A survey study on different methods of controlling temperature of shell and tube heat exchangers


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ABSTRACT: Heat exchangers are devices that are used to transfer thermal energy between two fluid streams at different temperatures without mixing the two streams. Heat exchangers are key devices used in a wide variety of thermal applications in the chemical process industries. One of the most important designs in heat exchanger is controller design. Two main of controllers are conventional in nature and intelligent in nature. In the intelligent controller human intelligence is embed using soft computing algorithms. Most important note in design of intelligent controller is optimization of control results irrespective of every situation like plant and equipment non linearity, equipment saturation. In this research we survey different conventional and intelligent controllers implemented with a clear objective to control the outlet fluid temperature of shell and tube heat exchanger system.

Keywords: shell, tube, heat exchanger, controlling temperature, equipment saturation

INTRODUCTION

In recent years the performance requirements for process plants have become increasingly difficult to satisfy. Stronger competition, tougher environmental and safety regulations, and rapidly changing economic conditions have been key factors in tightening product quality specifications (Ayub, 2003). A further complication is that modern plants have become more difficult to operate because of the trend toward complex and highly integrated processes. For such plants, it is difficult to prevent disturbances from propagating from one unit to other interconnected units (chapra et al, 1985).

The two main subjects related are process dynamics and control. The term process dynamics refers to unsteady-state (or transient) process behavior. Transient operation occurs during important situations such as start-ups and shutdowns, unusual process disturbances, and planned transitions from one product grade to another.

In any of the control application, controller design is the most important part. There are different types of controller. The controller can be conventional in nature or intelligent in nature.

The conventional controller doesn’t posses the human intelligence; where in the intelligent controller human intelligence is embed with the help of certain soft computing algorithms. After the design of controller is performed, the performance evaluation part comes in to light. The designed controller has to give optimal control results irrespective of every situation like plant and equipment non linearity, equipment saturation.

Literature review

Heat exchangers are equipment which transfer the heat from a fluid to another for thermal processes in which two fluids have different temperatures. Plate type heat exchanger (PHE) is the most efficient HEP (Chen et al., 2006).

A typical chemical process for heating consists of a chemical reactor and a shell and tube heat exchanger system. The process fluid which is the salt solution of sodium sulphate and aluminum sulphate is stored in the storage tank at a temperature of 32°C. The storage tank pumps the salt solution to the shell and tube heat exchanger system. The heat exchanger heats up the salt solution at a temperature of 52°C using super-heated steam at 180°C to get a concentrated salt solution. The super-heated steam comes from the boiler and flows through the shell side, whereas, the salt solution flows through the tube side of the shell and tube heat exchanger system. After the steam heats up the salt solution, the condensed steam at 93°C goes out of the steam trap. The steam trap removes the condensate and non-condensing gases. The control objective is to control the temperature of the concentrated salt solution. Different control architectures and different
conventional controllers like PID, feed forward controller and internal model based controller can be implemented to achieve the control objective.

In practice, all chemical processes involve the production or absorption of energy in the form of heat. Heat exchanger is commonly used in industrial chemical processes to transfer heat from a hot liquid through a solid wall to a cooler fluid (Durmus et al, 2009). A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact (Jantzen, 2007).

There are different types of heat exchanger used in the industry but most of the industry use shell and tube type heat exchanger system. It consists of parallel tubes enclosed in a shell. One of the fluid flows in the tubes and the other flows inside the shell around the tube. These heat exchangers are very flexible and adaptable, can operate over full range of pressures and temperatures encountered in chemical plants. They have larger ratios of heat transfer surface to volume than double-pipe heat exchangers, and they are easy to manufacture in a large variety of sizes and configurations. They can operate at high pressures, and their 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.

A typical gasketed PHE is the plate-and-frame heat exchanger. The PHE consists of a pack of corrugated metal plates pressed together into a frame shown in Fig. 1. The gaskets between the plates form a series of thin channels where the hot and cold fluids flow and exchange heat through the metal plates. The flow distribution inside the plate pack is defined by the design of the gaskets, the opened and closed ports of the plates and the location of the feed connections at the covers (Khare, 2010). Appropriate design and gasketing permit a stack of plates to be held together by compression bolts joining the end plates. Gaskets prevent leakage to the outside and allow the inter-plate channels to be sealed and to direct the fluids into alternate channels, ensuring the two media never mix.

