International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I6P117

Volume 72 Issue 6, 159-169, June 2024

Original Article

Exploring the Novel Design and Control of Shell and Tube-in-Tube Heat Exchanger

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Received: 03 February 2024 Revised: 14 May 2024 Accepted: 18 May 2024 Published: 29 June 2024

Abstract - *The Shell and Tube-in-Tube (S&TinT) heat exchanger is a superior solution compared to conventional counterparts, boasting an innovative design that includes three heat-transfer elements for three fluid paths. This paper initially addresses the challenges in traditional heat exchanger designs and further, considering the drawbacks, a novel design of S&TinT heat exchanger is proposed, which provides dynamic control over heat transfer performance, facilitating rapid changes to meet specific operational requirements. Multiple advantages make the S&TinT heat exchanger a promising solution for industries demanding high efficiency and adaptability in their heat transfer processes. Secondly, the Logarithmic Mean Temperature Difference (LMTD) algorithm was chosen to calculate the necessary parameters, which modified the standard LMTD algorithm to accommodate heat transfer dynamics between the three fluids. The modified LMTD algorithm ensures the accuracy of the design process and contributes to a deeper understanding of the complex heat transfer mechanisms in multi-fluid systems. Finally, Controlling the parameters of the designed S&TinT heat exchanger is performed by a Model Predictive Controller (MPC) as it can handle multi-input, multi-output systems. Along with this, a comparative analysis with a conventional Proportional-Integral-Derivative (PID) controller is studied and it reveals considerable insights. The error analysis further confirms the superior performance of the MPC controller, establishing it as an effective and effective control technique for advanced heat transfer systems such as the S&TinT heat exchanger.*

Keywords − *Heat exchanger, CAD, S&TinT, LMTD, MPC.*

1. Introduction

The heat exchanger is a device that transfers heat energy among fluids by the convention, conduction, and radiation modes of heat transfer through a solid medium [1]. Single-phase or one-phase heat exchangers are used to transfer the heat among one phase, like liquid or gas. The heat exchanger used to generate steam from water or produce liquid from gas is called two-phase heat exchangers [2]. S&T HE consists of a bundle of tubes inside a shell. In this type of heat exchanger, a fluid flows over the tube bundle, and another fluid flows through the tubes of the tube bundle, promoting the heat exchange between shell fluid and tube fluid [3].

In heat exchanger design, one of the noticeable types is the S&T heat exchanger [4]. Also, S&T heat exchangers have a wide range of high-pressure applications like oil refineries, food processing units, power generation plants, refrigeration and air conditioning systems [5]. Based on application and customer design, the Tube bundle configuration may differ. To increase the heat transfer rate of a heat exchanger, some extra surfaces called fins can be added in various geometries according to the application [6]. Another simple structured heat exchanger is Tube in Tube heat exchanger. Tube in Tube heat exchanger is designed whereby one tube is centrally located within a large tube [7]. The S&TinT heat exchanger has a combinational structure of S&T heat exchanger and Tube in Tube heat exchanger. S&TinT heat exchangers are mainly used to transfer heat between different mediums. They can also recover heat from a hot fluid and utilize it to warm up a cold fluid entering a hot process system.

These heat exchangers find applications in a wide range of industrial processes, such as oil refining, preheating and cooling, steam generation, heat recovery in boilers, vapor recovery systems, and industrial cooling processes where smaller heat transfer areas are required.

The focus of the S&TinT is to support the societal needs of heat transfer. Industries like oil and gas industries or thermal power plants can use S&TinT to transfer the thermal energy from the process fluids to process it. The consumption of water is reduced in the S&TinT by reducing the flow rate of heat-absorbing liquids to increase efficiency. With this, The S&TinT will have its good impacts on society indirectly.

2. Scope and Novelty

S&TinT Heat Exchanger is totally modified in the step of design and it is different from the conventional heat exchanging devices. The complete structure of S&TinT gives an advanced level of heat transfer among fluids. Since S&TinT is utilizing three fluids the possible way of heat transfer is increased in it.

There are eight combinations of heat transfer are possible in S&TinT. Liquid-Liquid-Liquid, Liquid-Liquid-Gas, Liquid-Gas-Liquid, Liquid-Gas-Gas, Gas-Liquid-Liquid, Gas-Liquid-Gas, Gas-Gas-Liquid and Gas-Gas-Gas are the possible combinations of fluids that can be used in S&TinT.

The first fluid is pouring over the Tubes that carry the second fluid, and the third liquid is flowing through the tubes that are inserted in the second fluid's tubes. With this novel structure, the temperature of the second fluid can be increased or decreased in a short time by changing the flow direction, flow rate and heat of the first and third fluids. Increasing the speed of the heat-transfer agent flowing through the heat exchanger tubes leads to a higher heat transfer efficiency, which is reflected in the heat-transfer coefficient on the tube side of the exchanger.

Therefore, in addition to single-pass shell-and-tube heat exchangers, multi-pass heat exchangers with two, four, or six passes are used. These multi-pass exchangers have the same number of tubes but the velocity of the heat-transfer agent is increased two, four, and six times, respectively. The S&TinT is designed with three heat-transferring elements; in the case of conventional heat exchangers, it is two. The three fluid's paths are designed in cross-flow configuration to increase the heat transfer rate. These elements will overcome the existing problems available in the design of conventional heat exchangers.

3. Computer-Aided Design of S&TinT

S&TinT heat exchanger is a specialized heat transfer device, and it is used to transfer thermal energy between three fluid (two cold fluids + one hot fluid) domains in three different temperatures. The S&TinT heat exchanger consists of three water inlets and three water outlets. The design of the S&TinT heat exchanger is illustrated in the figure. Since S&TinT is working with three fluids, the full design is split into three fluid domains (domain of cold fluid 1, domain of hot fluid and domain of cold fluid 2).

Domain of cold fluid 1 consists of 9 copper tubes that are going to carry the first cold fluid inside the hot fluid. Since the diameter of these inner tubes is less, a small amount of cold liquid only can flow through them. Specifically, copper pipes are chosen as they as higher thermal conduction properties compared to other thermal conductors. Due to this large amount of heat conduction is observed even when a small amount of cold fluid flows through the inner tubes.

