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Analysis of Shell and Tube heat exchanger design using Comsol Multiphysics

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Abstract

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, at different temperatures and in thermal contact. This paper is concerned with the study of shell and tube type heat exchangers with its design optimization. An excel program has been developed for the ease of calculation and obtaining results after changing different parameters. The tube diameter, tube length, shell type etc. are all standardized and available in certain sizes and geometry. Moreover, constructional details, design methods and the reasons for the wide acceptance of shell and tube type heat exchangers have been described inside the paper. This paper consists of extensive thermal analysis and these steady state thermal analyses have carried out on COMSOL Multiphysics to justify the design. To serve the purpose a simplified model of shell and tube type heat exchanger has been designed to heat the water from 45^0 C to 55^0 C. This commercial finite element modeling software has been employed to simulate a theoretical 2 dimensional model for shell and tube heat exchanger. The main aim of this paper is to analyze of shell and tube heat exchanger for heating operation of water. This 2-D model demonstrates the effect of inlet and outlet fluid velocity and the material used for construction of heat exchanger for the required heat transfer. In this problem of heat transfer involved the conditions where different constructional parameters are changed for getting the performance review under different conditions. Indeed, the design of shell and tube type heat exchanger includes thermal design and mechanical design. Since several discrete combinations of the design configurations are possible, the designer needs an efficient strategy to quickly locate the design configuration having the minimum heat exchanger cost.

Keywords: Reynolds Averaged Navier-Stokes (RANS), COMSOL Multiphysics, Heat Exchanger, Nusselt Number, Heat Transfer

Introduction

Heat transfer between two fluids at different temperatures is vital for most industrial processes, and heat exchangers are the devices that specifically designed for this purpose. Heat exchanger is a mechanical device which is used for the purpose of exchange of heats between two fluids at different temperatures. There are various types of heat exchangers available in the industry, however the Shell and Tube Type heat exchanger is probably the most used and widespread type of the heat exchanger's classification. It is used most widely in various fields such as oil refineries, thermal power plants, chemical industries and many more. This high degree of acceptance is due to the comparatively large ratio of heat transfer area to volume and weight, easy cleaning methods, easily replaceable parts etc. Shell and tube type heat exchanger consists of a number of tubes through which one fluid flows. Another fluid flows through the shell which encloses the tubes and other supporting items like baffles, tube header sheets, gaskets etc. The heat exchange between the two fluids takes through the wall of the tubes.

Component details of shell and tube type heat exchanger

Some of the very basic components of a shell and tube type heat exchangers are as given below:

Tubes

The tubes are the basic components of a shell and tube type heat exchanger. The outer surfaces of the tubes are the boundary along which heat transfer takes place. It is therefore recommended that the tubes materials should be highly thermal conductive otherwise proper heat transfer will not occur. The tubes of Copper, Aluminum and other thermally conductive materials are commonly used in practice.

Tube sheets

The tubes are held in place by being inserted into holes in the tube sheet and there either expanded into grooves cut into the holes or welded to the tube sheet where the tube protrudes from the surface. The tube sheet is usually a single round plate of metal that has been suitably drilled and grooved to take the tubes (in the desired pattern), the gaskets, the spacer rods and the bolt circle where it is fastened to the shell. However, where mixing between the two fluids (in the event of leaks where the tube is sealed into the tube sheet) must be avoided, a double tube sheet may be provided.

Shell

The shell is simply the container for the shell side fluid, and the nozzles are the inlet and exit ports. The shell normally has a circular cross section and is commonly made by rolling a metal plate of the appropriate dimensions into a cylinder and welding the longitudinal joint ("rolled shells").

Impingement plates

When the fluid under high pressure enters the shell there are high chances that if the fluid will directly impinge over the tubes then their breakage or deformation may occur. To avoid the same the impingement plates are installed to waste the kinetic energy of fluid up to some extent so that the fluid may impact the tubes with lower velocity.

Channel covers

The channel covers are round plates that bolt to the channel flanges and can be removed for the tube inspection without disturbing the tube side piping. In smaller heat exchangers, bonnets with flanged nozzles or threaded connections for the tube side piping are often used instead of channel and channel covers.

