Controller Design for Temperature Regulation in a Nonlinear Industrial Heat Exchanger System

Vakiti Srilatha Reddy[1]*, *Harivardhagini Subhadra*[2], S.Prananvanand[3] , A. Vimala *Juliet*[4] *Gopisetty Ramesh*[5]

[1,2,5]Department of EIE, CVR College of Engineering, Ibrahimpatnam, Telangana, India.
[3]Department of EIE, Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India
[4]Department of EIE, SRM Institute of Science and Technology, Kattankulathur, India

Abstract. A heat exchanger enables heat transfer between two fluids without mixing them. Its performance depends on factors like temperature difference, heat transfer area, and fluid flow rates. Heat exchangers are used in industries such as petroleum refining, food processing, nuclear power, thermal management in spacecraft, and electricity production. This study focuses on designing, modeling, and testing controllers for a nonlinear heat exchanger system. Initially, the baseline performance is evaluated, followed by an analysis of system behavior under various conditions. The transient response and error criteria of control strategies are assessed through setpoint tracking. MATLAB is used to implement the control algorithm, allowing real-time monitoring of the system's input and output for different setpoints. The controller adjusts to ensure optimal heat transfer and performance.

1 Overview

1.1 Introduction

Figure 1 illustrates heat exchangers, vital devices for transferring heat between two fluids while keeping them separated by a solid barrier to prevent direct contact. These systems, typically free from external heat or work interactions, are widely used across industries such as power generation, refrigeration, food processing, and aerospace. Heat exchangers are classified into direct transfer types (recuperators), which use a heat transfer surface to prevent fluid mixing, and indirect transfer types (regenerators), which allow continuous heat exchange but may encounter leakage due to pressure differences. Examples include shell-and-tube exchangers, condensers, and radiators. In sensible heat exchangers, fluids do not undergo phase changes, while some designs incorporate internal energy sources or facilitate chemical reactions. Standard components like cores, headers, and fins enhance heat transfer, with fins extending the surface area for better conduction. Advanced designs, such as heat pipe

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* Corresponding author : srilathareddy.cvr@gmail.com

exchangers, utilize evaporation and condensation, while direct-contact exchangers use the fluid interface as the heat transfer surface. These versatile systems are integral to applications in cryogenics, alternative energy, transportation, and manufacturing.
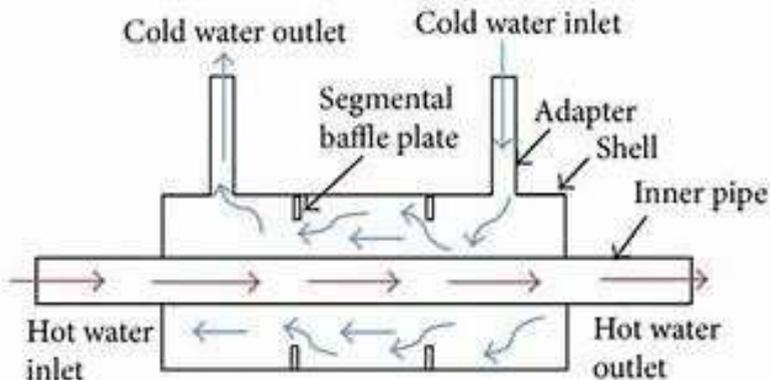

Fig. 1. Heat Exchanger

1.2 Objectives

The main objective of this project is to develop and implement a control system for a heat exchanger. This system is intended to manage the hot and cold outlet streams of the heat exchanger to reach the specified setpoint values. MATLAB software will be used to program the controllers, enabling real-time monitoring and control of temperature data. The heat exchanger will first be analyzed using a PID controller, and its performance will then be compared to that of a cascade controller to identify potential improvements.

1.3 Problem Statement

A feed-forward controller was implemented to address disturbances in the system, allowing for corrective actions to be taken before they impacted the process. The response to similar disturbances was monitored and compared to evaluate the effectiveness of the feed-forward controller. Measures were taken to prevent overheating, and the system was designed to maintain the desired temperature setpoint level despite process disturbances and environmental variations.

