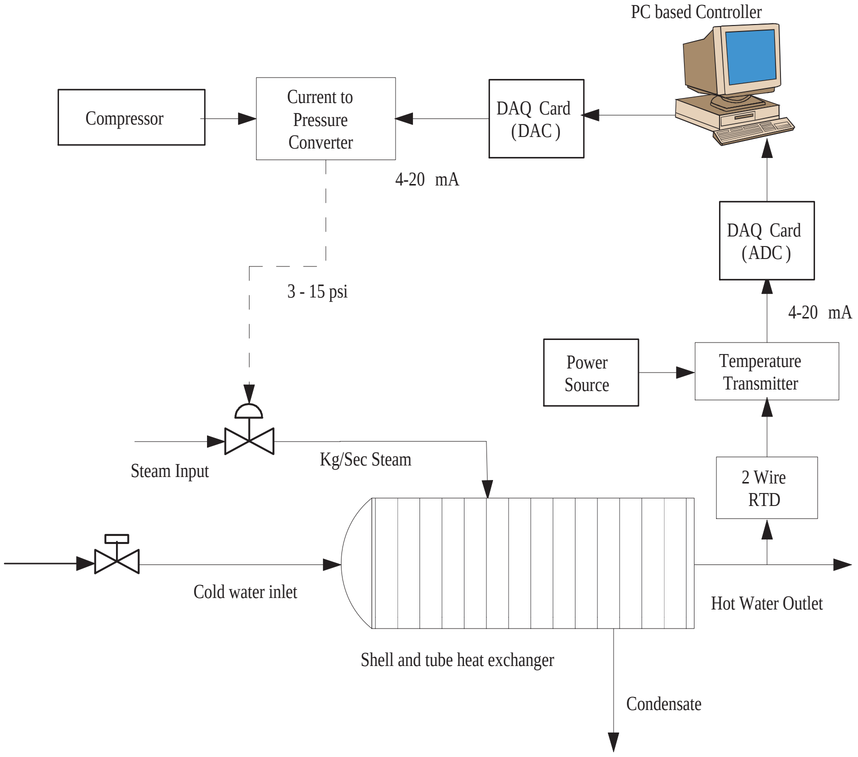

Figure 3: Schematic diagram of temperature control of heat exchanger

valve $1.6kg/\sec$, time constant for control valve is 3 sec, time constant for sensor is 10 sec.
From the experimental data linearized mathematical model of heat exchanger is developed.

2.2 Mathematical Model

To design a controller, a proper mathematical model of the process has to be determined. Most of the industrial system are non-linear in nature and can be approximated as first order plus time delay (FOPTD) or second order plus time delay (SOPTD) models. The general form of FOPTD model can be expressed as

$$G(s) = \frac{K_p e^{-\tau_D s}}{\tau s + 1} \tag{1}$$

The general form of SOPTD model can be expressed as

$$G(s) = \frac{K_p e^{-\tau_D s}}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{2}$$

Here K_p is the process gain, τ_D is the time delay, τ is the time constant of FOPTD system, τ_1 and τ_2 are the time constant of SOPTD system. The parameters are obtained from open loop step response data or frequency response data. The time delays are measured from the step response data.
This paper considers the experimental data mentioned in Section 2.1 while developing the transfer function model of heat exchanger system.
Transfer function model of heat exchanger system is

$$G_p(s) = \frac{50}{30s + 1} e^{-1s} \tag{3}$$

Transfer function model of valve is

$$G_v(s) = \frac{0.13}{3s + 1} \tag{4}$$

Transfer function model of sensor is

$$H(s) = \frac{0.16}{10s + 1} \tag{5}$$

Transfer function model of disturbance is

$$G_d(s) = \frac{1}{10s + 1} \tag{6}$$

The process transfer function is represented as

$$G(s) = \frac{5e^{-1s}}{90s^2 + 33s + 1} \tag{7}$$

which is in the form of SOPTD represented in Eq. 2

3 Control Algorithms

To control the outlet temperature of heat exchanger system closed loop control is required which can be achieved by a controller. The control algorithm considered to achieve the desired control objective are Proportional-Integral-Derivative (PID) control, feed forward controller and internal model controller.