Baffles

Baffles serve two functions; Most importantly, they support the tubes in the proper position during assembly and operation and prevent vibration of the tubes caused by flow induced eddies, and secondly, they guide the shell side flow back and forth across the tube field, increasing the velocity and heat transfer coefficient.

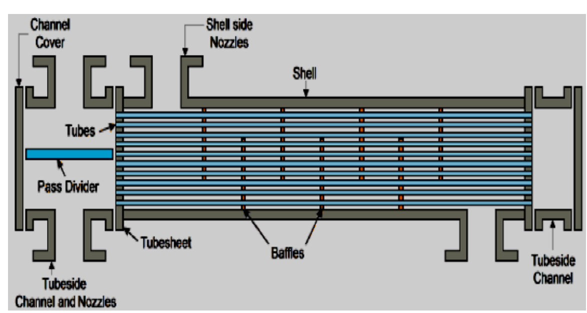

Fig. 1: Component Schematic of Shell and Tube type Heat Exchanger.

Literature review

While reviewing the works of renowned scholars it has been seen that significant amount of works has been done in fields of shell and tube type heat exchangers (STHE). Some important works have been described in detail as under:

Ahmad Fakheri[1] in his paper shows that how to calculate the efficiency of the heat exchangers based on the second law of thermodynamics. He says that corresponding to every heat exchanger there is an ideal balanced counter flow heat exchanger which has the properties of same UA, same AMTD and minimum entropy generation corresponding to minimum losses and irreversibility. The efficiency of the heat exchanger may be calculated by comparing the heat transfer capability of actual heat exchanger with that of the ideal heat exchanger. Ahmad Fakheri[2] in this article extends the concept of heat exchanger efficiency to the networks of heat exchangers. This paper provides a simple equation that can be used to calculate the efficiency of heat exchangers in networks. It also assists for calculating the effectiveness or efficiency of individual heat exchangers as well as the number of heat exchangers required for the purpose. Rajeev Mukherjee[3] explains the basics of exchanger thermal design, covering such topics as: STHE components; classification of STHEs according to construction and according to service; data needed for thermal design; tube side design; shell side design, including tube layout, baffling, and shell side pressure drop; and mean temperature difference. The basic equations for tube side and shell side heat transfer and pressure drop. Correlations for optimal condition are also focused and explained with some tabulated data. This paper gives overall idea to design optimal shell and tube heat exchanger. The optimized thermal design can be done by sophisticated computer software however a good understanding of the underlying principles of exchanger designs needed to use this software effectively. Jiangfeng Guo et.al[4] took some geometrical parameters of the shell-and-tube heat exchanger as the design variables and the genetic algorithm is applied to solve the associated optimization problem. It is shown that for the case that the heat duty is given, not only can the optimization design increase the heat exchanger effectiveness significantly, but also decrease the pumping power dramatically. A. Pignotti[5] in his paper established relationship between the effectiveness of two heat exchanger configurations which differ from each other in the inversion of either one of two fluids. This paper provides the way by which if the effectiveness of one combination is known in terms of heat capacity rate ratio and NTUs then the effectiveness of the other combination can be readily known. M. S. Bohn[6] in his article presents a method of calculating the electric power generated by a thermoelectric heat exchanger. The method presented in this paper is an extension of the NTU method used to calculate heat-exchanger's heat-transfer effectiveness. The effectiveness of thermoelectric power generation is expressed as the ratio of the actual power generated to the power that would be generated if the entire heat-exchanger area were operating at the inlet fluid temperatures. V.K. Patel and R.V. Rao[7] explore the use of a non-traditional optimization technique; called particle swarm optimization (PSO), for design optimization of shell-and-tube heat exchangers from economic view point. Minimization of total annual cost is considered as an objective function. Three design variables