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Modeling and Simulation of Feed Forward Temperature Controller with Effect of Higher Gain on Chemical Reactors' Heat Exchangers

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Abstract

Chemical reactors are widely being used in pharmaceutical process industries. The temperature controller design is an essential part of heat exchanger (HE) design for such reactors. The goal of this research is to design and validate the feed forward (FF) temperature compensator for the stirred tank chemical rectors. The aim is to analyze the impact of high turbulence (gain) performance on step response. For temperature management, a transfer function (TF) control based on proportional integral (PI) controllers is anticipated. The main purpose of the PI compensatory is to lessen the influence of rising time. The modeling and assimilation of the temperature control for the heat exchanger designs is proposed to be implemented in MATLAB using the Simulink and soft computing-based analysis. Expected results of the step response of the temperature controller are plotted for HE designs. The two-point technique is also used to identify the model function and its parameters. Identifying the t1 and t2 points, which appear to contribute 28.3% and 60%, respectively, to the system's maximum responsiveness. The variation in [t1, t2] is evaluated as valuable gain.

Keywords: Chemical reactors' heat exchanger, temperature control, U tube, fin-plate heat exchanger, flow configuration, gain impact

INTRODUCTION

Stirred tank reactors (STRs) are the most common reactors used in the chemical industries [1]. For design of STR, feed forward (FF) control of temperature is a frequently employed technique to enhance the overall effectiveness of temperature management. The temperature compensators operate by taking direct measurements of temperature and flow rate data to predict how the disturbance will affect a controlled reactor temperature, by taking preventative measures, reactor temperature fluctuations can be greatly decreased, and the overall temperature stability can be raised.

The heat exchanger (HE) is the essential part of any chemical reactor. The final goal of this project is to model and simulate a HE's temperature compensator using MATLAB, a standard technique for engineers and researchers. Many chemical reactions required to maintain or control the temperature of the HE during the mixing process. It is suitable for both the cooling and heating processes. The fluids in the exchanger may be in direct contact or may be divided by a solid wall. The ultimate aim of the paper is to evaluate the performance of the chemical reactor HE under the high gain or turbulence.

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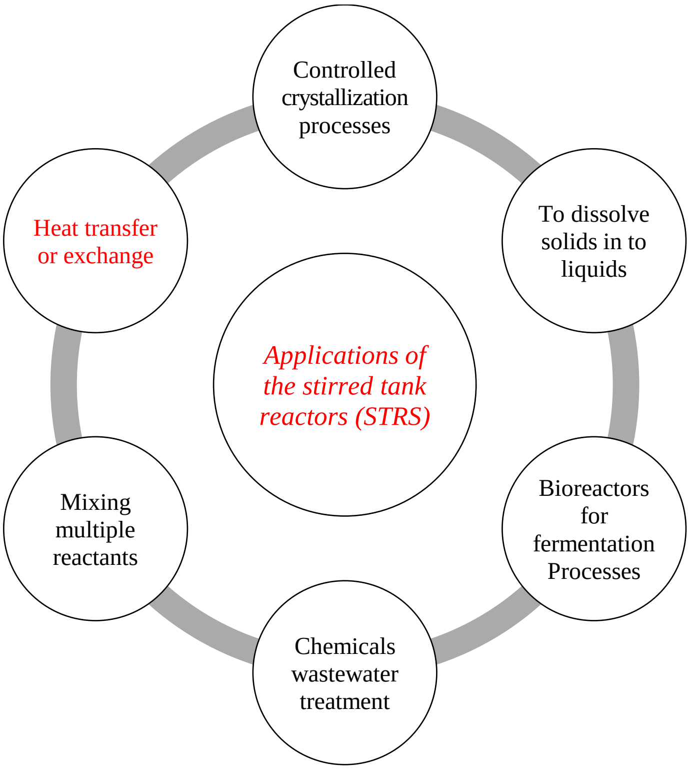

Figure 1. Application of heat exchangers.