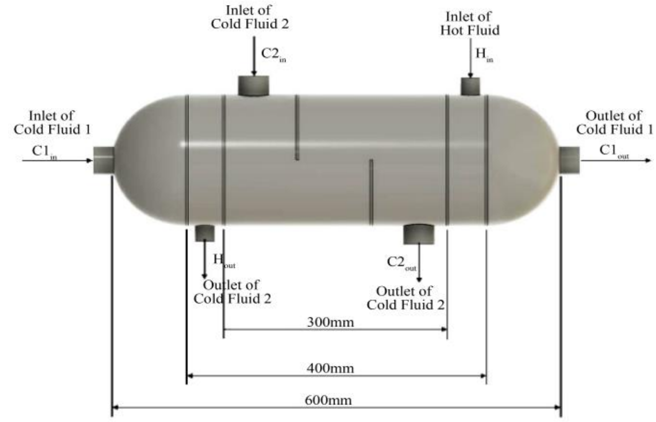

Fig. 1 Structure of S&TinT heat exchanger with fluid inlets and outlet details

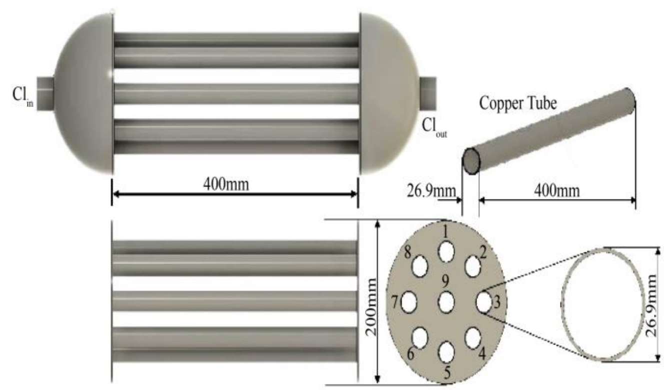

Fig. 2 Domain of cold fluid 1 with its dimensions

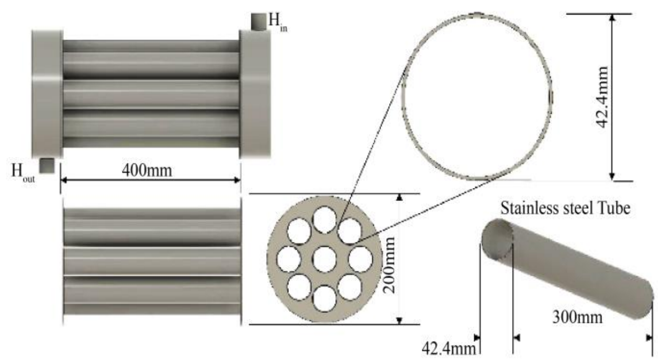

Fig. 3 Domain of hot fluid with its dimensions

Similarly, 9 tubes were introduced to the hot fluid domain but varied in length, diameter, and material. Since the inner tubes are arranged to pass into the intermediate tubes, the length of the intermediate tubes is less, whereas the diameter is greater than that of the inner tubes.Also, two baffles are designed and fixed to hold the intermediate tube bundle. These baffles are used to interrupt the flow of fluid flow in the shell which helps to increase the efficiency of the device. Cold fluid 2 is made to pass around the intermediate tubes. So, the amount of fluid in the shell is very high when compared with the amount of fluid that flows through the inner and Intermediate tubes.

Table 1. Design specifications of S&TinT heat exchanger

Parts	Materials	Sizes
Diameter of Cold Fluid 1's Inlet and Outlet	SS	42.4 mm
Diameter of Cold Fluid 2's Inlet and Outlet	SS	42.4 mm
Diameter of Hot Fluid's Inlet and Outlet	SS	26.9 mm
Number of Tubes carries Cold Fluid 1	Copper	9
Number of Tubes carries Hot Fluid	SS	9
Diameter of Tubes carries Cold Fluid 1	Copper	26.9 mm
Diameter of Tubes carries Hot Fluid	SS	42.4 mm
Length of Tubes carries Cold Fluid 1	Copper	400 mm
Length of Tubes carries Hot Fluid	SS	300 mm
Length of Shell	SS	300 mm
Number of Baffles	SS	2

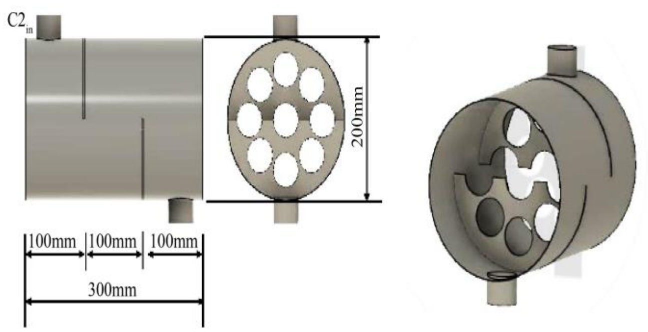

Fig. 4 Domain of cold fluid 2 with its dimensions

The nominal amount of heat will be transmitted from the hot fluid to the shell (cold fluid 2) fluid. By considering these factors, the material of the intermediate tube is chosen as stainless steel. In general, counter-current flow gives great heat transfer compared to co-current flow in heat transfer problems. To have a counter-current flow among the fluids, the inlets and outlets are arranged in such a way that the cold fluid will flow from the left to right direction and the hot fluid will flow from the right to left direction.