3.1 PID Controller

The block diagram of a closed loop feedback control setup of heat exchanger system is shown in Fig. 4. In this block diagram classical PID controller is used as the controller.

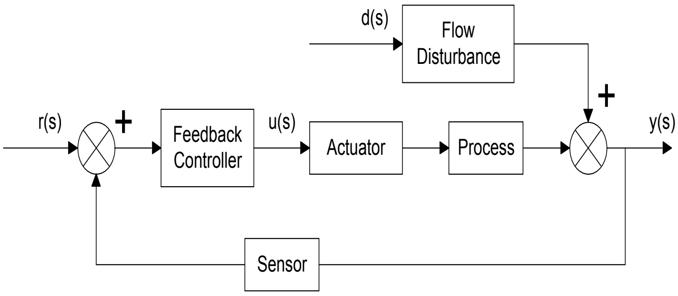

Figure 4: Block diagram of feedback control loop

An ideal interacting PID controller can be represented as

$$G_c\left(s\right) = K_c\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \tag{8}$$

K_c is proportional gain, τ_i is integral time and τ_d is the derivative time
There are different tuning methods of PID controller. Some methods are empirical methods (process reaction curve), some methods are based on frequency response analysis of the system and other methods are based on minimization of performance measures. Despite advances in PID tuning methods the ground reality is that in most of the cases, PID controller is tuned using trial and error method.

3.2 Feed-forward Controller

The inherent limitations of feedback controller is that the controller acts after the disturbance distorts the required control objective. If frequent disturbances occur then feedback control will not be able to attain the desired steady state. To limit such kind of drawbacks, feed-forward control is used. Feed-forward control limits the deviation caused by the disturbance but the feed-forward control works in one condition that is the disturbance should be measured or estimated. Feed-forward control cant work alone, so it works alongside feedback control.

The transfer function of feed-forward controller can be represented as

$$G_{cf}\left(s\right) = -\frac{G_d\left(s\right)}{G_p\left(s\right)} \tag{9}$$

Here $G_{cf}\left(s\right)$ is the transfer function of feedback-feed forward controller, $G_p\left(s\right)$ is the process transfer function and $G_d\left(s\right)$ is the disturbance transfer function.

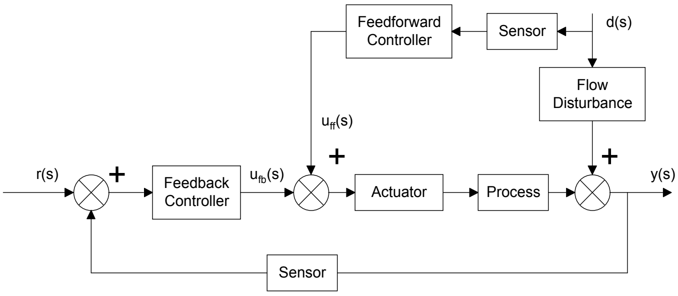

Figure 5: Block diagram of feedback control loop

The block diagram of feedback plus feed-forward controller is illustrated in Fig. 5. The flow disturbance is measured or estimated and the feed-forward compensator compensates the said disturbance. The control signal of feedback controller and feed-forward controller is summed up and provided to the process.

3.3 Internal Model Controller

One of the most popular techniques in the field of chemical engineering in internal model controller abbreviated as IMC. Internal model controller was introduced to limit the effects of error and disturbance which is caused by model mismatch. Internal model control is basically a model based approach [15]. The process model derived can be a forward model or inverse model. The controller is carved out from the inverse model whereas the forward model is placed in parallel with the actual process. The block diagram of internal model controller is shown in Fig. 6.
Here $G_p\left(s\right)$ is the process, $\tilde{G}_p\left(s\right)$ is the process model.
The process model can be classified in to two distinct parts such as invertible part $\tilde{G}_{p+}\left(s\right)$ and non-invertible part $\tilde{G}_{p-}\left(s\right)$.