The major application area for HE is illustrated in Figure 1. Most frequent ones are heat transfer and exchange as highlighted with red color in Figure 1 this research has used this application specific to chemical reactors.

In order to extend the life and effectiveness of the machinery, top-notch heat transfer is also required due to the rise in machine demands. For several uses, STRs are widely used in the chemical processing industry. Since controlling temperature is a crucial component of many industrial processes and applications, this paper aims to provide an overview of the fundamentals of HE hardware and associated simulation techniques.

These are the several hypotheses that are taken into account when modeling HEs. Temperature control of HEs in STRs is contingent upon the kind of the process or reaction being conducted, the characteristics of the products and reactants, and the intended conditions of the reaction. The main requirements of the heat exchanger design and criteria are as follows:

- *High- or low-pressure limits:* The cost of the exchanger is directly proportional to the pressure factor of the design.
- *Thermal performance indexes and ranges:* The type and shape of the heat exchangers are dependent on the thermal performance index and kind of fluids.
- Required temperature ranges of operations.
- Product mix (liquid/liquid, particulates or high-solids liquid).
- *Pressure drops across the exchange:* The increased turbulence obtained from the results of pressure drops is a beneficial result.
- *Capacity of the fluid flow:* The rate of fluid flow is directly proportional to the heat transfer rates.
- *Cleavability, maintenance and repair:* These must be on the lower side for long-term cost analysis.

Thus, efficient temperature compensatory design is the most essential requirement of HE design and is the main scope of this research.

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FEED FORWARD HEAT EXCHANGERS

HEs can be divided into four categories based on how the flow is configured: counterflow, concurrent flow, cross flow, including hybrids such multi pass flow and cross counterflow. Basic block diagram of the feed forward (FF) temperature compensator is shown in Figure 2. A FF temperature compensator is a type of control system that adjusts the system in advance of actual temperature changes by anticipating changes in that parameter. By doing this, significant temperature swings are avoided and the temperature is kept steadier.

CLASSIFICATION OF HEAT EXCHANGE METHODS

Several hardware architectures are offered in the literature for designing the HE. The types and classifications of HEs are depicted in Figure 3. In general, HE is classified based on the control methods. The broad classification is based on feedback control, shape wise, and FF control type HE, the U tube and bent pipe structured exchangers being the most commonly utilized.

REVIEW OF LITERATURE

Singh and Kumar [1] have investigated examines the contact ratio and heat transmission of water passing through a double-pipe thermal exchanger with bent tape plugs that have dimples. Rotation ratio (T) of 5.5, Reynolds number, or Re, of 6000 to 14,000, depression width (D) of 3 mm, 5 mm, and 7 mm, and depression size-to-depth ration (D/H) of 1.5, 3, and 6 are the variables under investigation. Nine twisting tapes with dimples were examined, and their results were compared to simple bent tape and clear tubes. For D = 5 mm and D/H = 3, the maximal Nusselt value (Nu) was determined to be 113.68 in Re 14,000 and 59.56 at Re 6000. Thus, the paper presented efficient HE parametric design.

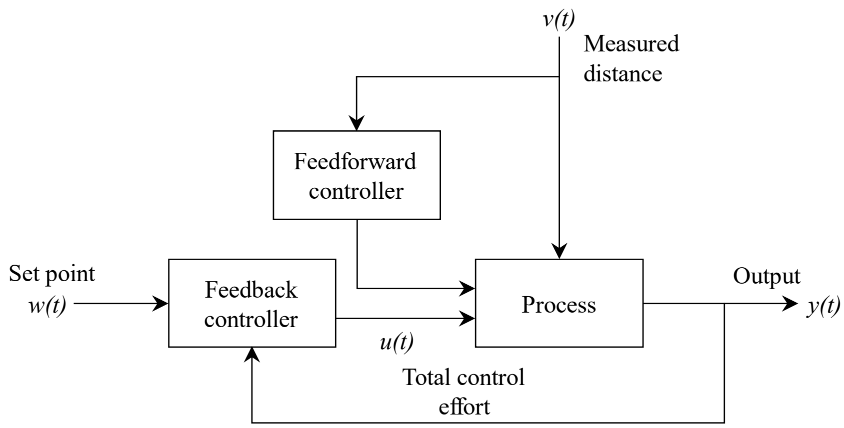

Figure 2. Basic block diagrams of the feed forward (FF) temperature compensator.