4. Mathematical Modelling

The mathematical model optimizes the system dynamics through specific formulas that require the calculation of parameters based on knowledge obtained from the type of system used and the nature of the plant [8]. Effective modeling requires a prior understanding of the basic system outline. The heat balance equation of the S&TinT heat exchanger is derived using the physics of the designed system. Since the S&TinT heat exchanger is transferring heat between three

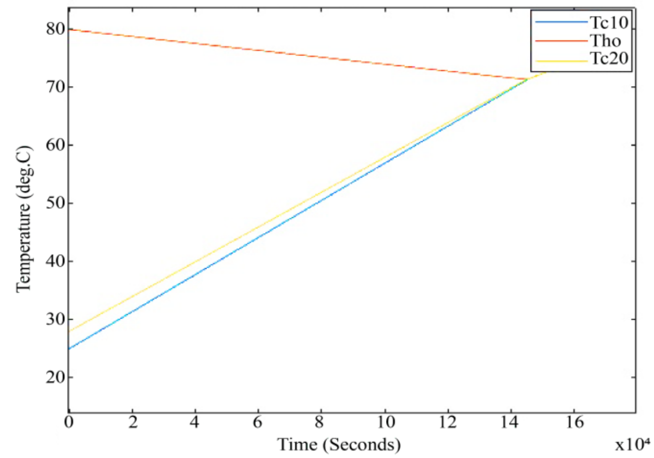

Fig. 5 Temperature Responses of S&TinT heat exchanger model

fluids, the thermal interaction between three fluids is derived as three heat balance equations with reference to the conventional heat exchangers.

$$T_{oc1}^{\cdot}(t) = \frac{F_{c1}}{\rho_{c1}V_{c1}\left(T_{oc1}(t) - T_{ic1}(t)\right)} + \frac{U_{c1}A_{c1}}{\rho_{c1}V_{c1}C_{pc1}\left(T_{oh}(t) - T_{oc1}(t)\right)} \tag{1}$$

$$T_{oc2}^{\cdot}(t) = \frac{F_{c2}}{\rho_{c2}V_{c2}\left(T_{oc2}(t) - T_{ic2}(t)\right)} + \frac{U_{c2}A_{c2}}{\rho_{c2}V_{c2}C_{pc2}\left(T_{oh}(t) - T_{oc2}(t)\right)} \tag{2}$$

$$T_{oh}^{\cdot}(t) = \frac{F_h}{\rho_h V_h\left(T_{oh}(t) - T_{ih}(t)\right)} + \frac{U_h A_h}{\rho_h V_h C_{ph}\left(\left(T_{oc1}(t) + T_{oc2}(t)\right) - T_{oh}(t)\right)} \tag{3}$$

The response of the heat balance equation is given in Figure 5. For the ideal conditions, the temperature of the hot fluid is actually reaching the equilibrium point with the cold fluid temperature. After reaching the equlibirum point, the temperature of the three fluids is trying to be constant. Where "T_{c1o}" and "T_{c2o}" are the outlet temperature values of cold fluid 1 and cold fluid 2, respectively. Also, "T_{ho}" is the outlet temperature value of the hot fluid. The necessary parameters in the heat balance equations are calculated using the modified Logarithmic Mean Temperature Difference algorithm (LMTD) [9].

5. Modified LMTD Algorithm

Heat exchanger geometry, overall heat transfer coefficient, inlet-outlet temperatures, and the rate of heat transfer are directly related to heat exchanger design [10]. To design the S&TinT heat exchanger LMTD algorithm is chosen. However, the challenge is to modify the LMTD algorithm to find the heat transfer between the three fluids. Because the standard LMTD algorithm is formulated for calculating the heat transfer rate between two fluids only [11]. In S&TinT heat exchangers, temperature is going to spread between three fluids. The modification in the LMTD algorithm for counterflow direction is given below.

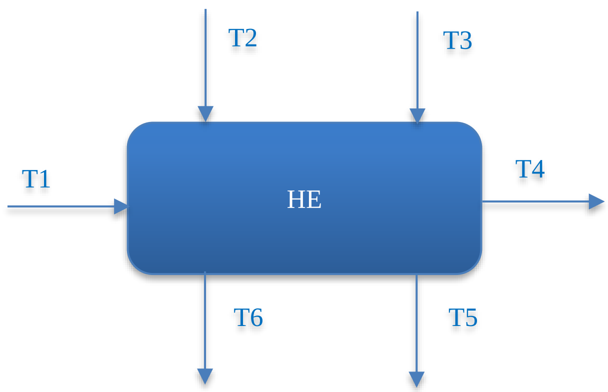

Fig. 6 Simple structure of three fluid heat exchangers

Step 1: For Counter Flow, calculate the ΔT_{LM} using mean temperature differences (ΔT_1 & ΔT_2) [12]. Whereas, ΔT_1 is the temperature difference between the inlet of hot liquid and the outlet of cold fluids on average. ΔT_2 is the temperature difference between an outlet of hot liquid and an inlet of cold fluids on average.

$$\Delta T_1 = T_3 - \left(\frac{T_4 + T_5}{2}\right)$$
$$\Delta T_2 = T_6 - \left(\frac{T_1 + T_2}{2}\right)$$
$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (4)$$

Step 2: Calculate the area of heat transfer using the physical dimensions of S&TinT. In conventional shell and tube heat exchangers, heat transfer is happening through tube walls only. So, the heat transfer area is common for both the cold fluid domain and the hot fluid domain.

In the case of S&TinT, heat transfer takes place in copper tube walls and stainless-steel tube walls. The stainless-steel tube diameter is reduced because of the copper tube arrangement. Three different heat transfer area calculations are formulated to find the appropriate heat transfer area of inner tubes, intermediate tubes, and the shell of S&TinT.

(a) Heat Transfer Area of Inner Tubes

$$d_{in} = 0.5(d_{i\,in} + d_{o\,in})$$
$$L_{in} = n_{in} l_{in}$$
$$A_{in} = \pi\, d_{in}\, L_{in}$$

(b) Heat Transfer Area of Intermediate Tubes

$$d_{im} = 0.5\big(d_{i\,im} + d_{o\,im} - (d_{i\,in} + d_{o\,in})\big)$$
$$L_{im} = n_{im}\, l_{im}$$
$$A_{im} = \pi\, d_{im}\, L_{im}$$

(c) Heat Transfer Area of Shell:

$$d_s = 0.5(d_{i\,im} + d_{o\,im})$$
$$L_s = n_{im}\, l_{im}$$
$$A_s = \pi\, d_s\, L_s$$

Step 3: One of the unknown process variables, like the flow or temperature of one stream, can be calculated by using the energy balance equations [13-15].