such as shell internal diameter, outer tube diameter and baffle spacing are considered for optimization. Two tube layouts viz. triangle and square are also considered for optimization. The presented PSO technique's ability is demonstrated using different literature case studies and the performance results are compared with those obtained by the previous researchers. PSO converges to optimum value of the objective function within quite few generations and this feature signifies the importance of PSO for heat exchanger optimization. Hetal Kotwal and D.S Patel[8] focus on the various researches on Computational Fluid Dynamics (CFD) analysis in the field of heat exchanger. Different turbulence models available in CFD tools i.e. Standard k-ε model, k-ε RNG model, Realizable k-ε, k-ω and RSM model in conjunction with velocity pressure coupling scheme and have been adopted to carry out the simulation. The steady increase in computing power has enable model to react for multi- phase flows in realistic geometry with good resolution. The quality of the solution has proved that CFD is effective to predict the behavior and performance of heat exchanger. Shiv Kumar Rathore and Ajeet Bergaley[9] worked with the aim to identify the advantages of low-finned tube Heat Exchangers over Plain tube (Bare Tube) units. To use finned tubes to advantage in this application, several technical issues were to be addressed; (1) Shell side and tube side Pressure, (2) Cost, (3) Weight and (4) Size of Heat Exchanger, Enhanced tubular heat exchangers results in a much more compact design than conventional plain tube units, obtaining not only thermal, mechanical and economical advantages for the heat exchanger, but also for the associated support structure, piping and skid package unit, and also notably reduce cost for shipping and installation of all these components. A more realistic comparison is made on the basis of respective cost per meter of tubing divided by the overall heat transfer coefficient for the optimized units, which gives a cost to performance ratio. This approach includes the entire thermal effect of internal and external heat transfer augmentation and fouling factors in the evaluation. This is typically quite close to reality and easy for the thermal designer to evaluate himself. The results of this analysis shows that the finned tube heat exchanger is more economical than Conventional Bare tube Exchanger, The tube side pressure drop and fluid velocity is higher than the conventional bare tube exchanger, which prevent fouling inside the tubes, The shell side pressure drop is some lesser but fluid velocity is higher than the conventional heat exchanger which saves the outer surface of tubes from fouling creation and fluid transfer time. The shell diameter of finned tube Exchanger is lesser than Conventional bare tube heat exchanger, which saves sheet material and reduces the size of the shell, which helps to easily installation in the plant. Hari Haran et.al[10] proposed a simplified model for the study of thermal analysis of shell and tube type heat exchangers of water and oil type is proposed. The robustness and medium weighted shape of Shell and Tube heat exchangers make them well suited for high pressure operations. This paper shows how to do the thermal analysis by using theoretical formulae and for this they have chosen a practical problem of counter flow shell and tube heat exchanger of water and oil type, by using the data that come from theoretical formulae they designed a model of shell and tube heat exchanger using Pro-E and done the thermal analysis by using ANSYS software and comparing the result that obtained from ANSYS software and theoretical formulae. For simplification of theoretical calculations they have also done a C code which is useful for calculating the thermal analysis of a counter flow of water-oil type shell and tube heat exchanger. The result after comparing both was that they were getting an error of 0.0274 in effectiveness.