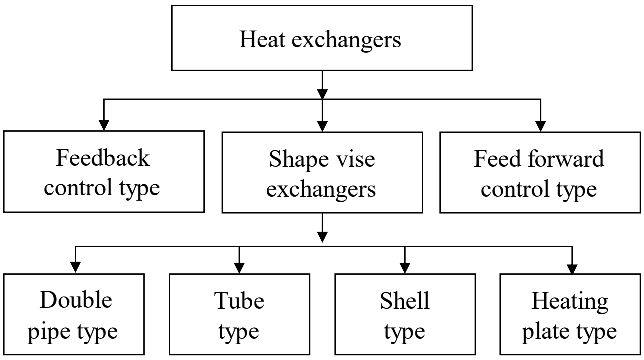

Figure 3. Classification of heat exchanger (HE) design methods.

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Porru et al. [2] have addressed the issue of controlling the solvent contaminant percentage in a manufacturing multicomponent distillation system (normal fuel split) with two feeds (paraffin-olefin) by adjusting the heating duty in response to disturbances in the olefin-to-total feed flow loading and plate temperatures. Challenge of quadratic state-feedback reliable management with a comprehensive model is tackled initially, determining the solvency criteria and feasible closed-loop applications behavior. After that, a result return proportional integral (PI) heat device with variable feed forward setting correction and ant windup safety restores its previous behavior. Viability of enhancing current adjustment approach with PI temperature monitoring + traditional set point adjustment is established by means of computerized simulations using an extensive simulator adjusted with data from industrial operations.

Mustafa et al. [3] have described the method of dissolving of metal in acidified dichromate, an approach that was used to study mass movement at the outermost layer of a straight ascend tube converter located at the bottom of a mixed tank. Several factors were taken into consideration, including (i) reactors configuration (i.e., presence of baffles that are get tube separation from the vessel's bottom, get tube size and length, and the impeller math), (ii) real estate of the acidified the dichromate process a solution, and (iii) mixing magnitude (i.e., impeller that rotating speed). It is shown that the existence of beads, helical tubing the pitch, and increased mix strength all cause an upsurge in transferred mass. The volume of transit decreases with increasing spiral tube diameter.

Miao and Xu [4] suggested a management strategy that combines proportional-integral-derivative management with anticipatory operational control. A predicting operational optimization models that uses a proportional-integral-derivative (PID) architecture is created through the use of the gradual PID management method to enhance the optimization objectives of the predicting functionally management method. To remove the impact of outside influences on the warmth converter temperature regulation system, forwarding compensating management is used. Feedback cascade composite control scheme, which has its foundation by a PID major administrator, is contrasted with the proposed approach to control during simulated.

Liu et al. [5] addressed two most commonly used types of forwarding controller development computations. Some additional common manufacturing FF controller standards are provided in this article along with their features, application areas, and helpful selection remarks in order to assist investigators and engineers with varying backgrounds in education. Additionally, a few commonly raised issues regarding FF management are also covered. To demonstrate how the forwarding controller enhances system efficiency and maximizes financial benefits, a case study based on manufacturing data is provided.

