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Temperature Response of Cellular Network Based Concentric Tube Heat Exchanger for Concurrent Flow Using Matlab/Simulink

Sharma Pankaj and Kumar Nittin
Department of Mechanical Engineering, JMIT, Radaur, Haryana, INDIA

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Abstract

Heat exchangers are extensively used in variety of fields, therefore are to be designed to give high performance with low cost. Prediction of behavior of heat exchanger can be done by virtual window. In this paper a simulation model of heat exchanger in virtual window has been made for outlet temperature analysis. Transient simulation of a concentric tube heat exchanger with parallel flow arrangement has been presented in this paper. Simulation model has been developed using Matlab/Simulink. Thermodynamic math model of heat exchanger has been taken as a base for simulation model. Model predicts the temperature response of liquids by framing a cellular network of heat exchanger divided into 4 cells of equal lengths. Mass/Energy conservation equations in transient mode has been used to create model for every cell of heat exchanger, which after simulation gives acceptable results

Keywords: Concentric tube heat exchanger, cellular network, Matlab/Simulink, Virtual Window.

Introduction

We can find extensive use of heat exchangers in our day to day life to ultra-modern industries. They are used in power plants, paper pulp industry, ice plants, oil refineries, food processing industry, domestic refrigerators and air conditioners etc. Since, they are the vital part for the successful working of above mentioned plants, therefore, it should be designed to have high effectiveness with low cost .To predict the performance of heat exchanger under different working conditions during the design cycle is of utmost importance. Its behavior under transient and steady state should be analyzed to minimize the future probabilities of failure.

A concurrent tube heat exchanger was modelled for simulation in this paper. Model developed in the environment of Matlab/Simulink can analyse performance of heat exchanger under different operating conditions as well as for different combinations of fluid and structure material through simulation. This model can be used successfully to find exit temperature of both streams of exchanger with known parameters.

Heat Exchanger Concentric Pipe: Heat exchanger with concentric pipe is taken for analysis in this work. It is a twin concentric tubular structure. Its schematic diagram is shown in figure-1. Water to water heat transfer study has been done in this work. Cold fluid flows through the inside of inner tube (Liquid 1), whereas hot fluid (liquid 2) passes from the annulus of heat exchanger[1]. This analysis focuses on simulating outlet temperature of hot and cold stream. Cold water passes through the tube while the hot water through the annular space.

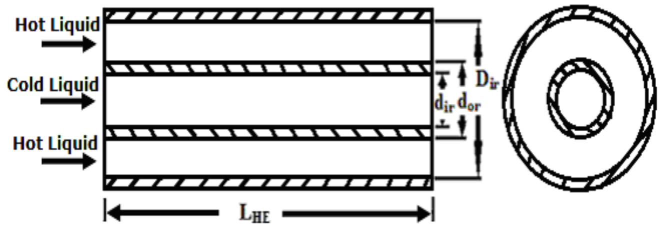

Figure-1
Concentric Tube Heat Exchanger

Cell Based Heat Exchanger Model: For simulating above unit, it is partitioned into four cells of equal length[2], shown in figure-2. Each cell consist of cold water volume, metal thickness of inner tube, hot water volume, and outer tube metal thickness[3]. Shape specifications of the model are: L_{HE} = heat exchanger length, d_{ir} = inner tube inside bore, d_{or} = outside diameter of inner pipe, D_{ir} = outside pipe inside diameter, r_{ir}= inside tube inside radius, r_{or}= outer radius inside tube, Th_{i_Tb} = wall thickness of inner tube, N_{Cell} = number of cells

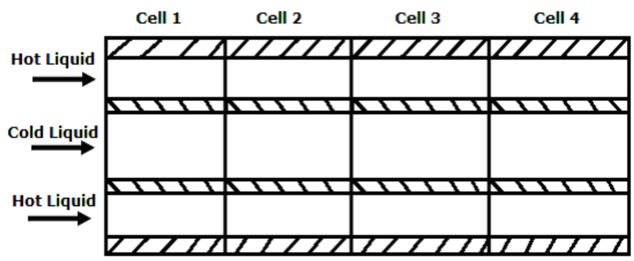

Figure-2
Cellular Model of Heat Exchanger

Electrical Analogy: Electrical analogy of heat exchanger under consideration is shown in figure-3. Total thermal resistance of the system and coefficient heat transfer overall is given by equation 1 and 2 respectively[4]. Since tube thickness is very small, so neglecting the effect of wall resistance, therefore equation 3 gives overall heat transfer coefficient for the system[5].