Application of shell and tube heat exchanger

Generally shell and tube type heat exchanger are widely used for various purposes having limitation to be designed for maximum up to 15000 Psi, 1000 ^{0}F and 30000 ft^2/shell. Beyond above given parameters special consideration is required for the design of heat exchanger. The design is ideal for high pressure and temperature services.

Shell and tube heat exchanger are easy to clean for floating head type configuration so can be used in dirty services. It can be used for higher temperature difference services as it can be accommodate thermal expansion. They are most suitable for gas services and phase change service. They can be designed for special operating conditions such as vibration, heavy fouling, highly viscous fluids, erosion, corrosion, multicomponent mixtures and so on. Again, they are used extensively as process heat exchangers in petroleum-refining and chemical industries; as steam generator, condensers, boiler feed water heater and coolers in power plants; as condensers and evaporators in some air-conditioning and refrigeration applications; in waste heat recovery applications with heat recovery from liquids and condensing fluids.

Design methodology

Shell and tube heat exchangers are designed normally by using either Kern's method or Bell-Delaware method. Kern's method is mostly used for the preliminary design and provides conservative results whereas; the Bell-Delaware method is more accurate method and can provide detailed results. It can predict and estimate pressure drop and heat transfer coefficient with better accuracy. In this paper we have described Kern's method of designing in detail. The steps of designing are described as follows:

• First we consider the energy balance to find out the values of some unknown temperature values. Certainly some inputs like hot fluid inlet and outlet temperatures, cold fluid inlet temperature, and mass flow rates of the two fluids are needed to serve the purpose. The energy balance equation may be given as:

$$Q = m_h c_{ph}(t_{h1} - t_{h2}) = m_c c_{pc}(t_{c1} - t_{c2})$$

• Then we consider the LMTD expression to find its value:

$$LMTD = \frac{(\Delta T_1 - \Delta T_2)}{\ln(\frac{\Delta T_1}{\Delta T_2})}$$

where $\Delta T_1 = t_{h1} - t_{c2}$ and $\Delta T_2 = t_{h2} - t_{c1}$

• Next step is to calculate the area required of the heat exchanger (on the basis of assumed (U_o), number of tubes, tube bundle diameter, diameter of shell and its thickness with the help of following expressions:

$$A = \frac{Q}{U_o \Delta T}$$

$$N_t = \frac{A}{\pi d_{t0} l}$$

$$D_b = d_{to}(\frac{N_t}{k_1})^{1/n_1}$$

$$D_i = D_b + additional\ clearance$$

$$D_o = D_i + 2 \times thickness$$

• Then we calculate the proper baffle dimension viz. its diameter, thickness and baffle spacing

• Our next step is to find out heat transfer coefficients on the inner and outer surface of the tubes using following correlation:

$$Nu = 0.27(\mathrm{Re})^{0.63}(P_r)^{0.36}\left(P_r / P_{rw}\right)^{0.25}$$

• Then by the values obtained by the above equation we calculate the actual value of heat transfer coefficient and check whether the actual value is greater than the assumed one or not. If the actual overall heat transfer coefficient is greater than the assumed one then the designing is considered correct, otherwise the steps need to be repeated guessing more accurately the value of overall heat transfer coefficient.

Comsol multiphysics

COMSOL Multiphysics was originally known as FEMLAB because it uses the finite element methods to analyze and solve complex problems. The software comes with several modules in its library for specific application such as Acoustics module, CAD Import module, Earth Science module, MEMS module, Structural Mechanics module etc.

The first step, to creating a model using COMSOL need to create the desired geometry i.e. 2D or 3D geometries which to be evaluated. Irregular geometries are also possible to be made using the various drawing tools available to COMSOL. The next step is to creating Mesh the model. This involves breaking the geometry into subsections that will be evaluated individually and then displayed together to give an overview of the phenomena taking place. It is generally most effective to specify a small mesh size at and near boundaries as this where the most irregularities will occur. After meshing the physics of the model may be defined both throughout the sub domain of the model and at each of the boundaries. Then the model can be solved and post-processing can occur. Post-processing involves manipulating the solution to obtain plots for relevant data and fluxes. Parametric studies can then be performed in order to optimize the model.

Description of the problem and objectives

The problem presented in this paper is to design Shell and Tube type Heat Exchanger where water heating operation is taken into consideration and the heating medium is available at 45 ^{0}C or 318 K which to be heated to 55 ^{0}C or 328 K i.e. a increase of 10 K is desired from the heat transfer in heat exchanger, conforming to the ASME Standards, based on following input data:

► Inlet and outlet temperatures of fluids on shell and tube side

► Tube length= 12000 mm

► Tube outer diameter= 37.8 mm

► Shell outer diameter= 1300 mm

As per the requirement, the objective of the present work is to perform thermal and mechanical design of shell and tube type heat exchanger.

Table 1: Specification of Shell and Tube Heat Exchanger.