Shell-and-tube heat exchangers find widespread use in refrigeration, power generation, heating and air conditioning, chemical processes, manufacturing, and medical applications.

(Kolek et al, 2007), developed a model reference nonlinear controller with ID control action for heat exchanger system. The proposed controller is efficient from other controller sand is robust to modeling errors and disturbances. Rajiv Mukherjee in his research paper gave a basic overview of shell and tube heat exchanger system: components, classifications in details (Khare et al, 2010). G P Liu et al, presented three kind of optimal tuning of PID controller design. These types are time domain optimal tuning PID control, frequency domain optimal tuning PID control and multi objective optimal tuning PID control.

(Mazinan et al, 2008), has given a complete overview of modern tuning methods of PID controller, different patents in PID controllers, commercial hardware modules and software packages of PID controller available in market. This paper also reviews the contemporary intelligent PID controllers and reviews the future PID controller like plug and play PID controller.

Fernando G Martins has proposed a PID controller tuning method based on ITAE criteria. ITAE is a performance criteria which should be minimized for a better control action but the computation of ITAE is a difficult task.

Wen Tan et al has compared the performance of some well known PID controllers. He has taken two criteria for the comparison and those are disturbance rejection and system robustness.
(Padhee, 2010) applied ANN architecture to model the shell and tube heat exchanger system. In this research paper, ANN is used for estimation of exit temperature of both fluids as a function of inlet temperature condition and flow rates.

(Rajasekaran, 2010), in his research paper developed a nonlinear model of open plate reactor developed by Alfa Laval AB. In his research paper, he developed the control strategies for the heat exchanger system and experimentally verified the control strategy. He used a model predictive controller with extended Kalman filter.

Orlando Duran et al., in his research paper proposed a test model of cost estimating of shell and tube heat exchanger system using ANN. The proposed ANN test model reduces the uncertainties related to cost estimation of shell and tube heat exchanger system. (Skrjanc, 2000), experimentally investigated heat transfer study on a solvent and solution with a 1-1 shell and tube heat exchanger. The experimental findings were compared with the mathematical model of the system.

(Jantzen, 2007), in his research paper proposed a new method for calculation of heat power consumption in a heat exchanger. The method is based on the analysis of phenomena occurring between the heat exchanger and the ambient. An artificial neural network, trained with data obtained from infrared thermography measurements is used to calculate the heat power consumption in steady state.

MATERIAL AND METHODS

Different assumptions have been considered to develop the control architecture of the shell and tube heat exchanger system. The first assumption is that the inflow and the outflow rate of fluid are same, so that the fluid level is maintained constant in the heat exchanger. The second assumption is the heat storage capacity of the insulating wall is negligible. In this feedback process control loop, the controller is reverse acting, the valve used is of air to open (fail-close) type. A thermocouple is used as the sensing element, which is implemented in the feedback path of the control architecture. The temperature of the outgoing fluid is measured by the thermocouple and the output of the thermocouple (voltage) is sent to the transmitter unit, which eventually converts the temperature output to a standardized signal in the range of 4-20 mA. This output of the transmitter unit is given to the controller unit. In this heat exchanger system a PID controller has been taken as the controlling unit.

The PID controller implements the control algorithm, compares the output with the set point and then gives necessary command to the final control element via the actuator unit. The actuator unit is a current to pressure converter and the final control unit is an air to open (fail-close) valve. The actuator unit takes the controller output in the range of 4-20 mA and converts it into a standardized pressure unit, i.e., in the range of 3-15 psig. The valve actuates according to the controller decisions.

Feedback control is a control mechanism which regulates the controlled variable by taking negative feedback from the output and taking regulatory action through the controller and changing the manipulating variable accordingly.

Figure 2 shows the feedback control scheme for shell and tube heat exchanger system. PID controller is used as the controlling element to control the outlet temperature of shell and tube heat exchanger.
Fuzzy logic is capable of handling approximate information in a systematic way and therefore it is suited for controlling nonlinear systems and is used for modeling complex systems, where an inexact model exists or systems where ambiguity or vagueness is common. The fuzzy control systems are rule-based systems in which a set of fuzzy rules represent a control decision mechanism for adjusting the effects of certain system stimuli. With an effective rule base, the fuzzy control systems can replace a skilled human operator. The rule base reflects the human expert knowledge, expressed as linguistic variables, while the membership functions represent expert interpretation of those variables.