Miao and Xu [4] suggest control strategy combining PID management with anticipatory operational control. Predicting operational control optimization models with a PID architecture is created by using the gradual PID management engine to enhance the optimization objectives of the predicting functionally control method. To remove the impact of outside influences on HE temperature regulation system, forwarding compensatory management is used. Forwarding cascading compounded management scheme, which draws by a PID secondary manager, is contrasted with the suggested approach to control through simulated. The scheme's great interference suppression capacity and tiny over harmonies is demonstrated by the findings. The HE's output temperature can be efficiently managed, and the system's resilience and mobility have both greatly increased.

Kumar et al. [6] regulate the reactor's internal humidity. This study proposes two controllers: MPC, or model predictive control, and inverse, essential, and derivative management (PID). An examination of the two computers was done in comparison. By removing the influence of disruption and benchmark monitoring, predictive modeling can effectively regulate temperatures regarding consistency.

Edreis and Petrov [7] proposed technical and manufacturing procedures. The HEs are extensively investigated as the primary component of various forms of energy complexes. The use of heat radiators determines their classification. As a result, the primary categories of the HE apparatus will be discussed in this paper, along with how to choose a particular kind based on factors like humidity, flow, volume drop, and more. They briefly describe the benefits of each method utilized for analyzing how heat moves and its efficiency and tools for creating computational fluid dynamics (CFD) modeling.

Ismael et al.'s [8] research focused on employing dual/valve position-cascade control technique to optimize the thermal control method of a continuous stirred tank reactor (CSTR). Only the dynamic features of the entire design may satisfy the polyester process specifications when using classic PID control, which is analysis. The cooled properties of the pipe and the reservoir were examined in turn to fully exploit the control effectiveness of the CSTR. This "dual chilling" control notion efficiently overcomes this problem, and both the tubes and the reservoir are chilled. This allows the thermostat to take into consideration their individual benefits which result in coordinating usage with dual/valve position-cascade regulate methodology.

Hu [9] proposed tasks, appropriate hypotheses, designs, and the information needed for them are compiled in this article with an emphasis on continual responses. The healthcare sector uses plugged-flow reactors (PFRs) with CSTRs in sequence. A few instances of this kind of use are given. It is advised that process analytical equipment (PATs), which are crucial instruments that offer actual time consistent continual response surveillance, be considered while designing the reactor. Lastly, some other key topics are covered, including scaling-up, clogging/fouling, and pressure changing due to solid precipitating or expansion caused by temperature.

Vasičkaninová and Bakošová [10] proposed a technique to demonstrate the advantages of two sophisticated control schemes for HE control. H∞ management and -synthesis are two strong control methods that were applied in the motor controller design process. A frequency-domain optimization and design theory called H∞ optimal control was created in reaction to the requirement for a design process that specifically tackles simulation error concerns. Weight filtering and parameterized ambiguity are two examples of specified errors that are addressed through H∞ resilient controller layout concept.

Lottis and Kallert [11] primarily discussed a centrally generated energy source that feeds a flexibility heated generator (FHG) that links multiple dispersed hardware-in-the-loops (HIL). Nearly any heat generator ought to be able to be mapped by the FHG's HIL units, opening a variety of investigative situations. A heat exchange system (HEx) that links the HIL devices to the FHG must draw out or input an established amount of heat from the electrical grid while also guaranteeing a specified secondary-side output temperature to meet this demand. To the best of our understanding, a review of the literature revealed that just one temperature in the outlet is monitored in all technological uses.

Girirajan and Rathikarani [12] found an appropriate optimization strategy amongst the grey wolf optimization (GWO) and whale optimization algorithm (WOA) methods to increase the third-order crone controller's durability against variable fluctuations is the main goal of this study. To calculate non-integer variables and get the best possible control efficiency, a theoretical representation of HE is created. The goal is to maximize the speed of heat exchange while minimizing expense of fluid movement. Fluid pressure drop, transference rate, area, connecting method, and the amount of process equipment all challenge exchanger optimization. Multifaceted irregular WOA yields a competitive solution over an extensive spectrum of process parameter changes. To validate the suggested WOA optimized third-generation CRONE administrator, an experiment is run using the MATLAB program.