1.4 Motivation

Maintaining precise temperature control in heat exchangers is critical for optimal performance, efficiency, and safety across industries such as power generation, chemical manufacturing, and industrial processing. However, external disturbances and varying process conditions often pose challenges to achieving the desired temperature. To address this, the research work focuses on implementing advanced control strategies by integrating a feedforward controller with a PID controller, enhancing responsiveness and stability. MATLAB simulations and real-time monitoring will evaluate these strategies, offering insights into their effectiveness. This approach aims to improve temperature regulation, minimize disruptions, and optimize system performance, contributing to more reliable and efficient heat exchanger operations across various applications.

2   Literature Survey

S. Skogestad et.al paper explores the optimal tuning of PID controllers, focusing on achieving smooth control and effective disturbance rejection. It establishes a minimum limit for the controller gain, demonstrating that, when variables are appropriately scaled, a minimum gain of approximately 1 is sufficient. This threshold supports the commonly used default settings in industrial practice, ensuring that the PID controller operates effectively while balancing performance and stability[1].

V. R. Segovia et al. compare standard Feedback PID controllers with advanced Feedback plus Feedforward controllers for regulating outlet temperature in a shell and tube heat exchanger. A mathematical model based on experimental data is used to design and tune the controllers, addressing measurement noise with filtering techniques. The study highlights the benefits of integrating feedback with feedforward control and the importance of noise filtering for optimal performance[2]. Ang, Chong, and Li review modern PID control systems, highlighting advancements in functionality and tuning through patents, software tools, and hardware. They discuss how system identification and intelligent techniques in software-driven PID systems automate design and tuning, enabling efficient and precise controller configurations. The study showcases how these innovations enhance PID performance and adaptability, fostering robust control solutions[3].

Mudi and Pal present an innovative self-tuning scheme for PI (Proportional-Integral) and PD (Proportional-Derivative) fuzzy controllers. This approach is distinguished by its simplicity and its applicability across various control scenarios, as it does not rely on specific system models. The self-tuning mechanism adjusts the parameters of the fuzzy logic controller in real-time, enhancing performance without necessitating an in-depth understanding of the controlled system[4]. This model-independent characteristic enables the fuzzy controllers to adapt effectively to changing conditions and uncertainties, thereby increasing their robustness and reliability. The paper outlines the methodology for implementing this self-tuning process and illustrates its effectiveness through a series of simulations and practical examples, highlighting its capability to enhance control accuracy and stability in a range of applications.

Carmona Morales et al. assess the effectiveness of different controllers, including Feedback, Feedback plus feedforward, and Internal Model Controllers (IMC), for managing the outlet temperature of a shell and tube heat exchanger. They analyze these controllers based on their ability to maintain the target temperature. Additionally, the paper presents an educational tool that employs evolutionary strategies for optimal tuning of controllers. This tool showcases how evolutionary algorithms can enhance the design and adjustment processes, leading to improved performance in temperature regulation tasks[5][6][7].

3 Implementation

3.1 Temperature Control System Overview

Fig 2 is a Temperature Control System maintains an environment or object's temperature at a desired level through a feedback loop involving sensors, control algorithms, and actuators. Unlike fixed thermostats, modern systems dynamically adjust temperature settings to optimize energy use and reduce costs. Key components include programmable digital controllers and heating or cooling units that act based on the controller's commands. Programmable