$$\tilde{G}_p\left(s\right) = \tilde{G}_{p-}\left(s\right)\tilde{G}_{p+}\left(s\right) \tag{10}$$

The internal model controller can be designed by taking the inverse of process model along with

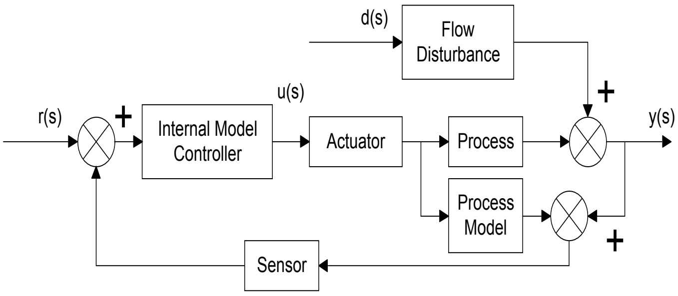

Figure 6: Block diagram of internal model controller

the filter transfer function. The transfer function representation of internal model controller is

$$Q\left(s\right)=\tilde{G}_{p-}\left(s\right)f\left(s\right) \tag{11}$$

$$Q\left(s\right)=\tilde{G}_{p-}\left(s\right)\frac{1}{\left(\lambda s+1\right)^{n}} \tag{12}$$

4 Simulation Results

To control the temperature of a shell and tube heat exchanger system different controllers are used and the simulated studies of the controller performance is discussed in this section. Performance assessment of industrial controller is one of the widely researched area which determines the performance of the controller by various methods [16]. Oscillations in process control loop is determined using different parameters summarized below. The methods of oscillation detection was first introduced by [17].

Some of the parameters used to evaluate the performance of control loops are

$$IAE=\int_{0}^{\infty}\left|e\left(t\right)\right|dt=\int_{0}^{\infty}\left|r\left(t\right)-y\left(t\right)\right|dt \tag{13}$$

$$ISE=\int_{0}^{\infty}e^{2}\left(t\right)dt \tag{14}$$

$$ITAE=\int_{0}^{\infty}t\left|e\left(t\right)\right|dt \tag{15}$$

$$ITSE=\int_{0}^{\infty}t^{2}e\left(t\right)dt \tag{16}$$

Classical PID controller tuned using Zigler-Nichols tuning method is used to control the output temperature of heat exchanger. Set point tracking and disturbance rejection of the feedback controller is shown in Fig. 7. The feedback PID controller shows 29.56% of overshoot and 115.2 sec of settling time.

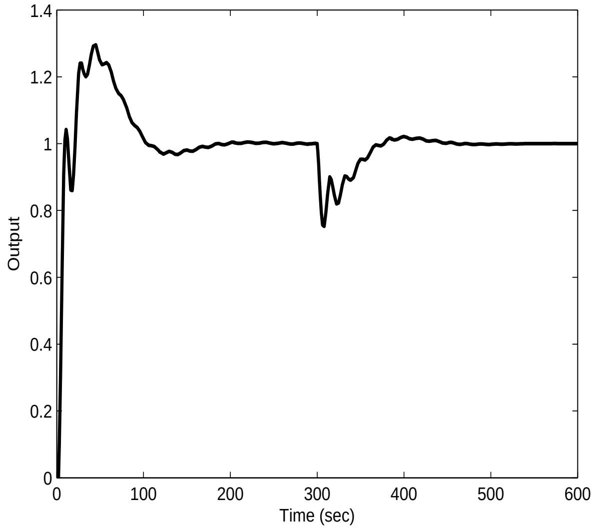

Figure 7: Set point and load disturbance response using PID controller

Due to the high overshoot of classical PID controller, feed-forward controller is added with feed back controller. The combination of feedback plus feed-forward controller reduces the overshoot to 25.1%. The unit step response of feedback plus feed-forward controller for temperature control of heat exchanger system is shown in Fig. 8. Due to relatively higher overshoot of feedback plus