$$R_{total} = R_{h\_L2} + R_{ir\_Tb} + R_{h\_L1} \quad (1)$$

$$R_{h\_L1} = \frac{1}{h_{L1}A_i}; R_{h\_L2} = \frac{1}{h_{L2}A_o}; R_{ir\_Tb} = \frac{Th_{ir\_Tb}}{K_{ir\_TB}A_i} \quad U_{L1}A_{ir} = U_{L2}A_{or} = \frac{1}{R_{h\_L2}+R_{ir\_Tb}+R_{h\_L1}} \quad (2)$$

$$U_{OA} = \frac{h_{L1}h_{L2}}{h_{L1}+h_{L2}} \quad (3)$$

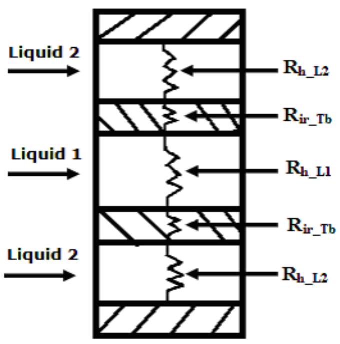

Figure-3
Electrical Analogy of Heat Exchanger

Math Model

Mathematical modelling of heat exchanger deals with forming the equations of heat transfer between hot and cold fluid for every cell. The hypothesis used for modelling the unit thermodynamically are: i. no phase change of fluids during the process, ii. uniformly distributed heat exchange area, iii. axial conduction of heat conduction is neglected, iv. perfectly insulated outer tube, v. predefined mass flow rate and inlet temperature

Energy Balance for Cold Water: Mass/energy input and output to and from cold water in cells have been shown in figure-4. The conservation of energy for cold fluid, in transient conditions for cell 1, is given by equation 4. Heat flux entering to the cold stream based on overall heat transfer area of cell and mass of liquid holdup for liquid 1 is given by equation 5, 6 and 7 respectively[6]. Table 1 and 2 shows input and calculated parameter values. Since, Re_{L1} > 2000, from table 2 therefore Dittus-Boelter relation is used to calculate Nusselt number[7].

$$\dot{m}_{i\_L1}Cp_{L1}\left(T_{o\_Cell\_1\_L1} - T_{i\_Cell\_1\_L1}\right) + \phi_{Flux\_Cell\_1} = m_{HU\_L1}Cp_{L1}\frac{\partial T_{o\_cell\_1\_L1}}{\partial t} \quad (4)$$

$$\phi_{Flux\_Cell\_1} = U_{OA}A_{Cell\_1\_Tb}\Delta_{T\_Cell\_1} \quad (5)$$

$$\Delta_{T\_Cell\_1} = \left(T_{i\_Cell\_1\_L2} - T_{o\_Cell\_1\_L1}\right)$$

$$A_{Cell\_1\_Tb} = \pi\frac{\left\{\frac{d_{ir}+d_{or}}{2}\right\}}{4}\left(\frac{L_{HE}}{N_{Cell}}\right) \quad (6)$$

$$m_{HU\_L1} = \rho_{L1}\pi\left(\frac{d_{ir}}{2}\right)^2\left(\frac{L_{HE}}{N_{Cell}}\right) \quad (7)$$

$$Re_{L1} = \frac{4\dot{m}_{i\_L1}}{\pi d_{ir}\mu_{L1}} \quad (8)$$

$$Nu_{L1} = 0.023Re_{L1}^{0.8}Pr_{L1}^{0.3} \quad (9)$$

$$Pr_{L1} = \frac{\mu_{L1}Cp_{L1}}{K_{L1}} \quad (10)$$

$$h_{L1} = \frac{Nu_{L1}K_{L1}}{d_{ir}} \quad (11)$$

Energy Balance for Hot Fluid: Figure-4 shows mass and energy flow from and to the hot fluid in cells. Energy conservation of hot fluid, in transient conditions for cell 1, in differential form is given by equation 12 and mass hold up by equation 13. Heat transfer coefficient h_{F2} has been calculated, adopting the same procedure as that of cold fluid, since hot water is flowing through the annulus, equivalent (hydraulic) diameter is used to calculate Reynolds number, which is given by the equation 14. Since Re_{L2}<2000, from table 2 then according to Mills correlation Nusselt number was calculated. Table 1 and 2 shows the values of above mentioned input and calculated parameters respectively.