thermostats, a significant advancement, can adjust settings based on time and occupancy, enhancing efficiency and lowering energy bills. A Temperature Control System is a small programmable device, similar in size to a wall-mounted thermostat, that controls heating or cooling units to maintain a desired temperature (set point). It uses a circuit board and memory chips to regulate the system, adjusting as needed to keep the temperature consistent.
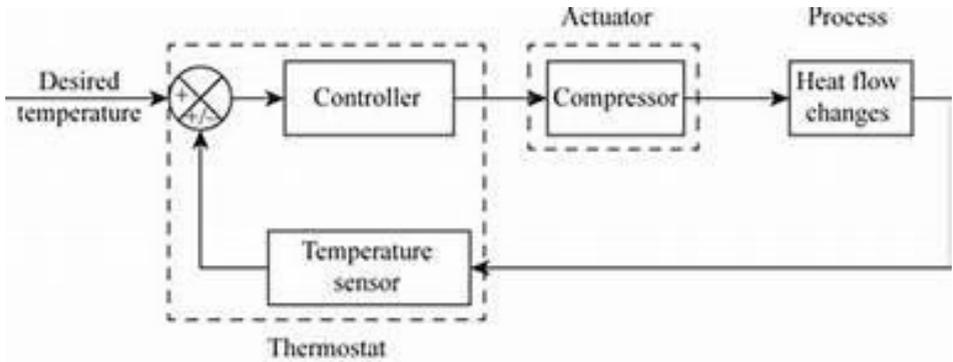

Fig. 2. Block Diagram of the Temperature control System

3.2 Shell and Heat exchanger

Fig 3 illustrates a Shell and Tube Heat Exchanger, which consists of a collection of round tubes housed within a cylindrical shell, with the axes of the tubes aligned parallel to the shell. One fluid flows through the tubes, while a different fluid circulates around them. The main components of this heat exchanger include the shell, tube bundle, front and rear headers, and baffles. Baffles support the tubes and redirect the fluid flow, enhancing turbulence and improving heat transfer efficiency. The design of the baffles covering aspects such as type, spacing, and shape is influenced by factors like flow rate, pressure drops on the shell side, the need for tube support, and potential vibrations caused by fluid flow.
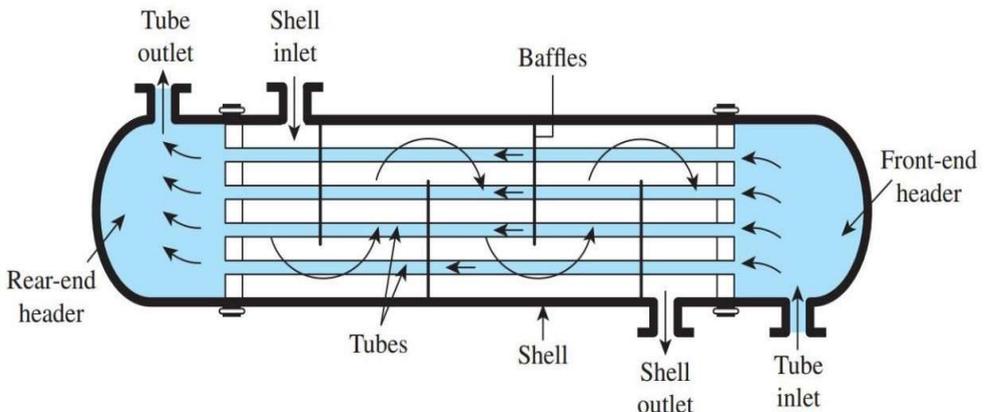

Fig. 3. Shell and Tube Heat Exchanger.

3.3 PID Controller

Figure 4 presents a block diagram of a closed-loop system, such as a PID controller, which uses feedback to regulate system output. By comparing the feedback variable to a set point, it generates an error signal to adjust the output until the error is minimized and the feedback matches the set point. Unlike an ON/OFF controller, which alternates between two states and causes fluctuations around the target value, a PID controller provides precise and stable control by continuously refining the output to reduce error.