Olana and Abose [13] proposed a numerical or practical computational framework to reflect the actual system and develop an appropriate regulator that minimizes error during steady state, settles quickly, and removes offset. To do this, using the Cohen–Coon approach, Padhee's [14] study examined how well various integrators—such as external modeling control devices, input plus FF controls, and

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feedback—perform in controlling a HE's output fluid temperatures to a particular benchmark value. Optimal control is determined by analyzing the devices' transitory efficiency and mistake criterion. The inbuilt modeling controller works better than input PID and input + feedback administrator, according to the simulation's findings.

Möller and Gullapalli [15] introduced a tool that can be used for quick decision making, like structure optimization based on idea generating ideas and thermal process choice, for system layout and heat exchanger choosing during the design stage, and for late afterwards choices in which a current layout could be used with alternative heating sources. The created shareware tool's main strength is its ability to integrate system effectiveness estimations for several cycles of thermodynamics with a huge fluid library and an external heat exchange pricing indication. The tool interfaces with an industry-standard thermal exchanger choice programmer (SWEP SSPG7), which allows for component-by-component comprehensive computations, heat exchangers setup, inventory examinations, price comparisons, and the generation of three-dimensional models.

Overall, it can be stated from the review that it is critical field of research to design temperature compensator for reactors' HE designs.

PROPOSED METHODOLOGIES

Figure 4 presents the overall process of optimum temperature control process. Three types of feedback controls are expected to design thus initially type of control is initialized for transfer function (TF) calculation. Coefficients are optimized using optimization technique.

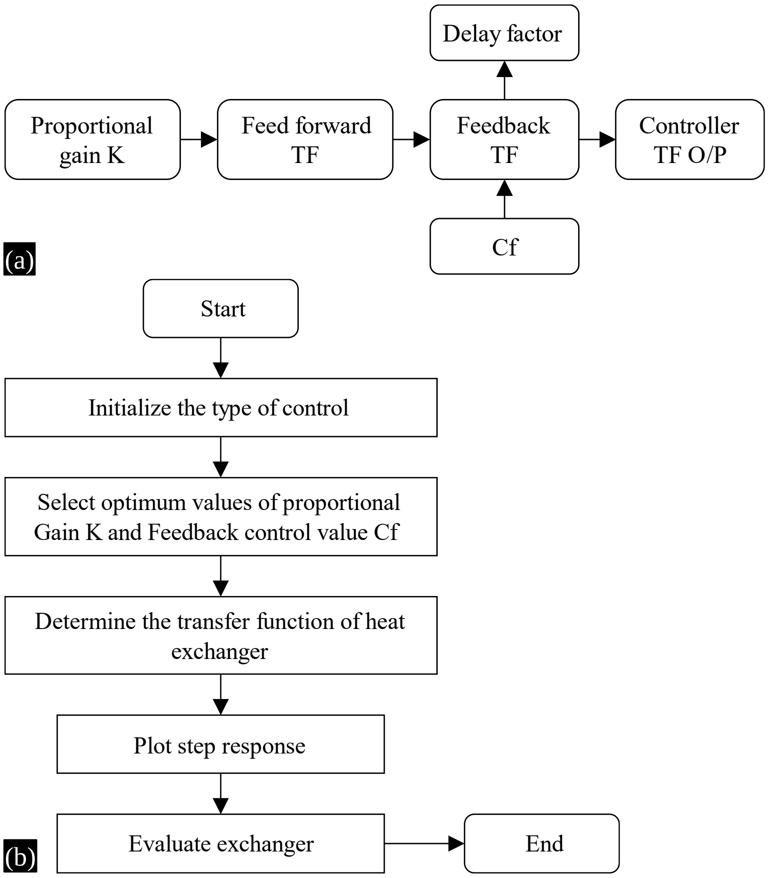

Figure 4. Flowchart of the design flow methodology: (a) proposed block diagram of temperature control and (b) design flow.