$$\dot{m}_{i_{L2}}Cp_{L2}\left(T_{i\_Cell\_1\_L1} - T_{o\_Cell\_1\_L2}\right) - \phi_{Flux\_Cell\_1} = m_{HU\_L2}Cp_{L2}\frac{\partial T_{o\_Cell\_1\_L2}}{\partial t} \quad (12)$$

$$m_{HU\_L2} = \rho_{L2}\pi\left\{\left(\frac{D_{ir}}{2}\right)^2 - \left(\frac{d_{ir}}{2}\right)^2\right\}\left(\frac{L_{HE}}{N_{Cell}}\right) \quad (13)$$

$$Re_{L2} = \frac{4\dot{m}_{i\_L2}}{\pi(D_{ir}+d_{or})\mu_{L2}} \quad (14)$$

$$Nu_{L2} = 3.66 + \frac{0.065RePr\frac{D}{L_{HE}}}{1+0.04\left(RePr\frac{D}{L_{HE}}\right)^{\frac{2}{3}}} \quad (15)$$

$$Pr_{L2} = \frac{\mu_{L2}Cp_{L2}}{K_{L2}} \quad (16)$$

$$h_{L2} = \frac{Nu_{L2}K_{L2}}{(D_{ir}-d_{or})} \quad (17)$$

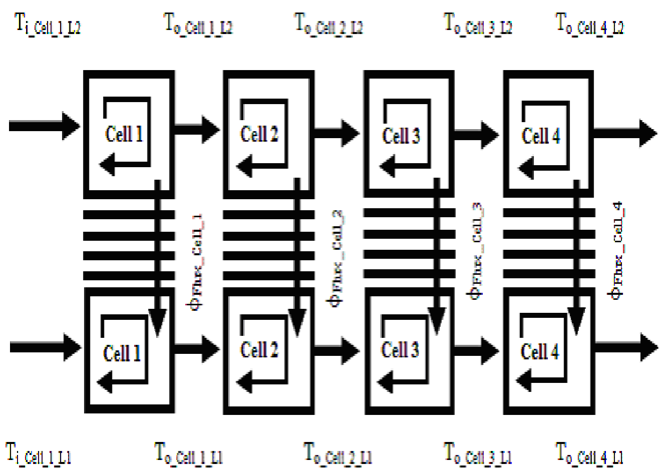

Figure-4
Cell Network of Heat Exchanger
Table-1

Input Parameters of Liquid 1 and 2

S.No.	Parameter	Values
1.	$\dot{m}_{i\_L1}$	0.0263
2.	d_{ir}	10.5
3.	μ_{L1}	0.7901
4.	Cp_{L1}	4.179
5.	K_{L1}	0.6176
6.	L_{HE}	1500
7.	$T_{i\_L1} = T_{i\_Cell\_1\_L1}$	31
8.	$\dot{m}_{i\_L2}$	0.0194
9.	d_{or}	12.5
10.	D_{ir}	28
11.	μ_{L2}	0.4505
12.	Cp_{L2}	4.186
13.	K_{L2}	0.6567
14.	$T_{i\_L2} = T_{i\_Cell\_1\_L2}$	63

Table-2
Calculated Parameters

S. No.	Parameters (Liquid 1&2)	Values
1.	Re_{L1}	4046.1538
2.	Re_{L2}	1356.6433
3.	Pr_{L1}	5.3462
4.	Pr_{L2}	2.8716
5.	Nu_{L1}	34.5605
6.	Nu_{L2}	6.445
7.	h_{L1}	2032.8156
8.	h_{L2}	273.6108
9.	U_{OA}	241.1524

Simulink Model: Simulation model of heat exchanger has been created in Simulink environment and is shown in figure-5. Parallel flow, 4 cell simulation model has been simulated to analyse output temperatures of hot and cold fluids[2]. The inputs to the simulator are: i. mass flow rates of cold and hot fluids, ii. inlet temperature of cold and hot fluids

Simulator is also provided with shape dimensions, physical properties and thermal properties of fluids and metal structure. The output of simulation comes out as: i. cold stream exit temperature, ii. hot stream exit temperature

These outputs are plotted as a function of time in simulink window. Simulink subsystem models of cold and hot fluid, for cell 1 are shown in figure- 6 and 7 respectively. Input parameters to these subsystems are their respective mass flow rate and inlet temperature, whereas their respective outputs are outlet temperature which becomes input to the next cell.