An ideal PID controller can be represented by the following equation (1):
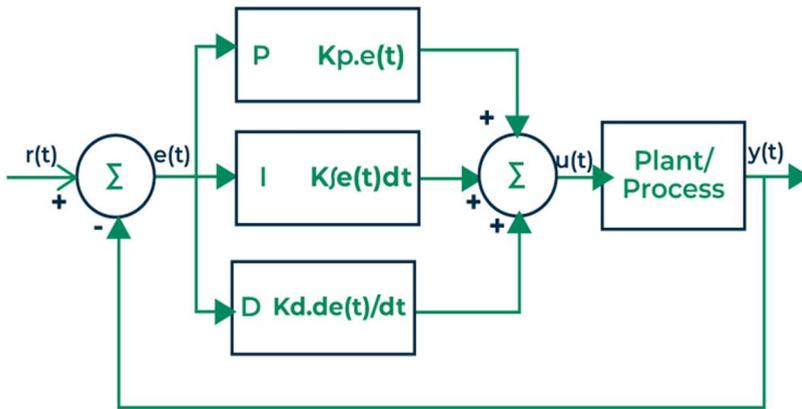$G_{c(s)} = K_c (1 + 1 / \tau_{is} + \tau_{ds}) \rightarrow 1$

Fig.4. Block diagram of PID Controller

Where Kc is the proportional gain, τi is the integral time, and τd is the derivative time. While low-cost ON/OFF controllers are sufficient for applications requiring only two states fully on or off their oscillating behavior limits their effectiveness in more complex systems. For this reason, PID controllers, which maintain the output with zero error between the process variable and the setpoint through closed-loop control, have largely replaced ON/OFF controllers. A PID controller operates using three key control actions: proportional, integral, and derivative control.

Fig 5 displays the block diagram of a feedback plus feed-forward controller. In this configuration, flow disturbances are either measured or estimated, allowing the feed-forward compensator to address these disturbances. The control signals generated by both the feedback and feed-forward controllers are then combined and applied to the process.

3.5 Flow chart

Fig 6 shows the experimental setup consisting of a reservoir tank, two process tanks, pneumatic control valves, pumps, I/P converters, thermocouple sensors, heat exchanger, heaters, differential pressure transmitter (DPT), rotameters, and a DAQ card. Water from the storage tank is pumped to process tank 1, with cold water flowing to the heat exchanger through control valve 1 and rotameter 2. Temperature is monitored by thermocouple sensor 3. Process tank 2

maintains a temperature of 70-80°C, with hot water flowing to the heat exchanger through control valve 2 and rotameter 4. Signals from thermocouples and DPT are processed and interfaced with MATLAB, which controls the valves via a V/I and I/P converter system for flow regulation.
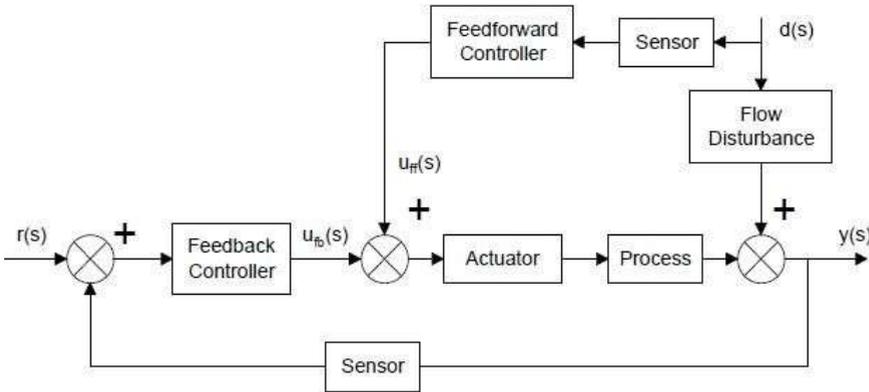