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Finally, the step response evaluation is performed for decision making. The proposed FF-FB based temperature compensator control technique is given in Figure 4(a). For performance evaluation, the transfer function of system is controlled by varying TF gain *k* and the delay *d* of the system.

EXPECTED RESULTS

The research in this paper is the proposed design of an efficient optimum temperature compensation based HE. In this section, the expected outcomes of the proposed research methodology are presented in two parts. In the first part, some of the expected results are described for achieved step response plots but under variable gain for the feedback control system of the HE. In the second part, basic temperature controller based steady state response plots are presented for the feedback control system. The results are also expected to evaluate for the stability of the system in terms of the pole zero analysis of the transfer functions.

Modeling and Simulation

The modeling and assimilation of the temperature control for the HE designs is proposed to implement in n MATLAB using the Simulink and soft computing–based analysis. The control system tool box and optimization tool box is used for the design and analysis.

The purpose of this temperature modeling was to see how the cost estimate changed over materials properties. The dynamic analysis for the HE provides data about how the processes responds to external disturbances [5]. Process modeling is primarily used to conduct computational methods in order to understand the system behavior, which aids in better control and optimization.

Outcomes of Step Response

To produce the first-order model, a step change as in solenoid valve voltage is performed, and the effect on temperatures is recorded as just a function of time. In Figure 5, the normalized mature response is shown. A diagram of a first-order-plus-dead-time (FOPDT) system will look like this.

Simply replacing in the following equation yields value of

$$\tau = \frac{3}{2}(\tau_2 - \tau_1) \quad (1)$$

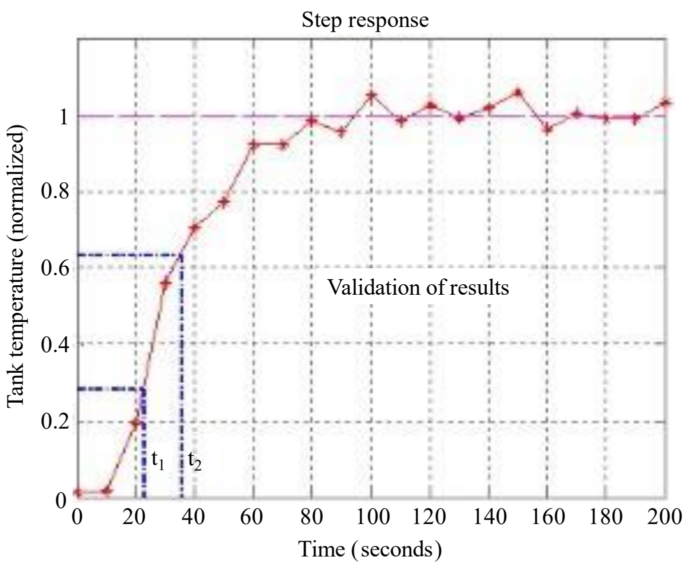

Figure 5. Validation results of the step response of the temperature controller.

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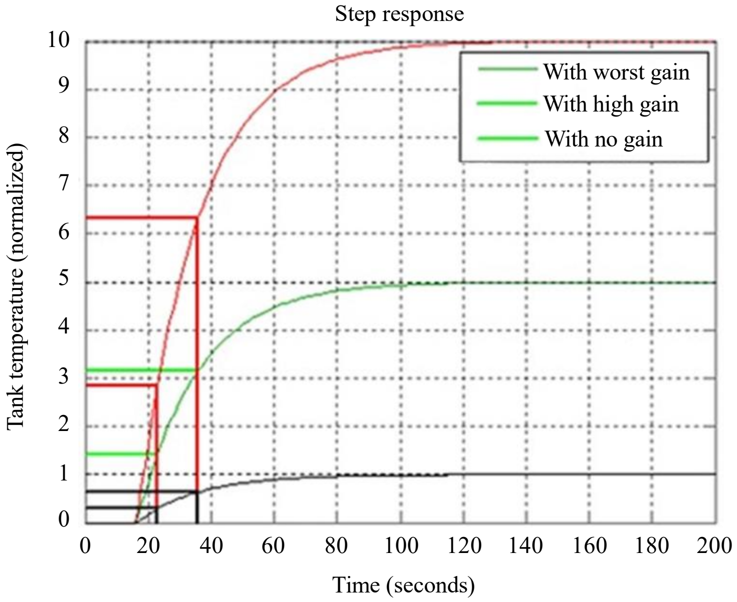