With constant specific heat capacity without any phase change is taken into the count. Also, the heat transfer rate of a stream is directly proportional to the thermal difference between the outlet and inlet of the stream. Since S&TinT is working with three streams, the heat transfer rate should be calculated for the three streams.

(a) Heat Transfer Rate in Inner Tubes

$$Q_{c1} = q_{m\,c1}\, C_p\, (T_4 - T_1) \quad (5)$$
$$q_{m\,c1} = q_{v\,c1} \times \rho$$
$$q_{v\,c1} = F_{c1} \times (1.667 \times 10^{-5})$$

(b) Heat Transfer Rate in Intermediate Tubes

$$Q_h = q_{m\,h}\, C_p\, (T_3 - T_6) \quad (6)$$
$$q_{m\,h} = q_{v\,h} \times \rho$$
$$q_{v\,h} = F_h \times (1.667 \times 10^{-5})$$

(c) Heat Transfer Rate in Shell

$$Q_{c2} = q_{m\,c2}\, C_p\, (T_5 - T_2) \quad (7)$$
$$q_{m\,c2} = q_{v\,c2} \times \rho$$
$$q_{v\,c2} = F_{c2} \times (1.667 \times 10^{-5})$$

Step 4: Calculate the heat transfer coefficient for the three different streams by using the below expressions.

$$U_{c1} = \frac{Q_{c1}}{A_{in}\Delta T_{LM}} \quad (8)$$

$$U_h = \frac{Q_h}{A_{im}\Delta T_{LM}} \quad (9)$$

$$U_{c2} = \frac{Q_{c2}}{A_s\Delta T_{LM}} \quad (10)$$

Initial Conditions

T1-Inlet Temperature of Cold Fluid 1 : 25 ºC
T2-Inlet Temperature of Cold Fluid 2 : 28 ºC
T3-Inlet Temperature of Hot Fluid : 80 ºC
T4-Outlet Temperature of Cold Fluid 1 : 40 ºC
T5-Outlet Temperature of Cold Fluid 2 : 35 ºC
T6-Outlet Temperature of Hot Fluid : 50 ºC
Constant Flow Rate of three fluids : 25 kg/s

The heat transfer coefficient for three fluid domains is calculated with specific initial conditions and constraints using the formulated modified LMTD, and the values of those parameters are given in the below table.

Table 2. Symbols used in modified LMTD and its expansion with units

Symbol	Expansion	Unit
T_1	Inlet Temperature of Cold Fluid 1	ºC
T_2	Inlet Temperature of Cold Fluid 2	ºC
T_3	Inlet Temperature of Hot Fluid	ºC
T_4	Outlet Temperature of Cold Fluid 1	ºC
T_5	T5-Outlet Temperature of Cold Fluid 2	ºC
T_6	T6-Outlet Temperature of Hot Fluid	ºC
ΔT_{LM}	Logarithmic Mean Temperature Difference	ºC
$d_{i\ in}$	Inner diameter of the inner tube	m
$d_{o\ in}$	Outer diameter of the inner tube	m
d_{in}	Diameter of inner Tube	m
$d_{i\ im}$	Inner diameter of intermediate tube	m
$d_{o\ im}$	Outer diameter of intermediate tube	m
d_{im}	Diameter of intermediate tube	m
l_{in}	Length of Single inner tube	m
n_{in}	Number of inner tubes	-
L_{in}	Overall length of inner tubes	m
l_{im}	Length of Single intermediate tube	m
n_{im}	Number of intermediate tubes	-
L_{im}	Overall length of intermediate tubes	m
A_{in}	Heat transfer area of inner tubes	m^2
A_{im}	Heat transfer area of intermediate tubes	m^2
A_s	Heat transfer area of shell	m^2
F_{c1}	Flow rate of cold fluid 1	m^3 / s
$q_{v\ c1}$	Volumetric flow rate of cold fluid 1	m^3 / s
$q_{m\ c1}$	Mass flow rate of cold fluid 1	kg / s
Q_{c1}	Heat transfer rate of cold fluid 1	J/s (or) W
F_h	Flow rate of hot fluid	m^3 / s
$q_{v\ h}$	Volumetric flow rate of hot fluid	m^3 / s
$q_{m\ h}$	Mass flow rate of hot fluid	kg / s
Q_h	Heat transfer rate of hot fluid	J/s (or) W
F_{c2}	Flow rate of cold fluid 2	m^3 / s
$q_{v\ c2}$	Volumetric flow rate of cold fluid 2	m^3 / s
$q_{m\ c2}$	Mass flow rate of cold fluid 2	kg / s
Q_{c2}	Heat transfer rate of cold fluid 2	J/s (or) W
C_p	Specific heat capacity	J/(kg·°C)
ρ	Density	kg/m^3
U_{c1}	Heat transfer coefficient of cold fluid 1	W/(kg·°C)
U_h	Heat transfer coefficient of hot fluid	W/(kg·°C)
U_{c2}	Heat transfer coefficient of cold fluid 2	W/(kg·°C)

Table 3. Heat transfer dynamics of three fluids

Fluid Domain	ΔT_{LM} (°C)	A (m^2)	Q (W)	U (W/m^2 K)
Cold Fluid 1	32.0673	0.29292	26.25525	2.7951264
Hot Fluid		0.13148	52.5105	12.454843
Cold Fluid 2		0.35117	12.25245	1.0880438

6. Linearization of S&TinT Modal

The transfer function is an output-input relation of a system which is represented in the Laplace domain with zero initial conditions [16].

The input-output data taken from the S&TinT heat exchanger model is used to derive the transfer function of the designed S&TinT heat exchanger.