Fig. 5. Block diagram of Feedback plus Feed-forward control loop

The PID control algorithm is implemented in MATLAB, where the plant's input and output are monitored for various set point values. The controller adjusts its response based on the set point and the process variable. The resulting output from the controller is then directed to the final control element.
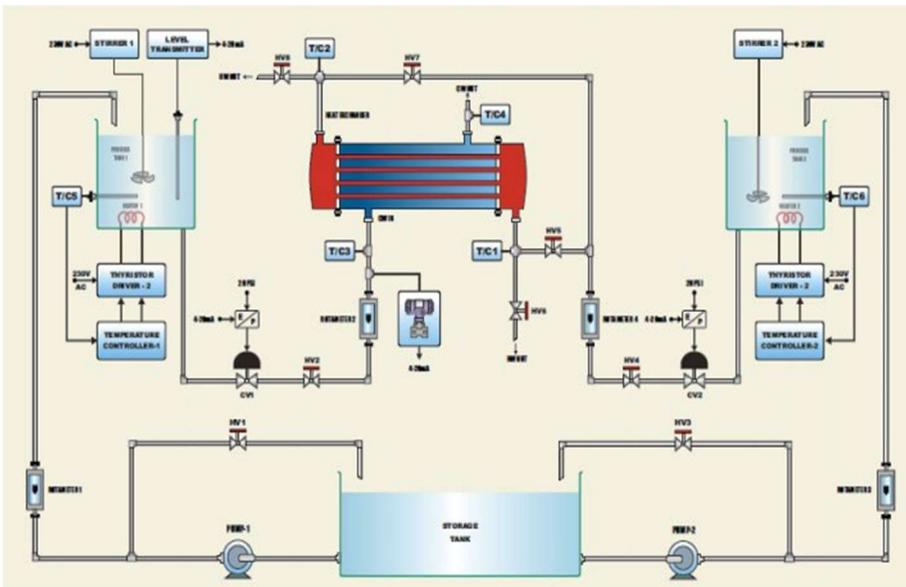

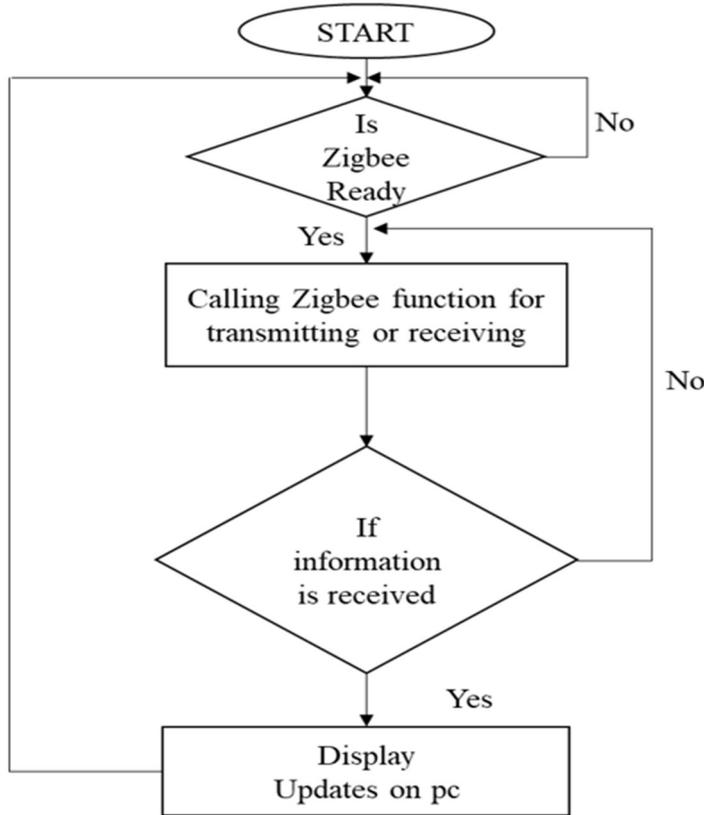**Fig. 6.** Flow chart for underground section (Transmitter).

Fig. 7. Flow chart of ground section (Receiver)

3.5. Modeling and Simulation

3.5.1. Mathematical Model

This section discusses using various controllers to regulate the temperature of a shell and tube heat exchanger system, with simulated studies evaluating their performance. While conventional controllers were used initially, intelligent controllers showed significantly improved results. The next section provides a detailed analysis of the intelligent controller using MATLAB, high lighting the need for practical and analytical testing[8][9].