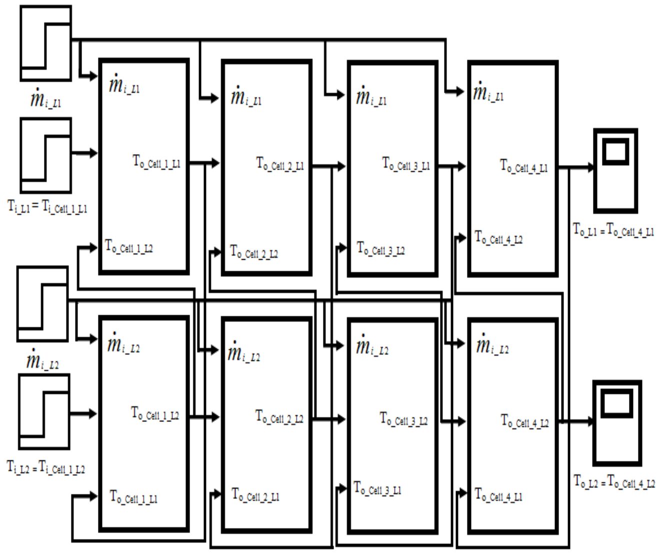

Figure-5
Simulink Model of 4 Cell Heat Exchanger

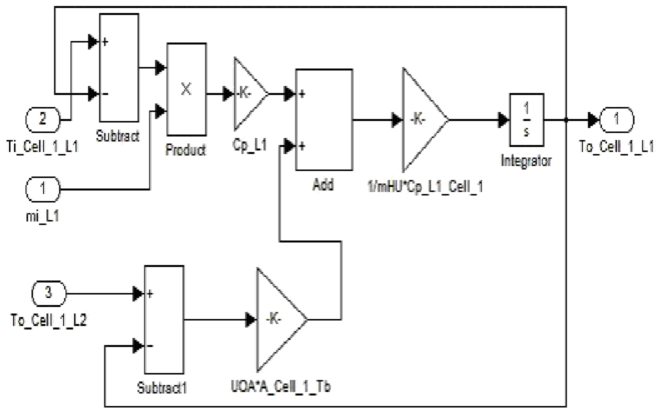

Figure-6
Simulink Subsystem for Cold Liquid, Cell 1

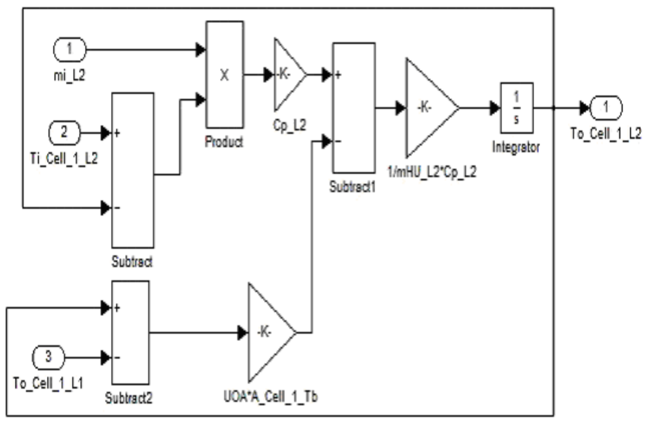

Figure-7
Simulink Subsystem for Hot Liquid, Cell 1

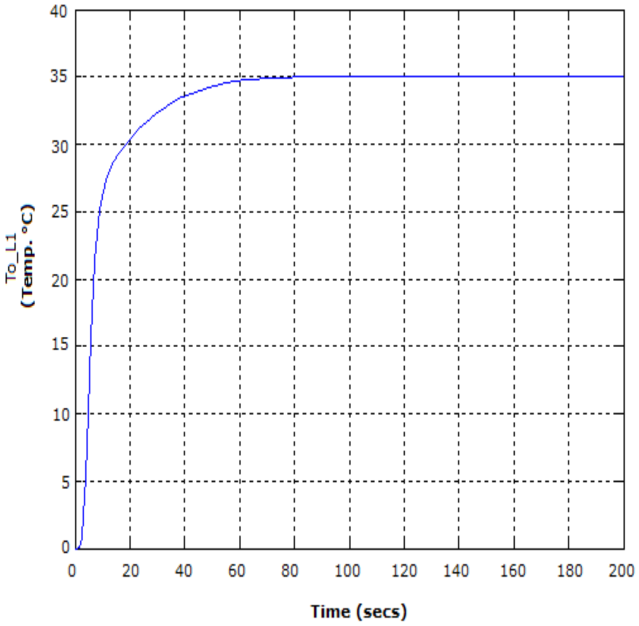

Figure-8
Cold Liquid Outlet Temperature Response

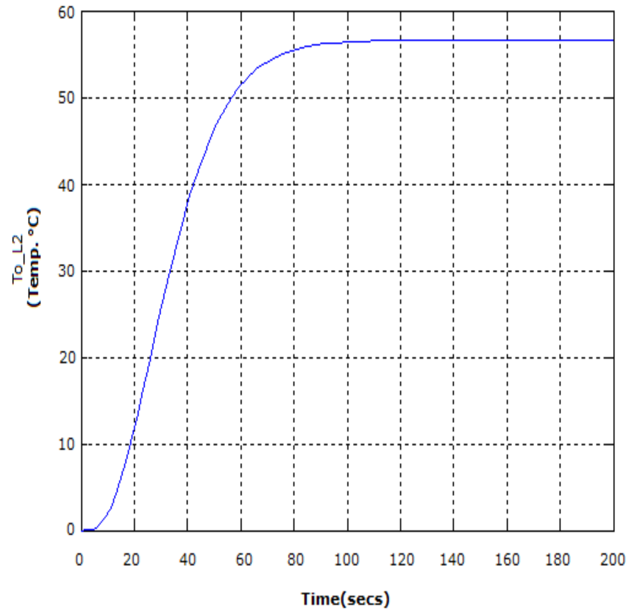

Figure-9
Hot Liquid Outlet Temperature Response

Results and Discussion

Simulation of 4 cell heat exchanger model with given input parameters, predicts exit temperature transient response ofboth streams. Cold and hot fluid outlet temperature comes out to be 33°C and 57°C respectively, shown in figure- 7 and 9. When compared with experimental results, simulated temperatures are very close to them and are shown in table 3.

Table-3

Outlet Temperature (C)

Fluid	Experimental	Simulated
Hot	58.5	57
Cold	35	33

Conclusion

Simulink model of heat exchanger developed predicts exit temperature of streams effectively. It can be used to simulate behaviour of heat exchanger with changing inputs e.g. changing values of inlet temperatures or mass flow rates of liquids. Prediction of heat exchanger performance for different materials and shape