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix} \quad (11)$$

Since the system consists of three inputs and three outputs, the designed transfer function model is a MIMO system and it consists of nine transfer functions to represent a S&TinT heat exchanger.

$$G_{11}(s) = \frac{785.823}{[s^2 + 28.481s + 1.371e - 05]}$$

$$G_{12}(s) = \frac{-1.839e - 12}{[s^2 + 3.446e - 05s + 2.104e - 09]}$$

$$G_{13}(s) = \frac{-647.358}{[s^2 + 21.996s + 1.059e - 05]}$$

$$G_{21}(s) = \frac{49765.620}{[s^2 + 76.252s + 0.0046]}$$

$$G_{22}(s) = \frac{-11599.219}{[s^2 + 43.621s + 0.0026]}$$

$$G_{23}(s) = \frac{-47713.450}{[s^2 + 110.898s + 0.0068]}$$

$$G_{31}(s) = \frac{-945.735}{[s^2 + 26.241s + 0.00020]}$$

$$G_{32}(s) = \frac{2490.036}{[s^2 + 89.514s + 0.00070]}$$

$$G_{33}(s) = \frac{147.070}{[s^2 + 13.841s + 0.00010]}$$

The MIMO structure of the discovered transfer function model is used to obtain the open-loop responses of the S&TinT heat exchanger. Based on the temperature interaction between the hot and cold fluids, the curves of open loop responses take the shapes of sigmoidal and decade curves.