Figure 6. Impact of turbulence or higher gain on the step response of the system performance.

Table 1. Variation in open loop transfer function (TF).

Case	Gp	Gp2	Gp3
Variable tau	$G(s) = \frac{e^{-19.1s}}{16s+1}$	$G(s) = \frac{e^{-19.1s}}{21.3s+1}$	$(s) = \frac{e^{-19.1s}}{22.3s+1}$

Gp is the open loop gain.

The value of ε is determined by the following equation:

$$\varepsilon = \tau_2 - \tau \quad (2)$$

The transfer function (TF) is determined as follows:

$$G(s) = \frac{Ke^{-s}}{\tau s+1} \quad (3)$$

The model function and its parameters are also identified using the two-point method as shown in Figure 5. The determination of t1 and t2 points, which seem to be 28.3% and 60% of the system's ultimate responsiveness of peak response, respectively, is the basis for this methodology. In the proposed works it is expected to design the PI controller-based transfer function control for temperature control. The PI compensator is primarily used to mitigate the rise time impact.

The value of the TF gain *k* is varied from 1:5:10 ratios and the impact on the theta ε and τ are evaluated although assuming temperature compensator keeps the t1 and t2 constant. Results of impact of gain variation are illustrated in Figure 6. It is concluded that increasing gain *k* can also increase the t1 and t2 in same proportion and thus the slope of the curvet to. The TFs are shown in Table 1.

Outcomes of Temperatures Compensation

The expected outcomes of the temperature compensators using the feedback control-based HE system are validated and modeled using the MATAB software. The results of the delay input, output temperature and the control output are plotted for the feedback control system shown in Figure 7. The system is designed and validated for the unity feed forward system gain as equivalent to the basic feedback control system.

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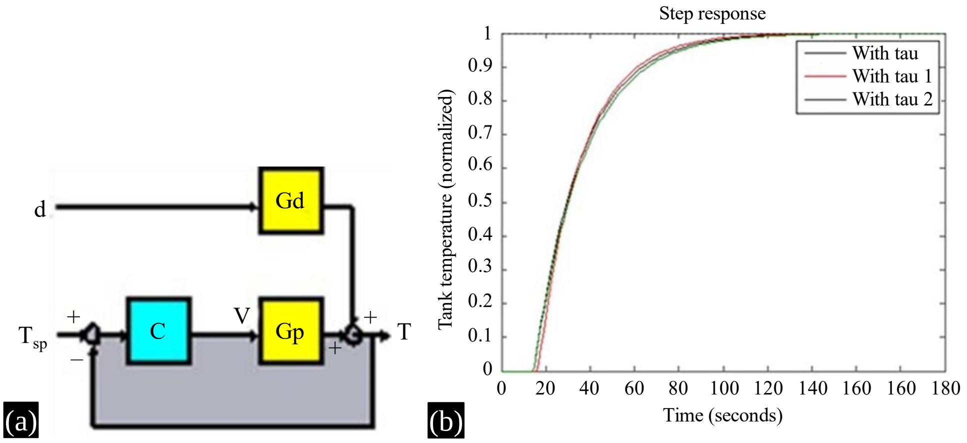

Figure 7. Result of step response for variable tau for transfer function (TF), Gp, and tank temperature for the feedback control system: (a) control system blocks: feedback control temperature control systems, (b) temperature results: step response.