Figure 3 shows the block diagram of fuzzy control system. The crisp inputs are supplied to the input side Fuzzification unit. The Fuzzification unit converts the crisp input into fuzzy variable. The fuzzy variables are then passed through the fuzzy rule base. The fuzzy rule base computes the input according to the rules and gives the output. The output is then passed through de-fuzzification unit where the fuzzy output is converted to crisp output.

**Hybrid Fuzzy-PID Controller**

Although it is possible to design a fuzzy logic type of PID controller by a simple modification of the conventional ones, via inserting some meaningful fuzzy logic IF-THEN rules into the control system, these approaches in general complicate the overall design and do not come up with new fuzzy PID controllers that capture the essential characteristics and nature of the conventional PID controllers. Besides, they generally do not have analytic formulas to use for control specification and stability analysis. The fuzzy PD, PI, and PI+D controllers to be introduced below are natural extensions of their conventional versions, which preserve the linear structures of the PID controllers, with simple and conventional analytical formulas as the final results of the design. Thus, they can directly replace the conventional PID controllers in any operating control systems (plants, processes).

The main difference is that these fuzzy PID controllers are designed by employing fuzzy logic control principles and techniques, to obtain new controllers that possess analytic formulas very similar to the conventional digital PID controllers.

System identification is the art and science of building mathematical models of dynamic systems from observed input–output data. It can be seen as the interface between the real world of applications and the mathematical world of control theory and model abstractions. System identification is an essential requirement in areas such as control, communication, power system and instrumentation for obtaining a model of a system (plant) of interest or a new system to be developed and for the purpose of development of control law, analysis fault diagnosis, etc. Major advances have been made in adaptive identification and control, in past few decades for identifying linear time-invariant plants with unknown parameters. The choice of the identifier structure is based on well established results in linear systems theory. Stable adaptive laws for the adjustment of parameters in these which assures the global stability of the relevant overall systems are also based on properties of linear systems as well as stability results that are well known for such systems.

**Closed-Loop Adaptation:** Close-loop adaptation on the other hand involves the automatic experimentation with these adjustments and knowledge of their outcome in order to optimize a measured system performance. The latter process may be called adaptation by performance feedback. The adaptation of process parameters depends upon the input as well as output signal. System identification techniques are two types:

1. Direct Modeling
2. Indirect Modeling
Direct Modeling: In this type of modeling the adaptive model is kept parallel with the unknown plant. Both the unknown system and adaptive filter are driven by the same input. The adaptive filter adjusts itself in such a way that its output is match with that of the unknown system. Upon convergence, the structure and parameter values of the adaptive system may or may not resemble those of unknown systems, but the input-output response relationship will match. In this sense, the adaptive system becomes a model of the unknown plant. Let \( d(n) \) and \( y(n) \) represent the output of the unknown system and adaptive model with \( x(n) \) as its input.

Inverse Modeling: We now consider the general problem of inverse modeling. In this diagram, a source signal \( s(n) \) is fed into a plant that produces the input signal \( x(n) \) for the adaptive identifier. The output of the adaptive identifier is subtracted from a desired response signal that is a delayed version of the source signal, such that \( d(n) = s(n - \tau) \) where \( \tau \) is a positive integer value.

The goal of the adaptive identifier is to adjust its characteristics such that the output signal is an accurate representation of the delayed source signal.

RESULT AND DISCUSSION

This section evaluates the performance of the conventional and intelligent controller. Performance evaluation scheme of controller is done using both time response analysis and frequency response analysis. In time response analysis unit step response of the respective controller is evaluated and maximum overshoot and settling time is calculated. To study the performance of the controller different performance indices are calculated.

In step response analysis different parameters are considered. From those parameters there are two most important parameters, these are peak overshoot and settling time. Peak Overshoot: It indicates the normalized difference between the time response peak and steady output. It is defined as

\[
\%M_p = \frac{c(t_p) - c(\infty)}{c(\infty)} \times 100\%
\]

Settling Time: It is the time required for the response to reach and stay within a specified tolerance band of its final value. The tolerance band is taken randomly as 5%.