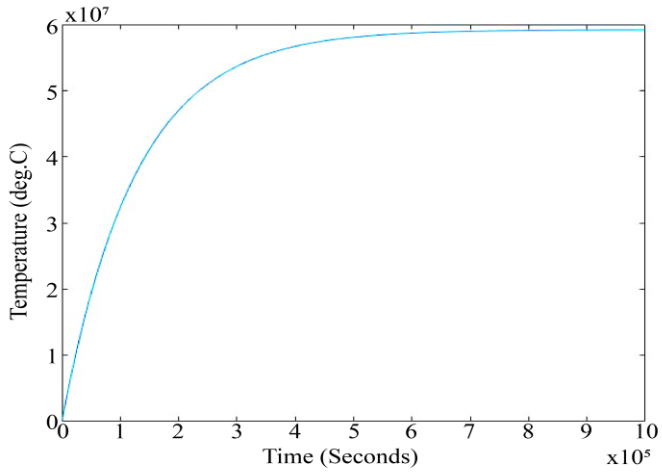

Fig. 7 Open loop response of cold fluid 1

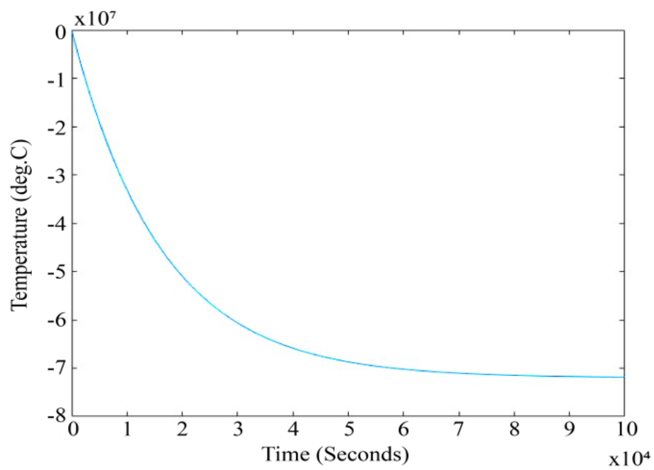

Fig. 8 Open loop response of hot fluid

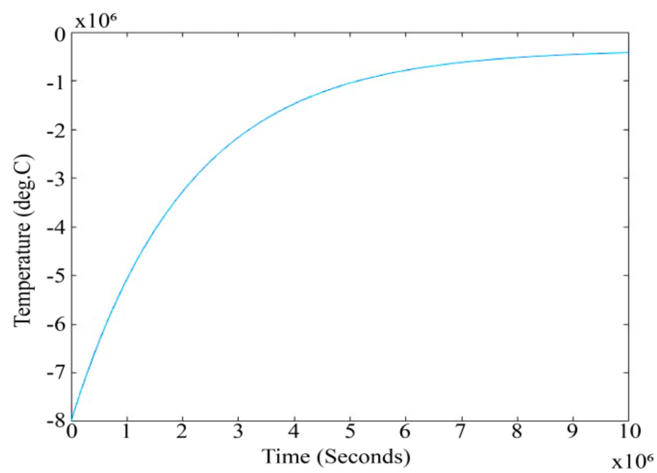

Fig. 9 Open loop response of cold fluid 2

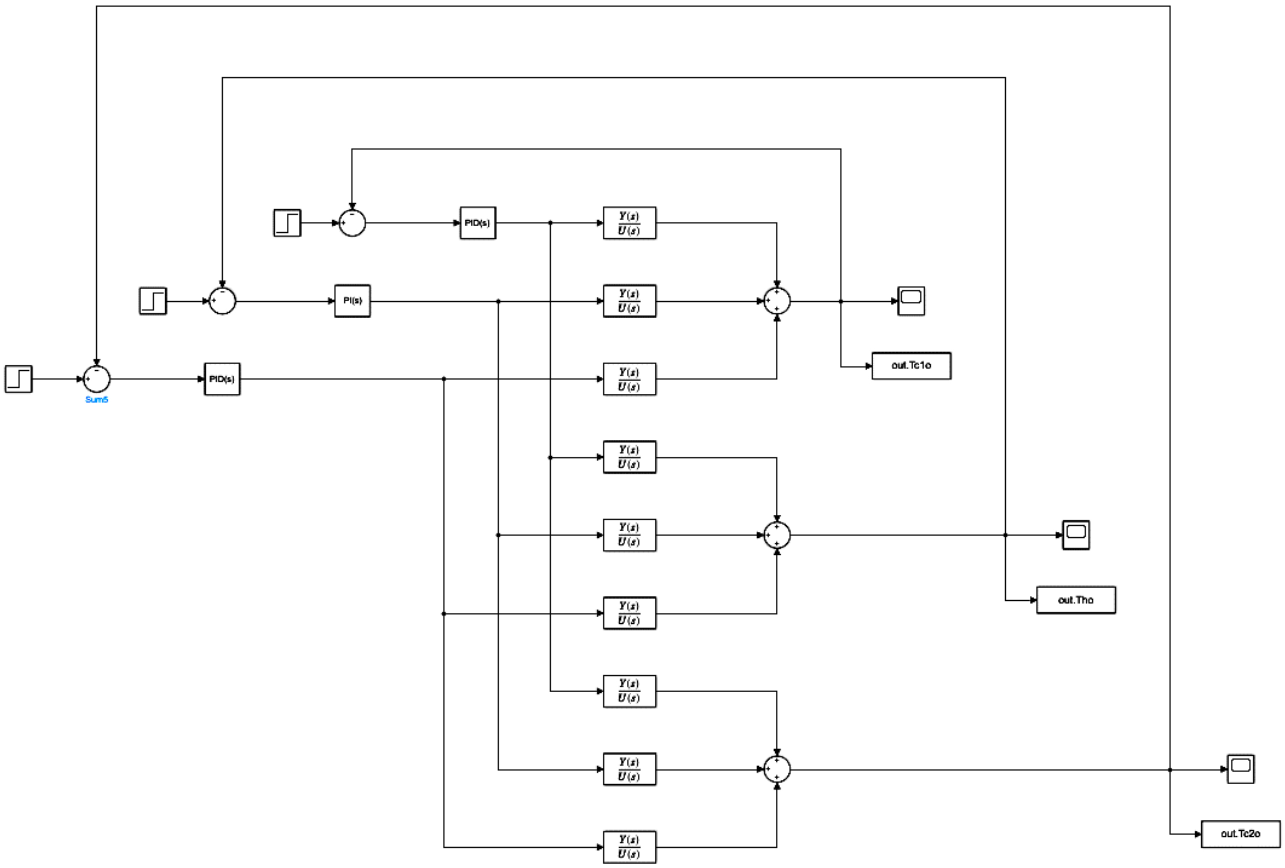

Fig. 10 Control structure of PID controller

Since the relationship between the cold fluid and hot fluid is indirectly proportional, the hot fluid takes the decade curve, and the cold fluid 1 and cold fluid 2 take sigmoidal curves. Also, the open loop responses have a high amplitude, and it takes a large period to attain a constant value. Some of the controller actions are introduced to overcome it [17].

7. Control of S&TinT Heat Exchanger

Providing the outlet temperature at a desired level is a major task in process industries [18]. To control the designed S&TinT heat exchanger parameters, several control techniques can be used [19]. In this work, the Model predictive controller is selected as it is involved in controlling MIMO systems, and it is being compared with a conventional PID controller and the results are discussed below.

7.1. PID Control

Initially, linearization of the non-linear S&TinT model is achieved by obtaining the open-loop responses of the system. Now the system behaves linearly, so that a conventional PID controller can be utilized to control the model [20]. Here, the challenge that occurred is process interactions among linearized transfer functions of cold and hot fluid domains. The controlled temperature response of cold fluid 1 is shown in Figure 11.

The setpoint for cold fluid 1 is 45 deg. C and, which got settled at the desired value but with a very high negative overshoot. When controlling the hot fluid, the controller actions of the cold fluid 1 and 2 are disturbing the response of the hot fluid temperature.