Parameter	Description
Size	1300/12000 mm
Surface Area	770 m^2
Shells	2
Heat exchanged	6000.80 kW
LMTD	8.97 ^{0}C

<u>Thermal Design:</u>

i. Mass Flow rate
ii. Heat exchanged
iii. Shell inside temperature
iv. Shell outside temperature
v. Tube inlet temperature
vi. Tube outlet temperature
vii. Heat transfer rate
viii. Tube outlet diameter
ix. Length of tube

▪ LMTD (Log Mean Temperature difference) (θ_m):

$$\theta_m = \Delta T_1 - \Delta T_2 \Big/ \ln\left(\frac{\Delta T_1}{\Delta T_2}\right)$$

$$\theta_m = \Delta T_1 - \Delta T_2 \Big/ \ln\left(\frac{\Delta T_1}{\Delta T_2}\right)$$

$$= (t_{h1} - t_{c2}) - (t_{h2} - t_{c1}) \Big/ \ln\left(\frac{t_{h1} - t_{c2}}{t_{h2} - t_{c1}}\right)$$

= 10.13 ^{o}C

▪ Number of Tubes (n):

$Q = U \times n \times \pi \times d \times L \times \Delta T$ Where n= 615 tubes

▪ Area (A):

$Q = U \times A \times \theta_m$ Where A= 698.32 m^2

Mechanical Design:

i. Internal design pressure
ii. External design pressure
iii. Shell outside diameter
iv. Joint efficiency for longitudinal joint
v. Joint efficiency for circumferential joint
vi. Allowable stress
vii. Element thickness
viii. Shell outlet dia with allowance
ix. Constant factor

▪Shell design under required internal pressure and thickness

(t_r)= $P_s \times D \times K \big/ 2 \times S \times E - 0.2 \times P_s$ = 5.20 mm

▪Maximum allowable working pressure at given thickness = $2 \times S \times E \times t \big/ k \times D + 0.2 \times t$ = 7.01 bar

▪Maximum allowable pressure = $2 \times S \times E \times t \big/ k \times D + 0.2 \times t$ =11.03 bar

▪Actual stress= $P_s \times R \big/ S \times E - 0.6 \times P_s$ = 5.22 N/mm^2

Steps of solving the problem with the help of computational method

a) *Governing equation*

⇨Governing physics selection:

An important characteristics of a flow is often described by the Reynolds number, which is defined as

$$\mathrm{Re} = \frac{\rho U L}{\eta}$$

If the Reynolds number is low, no turbulence model is needed. If, on the other hand, the Reynolds number is high, then the flow is dominated by convection, and a turbulence model is necessary. By using standard values of water for the density and viscosity, the equation gives an approximate Reynolds number of 5000, which is high enough to warrant the use of a turbulent model. The governing equations in this model are

⅄The Reynolds Averaged Navier-Stokes(RANS) equations and a k-ε turbulence model

⅄Fluid (water) heat transfer solid equations

The Non Isothermal Flow interface was selected; thus the above equations are coupled to model the fluid thermal interaction.

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

The temperature dependent properties for water and metals from the built-in material library were used in the model. The software incorporates the influence of the turbulent fluctuations on the temperature field by using the Kays-Crawford model for the turbulent Prandtl number.

$$k_{eff} = k + k_T$$

$$k_T = \frac{C_p \eta_T}{P_r T}$$

b) *Geometry of Shell and Tube Heat Exchanger*

Considering a single section of shell and tube heat exchanger in 2-D gives the following 'figure 2'

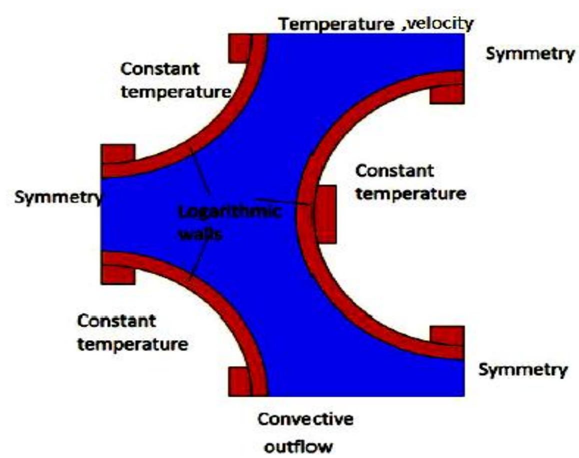

Fig. 2: Cross Sectional view of Shell and Tube type heat exchanger.