![Figure 4. Comparison of unit step response of different conventional controllers](image)

Figure 4 shows the comparison of unit step response of different conventional controllers. The PID controller shows a peak overshoot of 38%, a feed forward and feedback controller reduces the peak overshoot to 30% and the model based controller (IMC) significantly reduces the peak overshoot and the peak overshoot...
of IMC is 1%. It is clear from the step response analysis that the model based controllers give a better control than the conventional feedback and feed forward controllers.

Figure 5 shows the comparison of unit step response of different conventional and fuzzy controller. The model based controller IMC significantly reduced the overshoot but to give some intelligence to the controller and to get near zero overshoot, a fuzzy based hybrid controller is used.

The hybrid fuzzy controller retains the linearity characteristics of PID controller and gives a fuzzy touch to it. The unit step response of hybrid fuzzy controller gives a near zero peak overshoot or no overshoot.

The feedback controller (PID controller) gives 38.38% peak overshoot and 115.2 sec settling time. The peak overshoot is in a higher side. To compensate the high peak overshoot, feed forward controller was designed. The feed forward controller estimates the error and compensates it. In this project two types of feed forward controller is developed. In the first case it is assumed that there is no time delay between the unit step input to the process and unit step disturbance. In this case the combined effect of feedback and feed forward controller gives a peak overshoot of 30% and settling time is 91.3 sec. In the second case, it is assumed that there is a unit time delay between unit step input to the process and unit step disturbance. In the second case though the peak overshoot somewhat rises to 32.51% but the settling time reduces to 86.16 sec. but after the implementation of feed forward plus feedback controller still the peak overshoot is 30% which is very high. To further reduce the peak overshoot somewhat rises to 32.51% but the settling time reduces to 86.16 sec. but after the implementation of feed forward plus feedback controller still the peak overshoot is 30% which is very high. To further reduce the peak overshoot, model based controller (internal model controller) was designed. The internal model controller reduces the peak overshoot to 1.13% and reduces the settling time to 77.79 sec. To further improve the peak overshoot, fuzzy based hybrid controller was designed. The fuzzy based hybrid controller gives a peak overshoot of 0% (no overshoot) and reduces the settling time to 74.38 sec.

In section 6.1.1 the designed controllers were subjected to unit step input and their performance were evaluated according to the peak overshoot and settling time. In this section the controllers will be evaluated according to the performance indices.

A performance index is a quantitative measure of the performance of a system and is chosen so that emphasis is given to the important system specifications. A system is considered an optimum control system when the system parameters are adjusted so that the index reaches an extreme, commonly a minimum value. To be useful a performance index must be a number that is always positive or zero. Then the best system is defined as the system that minimizes the index.

Table 1. Comparison of performance indices of different controllers

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Type of Controller</th>
<th>IAE</th>
<th>ISE</th>
<th>ITAE</th>
<th>ITSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feedback</td>
<td>4.755</td>
<td>0.366</td>
<td>192.6</td>
<td>6.33</td>
</tr>
<tr>
<td>2</td>
<td>Feedback plus feed forward (No delay in disturbance)</td>
<td>4.441</td>
<td>0.311</td>
<td>188.1</td>
<td>5.569</td>
</tr>
<tr>
<td>3</td>
<td>Feedback plus feed forward (Unit delay in disturbance)</td>
<td>4.456</td>
<td>0.305</td>
<td>221</td>
<td>5.757</td>
</tr>
<tr>
<td>4</td>
<td>Internal model controller</td>
<td>4.37</td>
<td>0.27</td>
<td>181.9</td>
<td>5.15</td>
</tr>
<tr>
<td>5</td>
<td>Hybrid fuzzy</td>
<td>3.56</td>
<td>0.18</td>
<td>179.7</td>
<td>4.75</td>
</tr>
</tbody>
</table>
There are different performance indices of a control system and most common performance indices are IAE (integral absolute error), ISE (integral square error), ITAE (integral time absolute error) and ITSE (integral time square error).

\[
IAE = \int_0^\infty |e(t)| \, dt
\]

\[
ISE = \int_0^\infty e^2(t) \, dt
\]

\[
ITAE = \int_0^\infty t|e(t)| \, dt
\]

\[
ITSE = \int_0^\infty t e^2(t) \, dt
\]

From the table 1 it is clear that IAE of feedback controller is 4.755 and IAE of feedback plus feed forward controller is 4.441, the IAE of internal model controller is 4.37 and IAE of hybrid fuzzy controller is 3.56. It is observed that feedback controller showed 38% overshoot, so the IAE was a little bit higher. As the overshoot decreases the value of IAE also decreases. For this reason IAE of hybrid fuzzy controller is 3.56.