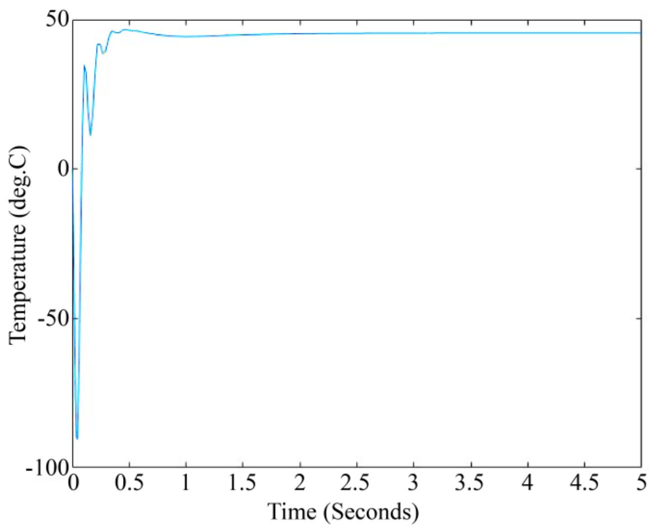

Fig. 11 Temperature response of cold fluid 1 with PID

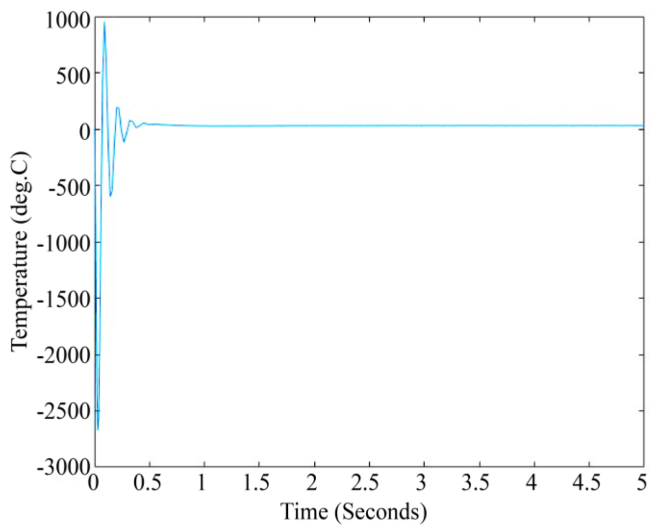

Fig. 12 Temperature response of hot fluid with PID

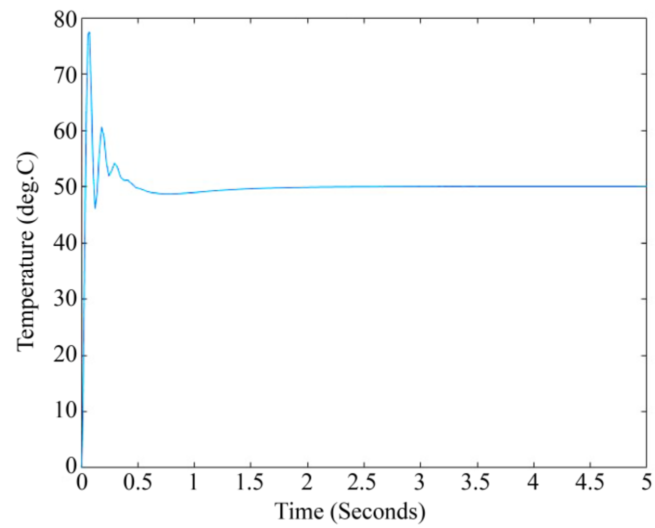

Fig. 13 Temperature response of cold fluid 2 with PID

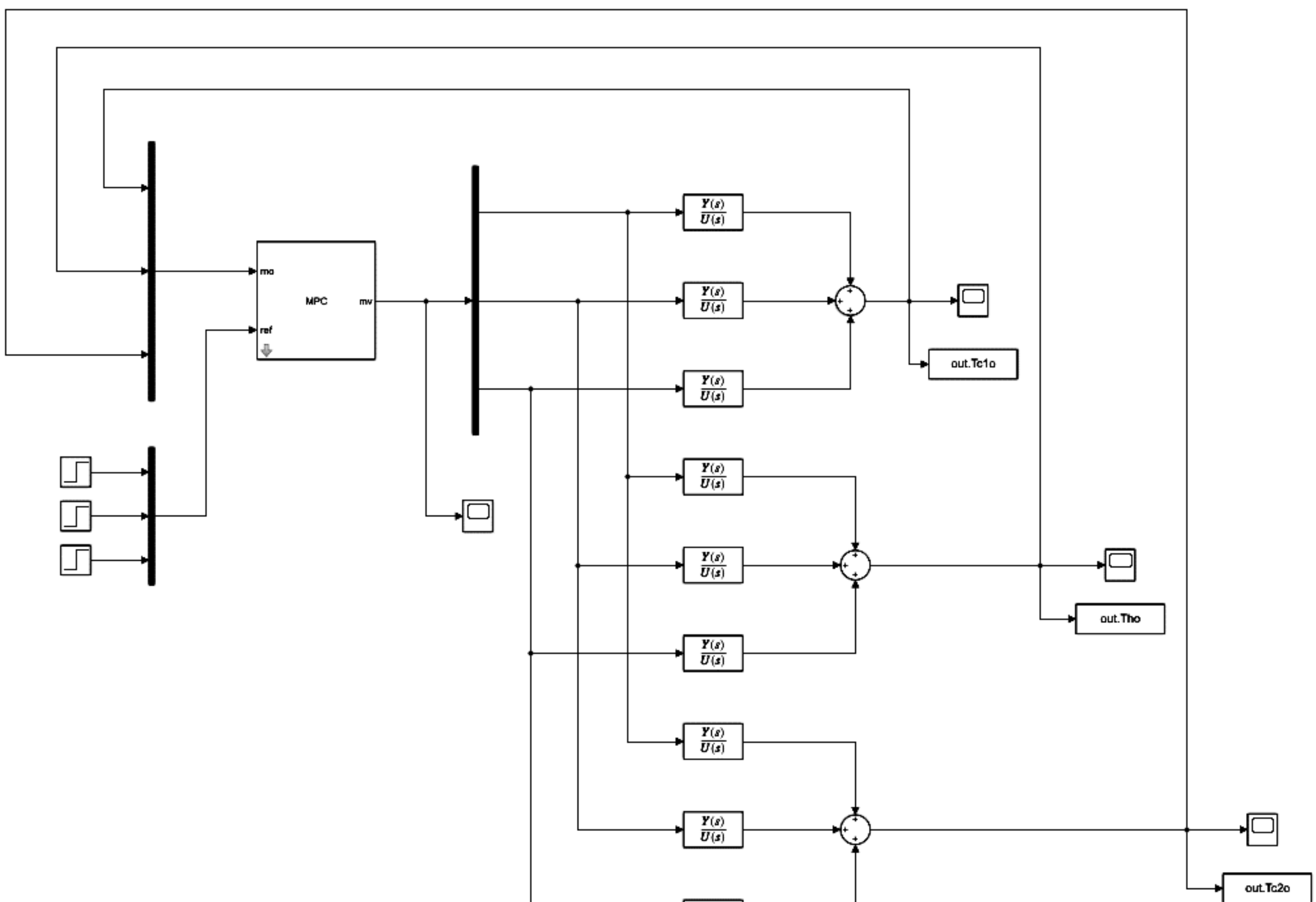

Fig. 14 Control structure of MPC controller

However, the S&TinT heat exchanger aims to keep the hot fluid temperature at the desired value. As a result, it is observed that the response of hot fluid is reaching the desired value using a PID controller, but the maximum peak value is seen due to process interaction, which is very high compared to the operating temperature range. Like cold fluid 1 (Figure 11), the temperature response of cold fluid 2 is also settling at the desired value (50 deg. C). The assumptions are made with ideal conditions while designing the model, and so the simulation results are obtained in less time.