To design a controller, it is essential to establish an accurate mathematical model of the process. Many industrial systems are inherently non-linear and can be approximated using first-order plus time delay (FOPTD) or second-order plus time delay (SOPTD) models.

The model was determined to be first order plus time delay (FOPDT) following the open loop system test. The time delay has been estimated using Zeigler-Nichols 2-point approach. The time constant and process time delay is determined as $\tau = 1.5 \, (t2\text{-}t1)$ and $td = t2 - \tau$, respectively, using the time constants t1 and t2, which correspond to reaching 28.3% and 63.2% of the final steady-state value. According to the formula, change in output variable/manipulated variable change $(\Delta yss) / \Delta x = 0.505$, Kp is the ratio of change in output steady state value to change induced in the manipulated variable. The final FOPDT model can be expressed in equation (2) as follows once the values have been substituted:

$$G(s) = \frac{K_p e^{-\tau s}}{\tau s+} \rightarrow 2 \quad \text{where} \quad K_p = \frac{\Delta y_{ss}}{\Delta x} \,, \tau = 1.5(t_2 - t_1)$$

4 Results

Case (i) : Design and Implementation of Feedback PID controller in MATLAB
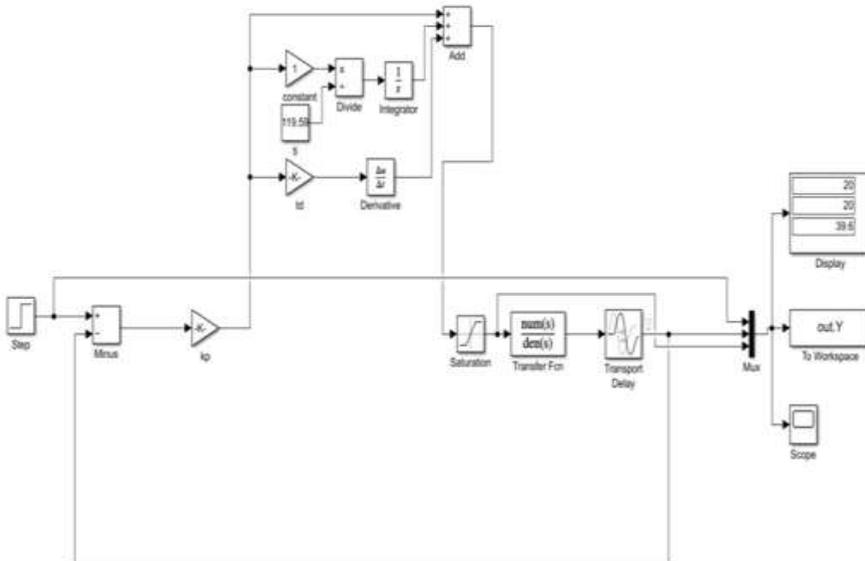

Fig. 8. Simulink program for System (PID).

Fig 8 illustrates a traditional PID controller that is adjusted using the Ziegler-Nichols method to regulate the heat exchanger's output temperature. Below is a demonstration of the feedback controller's set point tracking and disturbance rejection capabilities. Because of its zero steady-state error, quick reaction, lack of oscillations, excellent stability, and capacity to remove overshoot, this approach is preferred.

In many process control applications, the ability to reject disturbances is often more critical than merely tracking set points. To address this, modified PID controllers, known as disturbance rejection PID controllers, have been developed to enhance control performance, under the assumption that the plant model is precisely known.

The feedback PID controller exhibits a 35% overshoot and a settling time of 830 seconds.