configuration is also possible with this model. The future scope of this study lies in study of effect of axial flow of heat in pipe material and in fluids. Effect of increased number of cells, over the outlet temperature of liquids and on effectiveness can also be studied. This model can be used as a base model to develop simulation model for multi tube heat exchanger.

Nomenclature: *Symbol Description[Units]:* A =Area[m^2], Cp=Heat specific[J/Kg-K], d =Inside pipe diameter[mm], D = Outer tube diameter[mm], h = Convective heat transfer co-efficient[W/m^2-K], K = Conductivity thermal[W/m-K], L = Length [mm], m = Mass[Kg], $\dot{m}$ = Flow rate of liquid mass[Kg/s], N = Number, Nu = Nusselt number, Pr = Prandtl number, r = Radius[mm], R = Thermal resistance[deg/W], Re = Reynolds number, T = Temperature[°C], Th = Thickness[mm]
U = Heat transfer co-efficient [W/m^2-K].

Greek Symbol, Description [Units]: ϕ = Thermal flux[W], μ = Viscosity[centipoise], ρ = Density[Kg/m^3].

Subscript Description: Cell = cell, Cell_1 = Cell number 1, Flux = Flux, HE = heat exchanger, HU = hold up, i = inlet, ir = inner, L1 = liquid 1, L2 = liquid 2, o = outlet, OA = Overall, or = outer, Total = Sum total, Tb = tube.

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