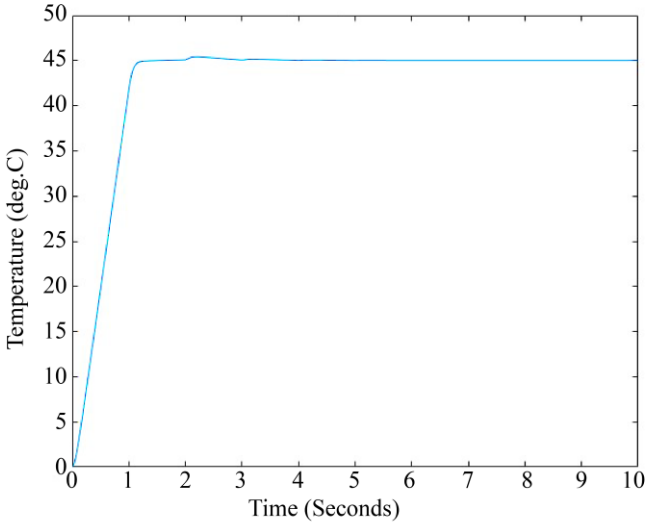

Fig. 15 Temperature response of cold fluid 1 with MPC

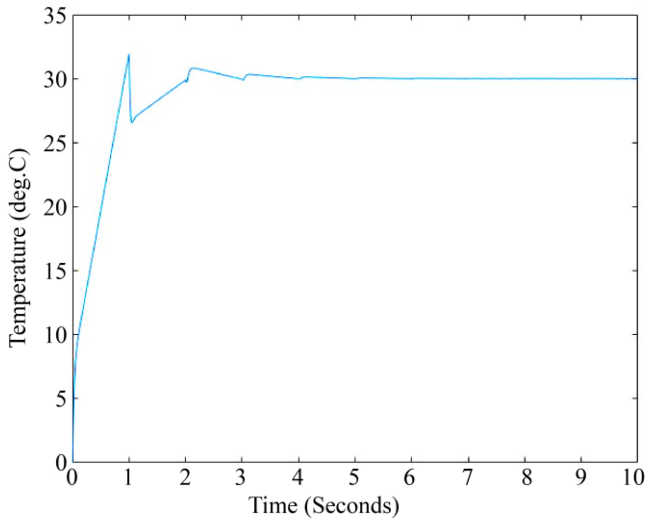

Fig. 16 Temperature response of hot fluid with MPC

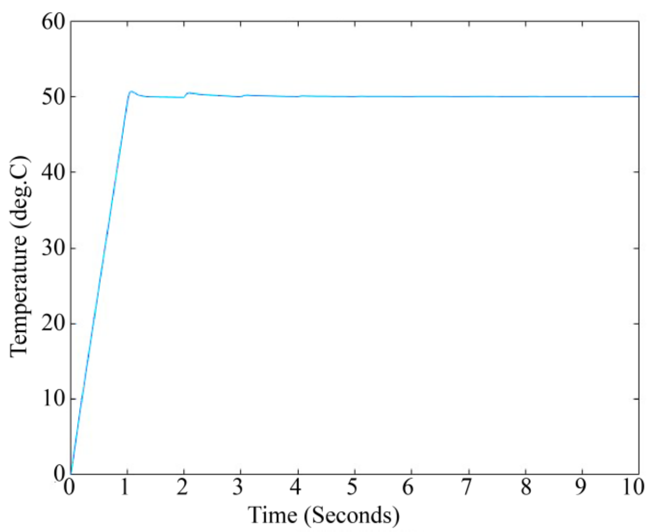

Fig. 17 Temperature response of cold fluid 2 with MPC

Table 4. Performance Metrix of S&TinT heat exchanger with PID controller

Criterion	IAE	ISE	ITAE	ITSE
Cold Fluid 1	4.669	80.75	1.58	4.653
Hot Fluid	188.4	$2.653e^5$	20.18	$1.201e^4$
Cold Fluid 2	13.54	951.8	6.401	50.94

Table 5. Performance Metrix of S&TinT heat exchanger with MPC controller

Criterion	IAE	ISE	ITAE	ITSE
Cold Fluid 1	25.82	791.9	10.47	215.2
Hot Fluid	13.07	170.5	7.779	41.68
Cold Fluid 2	26.06	858.7	9.797	218.3

Now, error estimation is performed to validate the PID controller action, and the results clearly show that the involvement of process interactions leads to overshoot and unrealistic response, that is, the temperature of the superheated stage and freezing stage, which is above 100 deg. C and below 0 deg. C respectively in the case of water. Further from the table, error values are exorbitant, which shows that the response of the conventional PID controller is truncated. To reduce the value of errors and to have a better-controlled response model predictive control technique is used.

7.2. MPC Control

Model predictive control is one of the most effective techniques to control MIMO systems [21, 22]. MPC controller will produce the controller action in the form of pulsated controller action due to that the final responses are controlled instantly [23]. In the figure.14 a single MPC controller has been introduced to control the S&TinT heat exchanger. From Figure 15, it is evident that reduced overshoot is seen when compared to the temperature response of cold fluid 1 with PID controller action. The focus of the S&TinT heat exchanger is to reduce or maintain the temperature of hot fluid, and that was done precisely by MPC, which is illustrated in Figure 16. Reasonable temperature range of 33 deg. C were obtained in the closed loop response of hot fluid. Similarly, the outlet temperature of cold fluid 2 is also controlled at the desired value with a minimal value of overshoot. Overall, observing the responses of MPC shows minimum overshoot, achieving smooth and gradual responses. Further on comparing error values of PID controller and MPC, the performance merix of MPC obtains better results. Thus MPC controller is very impactful on the S&TinT heat exchanger.

8. Conclusion

The S&TinT heat exchanger outperforms its conventional counterparts by incorporating three heat-transfer elements, as opposed to the usual two elements in traditional designs. Adopting a cross-flow configuration for three fluid paths contributes to a significant increase in heat transfer rates. This unique architecture addresses challenges inherent in conventional heat exchanger designs. In addition, the flexibility to change flow direction and rate provides a dynamic means of controlling heat transfer performance, allowing rapid changes to meet specific operational requirements. The manifold advantages offered by the S&TinT heat exchanger act as a promising solution for industries demanding greater efficiency and adaptability in their heat transfer processes. In the case of shell and tube-in-tube (S&TinT) heat exchanger, the logarithmic mean temperature difference (LMTD) algorithm is selected for design purposes.

However, a significant challenge arises in modifying the standard LMTD algorithm to accommodate the heat transfer dynamics between the three fluids. The traditionally designed LMTD algorithm for calculating heat transfer rates between two fluids is modified to effectively capture the temperature distribution and heat transfer interactions in three-fluid S&TinT heat exchangers.

Addressing this change in the algorithm not only ensures the accuracy of the design process but also contributes to understanding the complex heat transfer mechanisms in multi-fluid systems.

Control of designed shell and tube-in-tube (S&TinT) heat exchanger parameters is an important aspect. In this study, the Model Predictive Controller was chosen for its ability to handle multi-input, multi-output systems. A comparative analysis with a conventional proportional-integral-derivative controller revealed significant insights. PID control has shown success in stabilizing the temperature of cold and hot fluids but has faced challenges associated with process interactions, leading to high overshoot and unreliable responses.

The introduction of the model predictive controller showed significant improvements. The MPC controller effectively minimizes overshoot and provides precise control over the temperature of hot and cold fluids. Comparative analysis of error values further confirms the superior performance of MPC controllers over PID controllers in advanced heat transfer systems like S&TinT heat exchangers.

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