Table 2. Qualitative parameters used for the validation of work.

S.N.	Parameters	Values
1.	Forward feedback gain	Is taken as unity for making system feedback control only
2.	Delay time	Set right now to 14.6
3.	Controller type	Feedback control type
4.	Peak over soot	Achieved for feedback control by around 12% to 15 %
5.	Settling time	For validation is around 70 s which is very high and needs to be minimized
6.	Feed forward delay	Set to 26 n this example validation

Table 3. Variation in value of tau.

Case	Gp	Gp2	Gp3
Variable tau	16	21.3	223

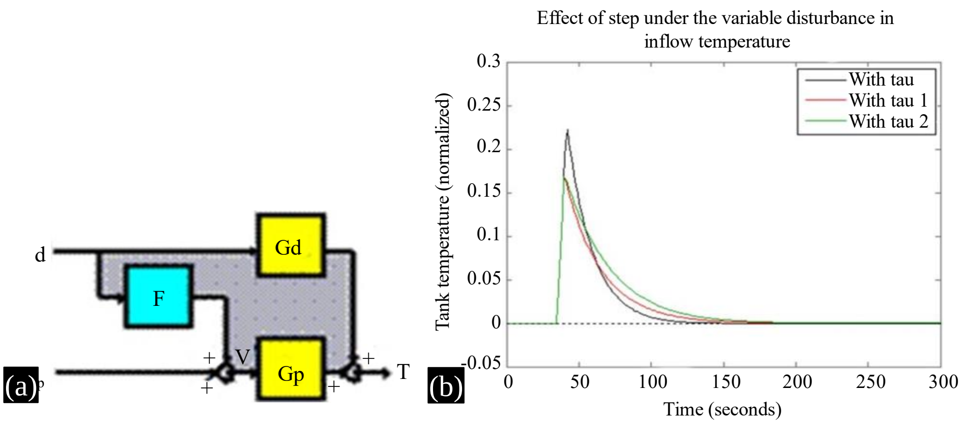

Figure 8. Expected response of the feed forward (FF) + feedback (FB) control cascade methodology: (a) feedback based FF controller and (b) step response comparison.

Gd and Gp = Gp2 = 21.3 and for another experiment Gp = Gp3 = 22.3 corresponds to the open loop gain system. Figure 7(b) presents the comparison of all the control inputs and outputs for the tank temperature. The basic control parameters used for result validation are shown in Table 2.

The variation in value of tau is shown in Table 3. It can be clearly seen that increasing the tau while keeping the theta constant means that controlling the slope of the system response may keep the system under damped state.

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The expected performance of the FF + FB based designs is presented in Figure 8. For the HE designs cascaded control based theirs may significantly reduction if rise time and settling time is observed but is having grate scope of improvement.

CONCLUSION AND FUTURE SCOPE

Temperature compensators have evolved as the essential part of all heat exchangers used in the mechanical process for heating or cooling purposes. This synopsis is primarily proposed focused on designing efficient soft computing methodologies for modeling the heat exchanger and control. The optimization technique-based temperature control and optimum parametric control is proposed to design the heat exchanger system. The additional contribution of work is to estimate the optimum cost of the heat exchanger.

It is proposed to compare the loop feedback controller, and the integrated combined approach provides a significant advantage. The soft computing methods are easy and suitable to control temperature and cost of heat exchanger system. The simulation and modeling of the heat exchanger system is proposed for chemical reactor process. MATLAB is used to model the system and fuzzy based soft computing rules will improve the design and cost estimation.

It is clear from the expected results presented that the basic idea is to minimize the rise time and the settling time along with steady state error of the controller system. Overall, it can be concluded that this might contribute to good design algorithms to improve existing heat exchanger designs.

Acknowledgments

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