ISE of feedback controller is 0.366 and ISE of feedback plus feed forward controller is 0.311, the ISE of internal model controller is 0.27 and ISE of hybrid fuzzy controller is 0.18. It is observed that feedback controller showed 38% overshoot, so the ISE was a little bit higher. As the overshoot decreases the value of ISE also decreases. For this reason ISE of hybrid fuzzy controller is 0.18.

A control system must satisfy desired performance characteristics for nominal operating conditions. In real world the model is never perfect, so the controller has to be robust. Robust controller literally means the controller should remain stable, even when the true plant characteristics are different from the process model. Frequency response analysis is performed because, it primarily provides a measurement of robustness of the controller tuning. It provides a measure of the amount of model uncertainty that can be tolerated before the controller will become unstable.

![Bode plot of system with and without controller](image1)

![Bode plot of system with and without controller](image2)

Figure 6. Frequency response of system with and without controller
Figure 6 shows the frequency response of the system with and without controller. The frequency response of a system consists of the magnitude response and phase response. Different process disturbance affects the stability of the system. To investigate the effect of stability due to addition of disturbance, bode plot is plotted.

The design for classical FL controllers is still considered premature in general, significant progress has been gained recently in the pursuit of this technology and it remains a difficult task due to the fact that there is insufficient analytical design technique in contrast with the well-developed linear control theories. The FL controller structure can be classified into different types, and the most popular one is PID fuzzy controller.

The control tuning of the PID fuzzy controller depends on the trial and error to find the scaled factors for each variable. The best values of the scaled factors were tuned using simulink program. The simulation model of PHE with PID fuzzy controller is illustrated in Fig. (7)

The inputs of PID fuzzy control are defined as the proportional gain (KR, cR), integral gain (KR, IR) and derivative gain (KR, DR). The output variable, is called the control action (u). Fuzzy sets are defined for each input and output variable. There are three fuzzy levels (negative (N), zero (Z) and positive (P)). The membership functions for inputs are triangular and the membership function for output variable is linear. By trial and error the proportional gain has a range of [0, 1.25], integral gain has a range of [-2, 2], derivative gain has a range of [0.1, 1.25] and control action has a range of [0, 1.25]. The system is a Sugeno fuzzy system and the rule base of PID fuzzy controller is shown in table (2)

<table>
<thead>
<tr>
<th>Integral gain (K_I)</th>
<th>N</th>
<th>N</th>
<th>N</th>
<th>Z</th>
<th>Z</th>
<th>Z</th>
<th>P</th>
<th>P</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional gain (K_P)</td>
<td>N</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Z</td>
<td>P</td>
<td>Z</td>
</tr>
<tr>
<td>Derivative gain (K_D)</td>
<td>N</td>
<td>Z</td>
<td>P</td>
<td>N</td>
<td>Z</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

27 PID fuzzy rules are used for this case because of using three dimensional rule set. For example, one of the rules for PID fuzzy controller:
IF KR cR is N AND KR IR is N AND KR DR is N THEN u is P.

**CONCLUSION**

The aim of the proposed controller is to regulate the temperature of the outgoing fluid of a shell and tube heat exchanger system to a desired temperature in the shortest possible time and minimum or no overshoot.
irrespective of step change in load and process disturbances, equipment saturation and non-linearity of different control equipments. After time response and frequency response based analysis carried out on different controllers it is observed that hybrid fuzzy controller provides a satisfactory performance in both steady state and transient state and overcomes the drawbacks of conventional PID controller, feedback plus feed-forward.

The key design challenge is to generate an optimized fuzzy rule base with minimum number of rules. An existing rule base of N number of rules can be optimized using different optimization techniques like genetic algorithm, PSO, ant colony optimization. This dissertation proposes a genetic algorithm based optimization of existing fuzzy rule base of N number of rules. The second challenge is to reduce the size of the rule base. To reduce the size of the rulebase, optimal number of membership function has to be chosen and the optimal width of membership function has to be calculated. To achieve this objective system identification and estimation approach is used. This dissertation proposes Kalman filter based H\(\infty\) estimation to achieve the objective.

REFERENCES