Case (ii): MATLAB SIMULINK Program for PID Controller -   with disturbance applied

Fig 8 is a PID controller is designed and implemented in MATLAB Simulink to regulate the output temperature of a nonlinear industrial heat exchanger system. The controller's performance is evaluated under disturbance conditions, showcasing its ability to maintain stability and reject disturbances effectively. Simulation results demonstrate precise set point tracking and enhanced system response.
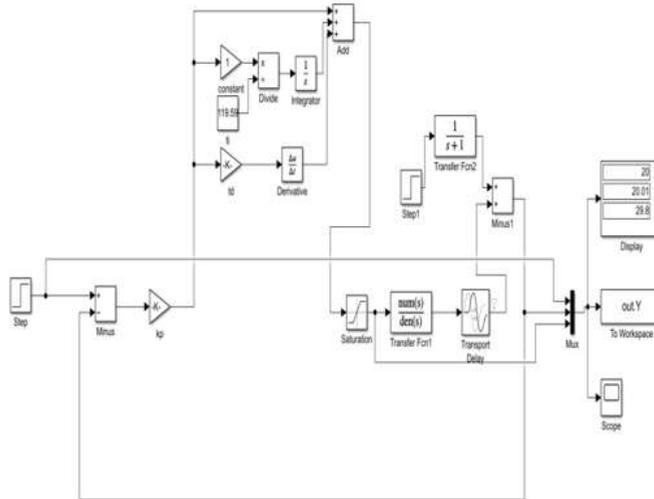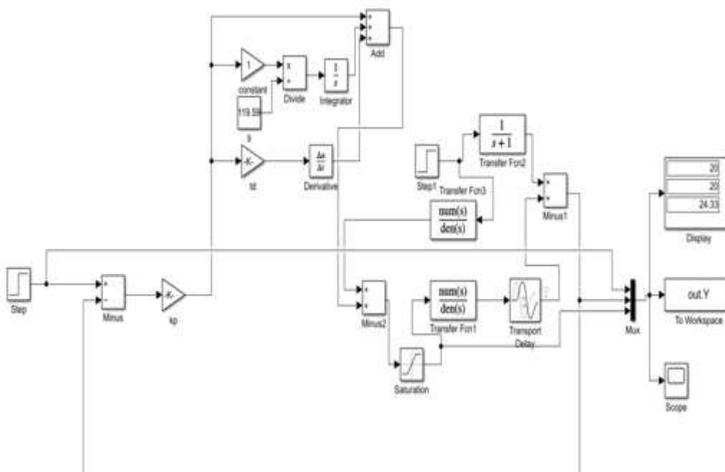
Fig.9. Temperature Control PID controller with Disturbance

Case (iii) : Design & Implementation of Feedback plus Feed-Forward Controller in Matlab

Reduce high overshoot from the classical PID controller, a feed-forward controller was integrated with the feedback controller, effectively minimizing overshoot. Feedforward control uses a system model to directly adjust the target parameter without relying on measurements. While it can eliminate the need for feedback, unpredictable disturbances may affect performance. Measuring these disturbances can improve the model and enhance feedforward control's effectiveness.

Fig.10.

Simulink

program

for

System.

(Feedback + Feed-Forward)

The primary goal was to design and implement a control system for a heat exchanger to regulate the hot and cold outlet streams to meet specified setpoints. MATLAB was used to program the controllers, facilitating real-time monitoring and control of temperature data. The heat exchanger's performance was analyzed using a PID controller and later compared with a cascade controller to assess enhancements in system behavior. The transient response, including peak

overshoot and settling time, for both the feedback and feedback plus feed-forward controllers is detailed in Table 9.1, illustrating the comparative effectiveness of each control strategy.

Table 1. Readings of Transient response of the controller

Controller	Overshoot (%)	Settling time (Sec)
Feedback PID	35	830
Feedback plus feed-forward	33.4	807

5 Conclusion

Various control strategies, including feedback and feedback plus feed-forward controllers, were implemented to regulate the outlet temperature of a shell and tube heat exchanger system. A mathematical model of the heat exchanger was developed from experimental data, which was then utilized to design the corresponding controllers. The performance of these controllers was evaluated based on transient characteristics. Simulation results show that the feedback plus feed-forward controller outperforms the feedback controller. The classical PID-based feedback controller exhibited greater overshoot and longer settling time, while the feedback plus feed-forward controller demonstrated more controlled overshoot and quicker settling time.

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