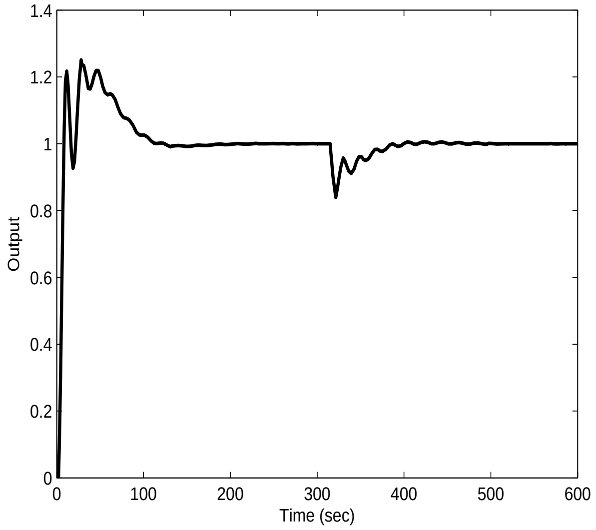

Figure 8: Set point and load disturbance response using feedback plus feed-forward controller

feed-forward controller, model based control (internal model control) is used. The unit step response of internal model controller for temperature control of heat exchanger system is shown in Fig. 9. The internal model control shows an overshoot of 1.13%.

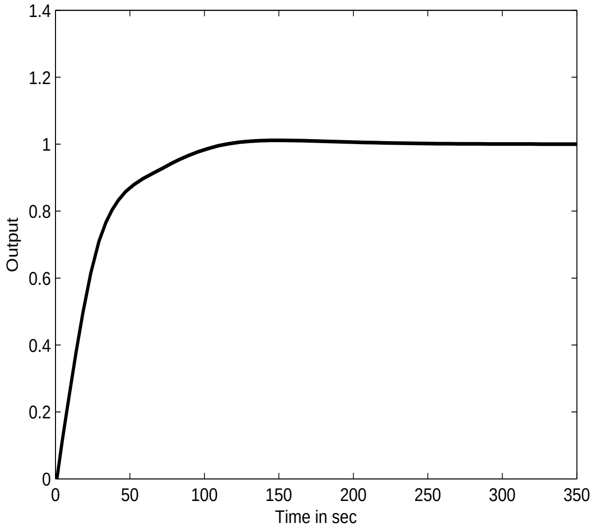

Figure 9: Set point response using internal model controller

The transient response (peak overshoot and settling time) in unit step response of all the controllers (feedback, feedback plus feed-forward and internal model controller) is summarized in Table 1. The error response of all the controllers (feedback, feedback plus feed-forward and internal model controller) is summarized is tabulated in Table 2.

Table 1: Results for transient response of controller

Controller	**Overshoot**	**Settling Time**
Feedback PID	29.56%	115.2 sec
Feedback plus Feed-forward	25.1%	91.3 sec
Internal Model Controller	1.13%	77.79 sec

Table 2: Results for error indices of controller

Controller	**IAE**	**ISE**	**ITAE**	**ITSE**
Feedback PID	5.55	0.3	610.8	11.75
Feedback plus Feed-forward	4.14	0.25	340.1	5.107
Internal Model Controller	3.58	0.18	279.5	4.729

From Table 2 it is observed that the error indices (IAE, ISE, ITAE and ITSE) decreases as the overshoot and settling time decreases.

5 Conclusion

This paper implements different controller (feedback, feedback plus feed-forward and internal model controller) to control the outlet temperature of a shell and tube heat exchanger system. Mathematical model of the heat exchanger is developed using experimental data and the process model is used to develop the respective controller. The performance of different controllers are evaluated using transient characteristics and error indices. From the simulation results, it is found that the internal model control has a superior performance than feedback and feedback plus feed-forward controller. The feedback controller implemented using classical PID controller shows a higher degree of overshoot and settling time whereas the internal model control negates the overshoot and has a manageable settling time.

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