c) *Boundary Condition*

The boundary conditions mentioned for the problem are

→K-Ɛ turbulence equations in the fluid domain:
•Specified initial velocity
•Symmetry at the region borders
•Wall function at the pipe/water interfaces
•Fixed outlet pressure
→Heat transport equations:
•Fixed temperature at the inlet
•Convection-dominated transport at the outlet
•Symmetry (thermal insulation) at the region borders
•Thermal wall function at the pipe/water interfaces
•Fixed temperature at the inner pipe surfaces

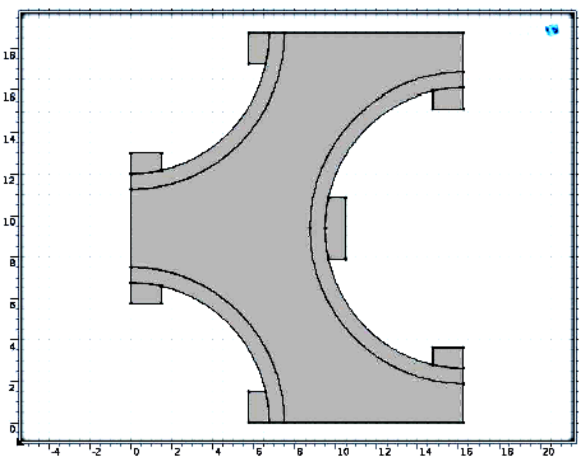

Fig. 3: 2-D geometry model with boundary conditions.

Table 2: Mesh Statistics for shell & tube heat exchanger.

S. no	***Property***	***Value***
1	Minimum element quality	0.8236
2	Average element quality	0.8794
3	Triangular elements	2198
4	Edge elements	184

d) *Meshing*
There are different types of meshing. Selecting a mesh is purely intuitive.
Default meshing was used for this model, because the temperature of the tube side fluid is fixed. This reduces the complexity of the problem. A default mesh with single refinement will give satisfactory results. The finished mesh will look like 'figure 4'.

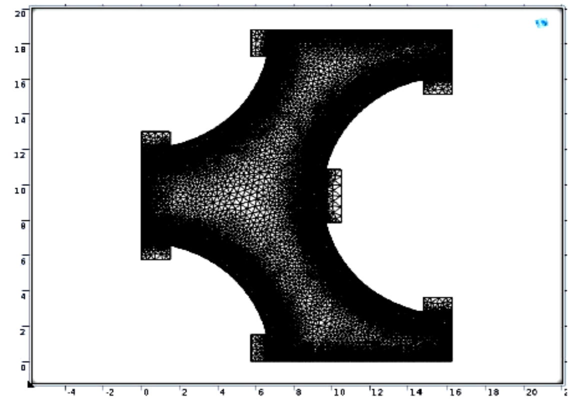

Fig. 4: Meshed view of the shell & tube heat exchanger.

e) *Solving the problem*
There are a wide range of solvers to select from in COMSOL. For all of our simulations, the auto select of solver was used, which detects the type of problem encountered and automatically selects the best solver apt for the given problem. The solver detected was stationery segregated solver, and the same solver was used in all our simulations.

Results and discussion
A software model of shell and tube type heat exchanger is generated using the above derived dimensions. After employing the meshing (a compromise between the accuracy of results and speed of meshing is done) and applying the above stated conditions, solving the model. The material assigned to the shell is stainless steel and assigned to the tubes and baffles is copper. The optimum flow rate for each case has been found and also recorded. Simulation in the COMSOL software is done by taking cross sectional area of shell and tube type heat exchanger. Parameters like heat flow rate of hot water, materials, tube diameter are studied.

Table 3: Parameters for Shell and Tube.

S. No	Mass Flow rate	Pipe material	Inlet temp cold water (K)	Pipe temp (K)	Outlet water temp (Obtained) (K)
Case1	0.302	Aluminum	318.0	324.0	328.3
Case2	0.291	Copper	317.3	322.3	328.2
Case3	0.311	Steel AISI 4340	317.4	324.2	328.0
Case4	0.228	Aluminum	318.1	323.0	328.2
Case5	0.285	Copper	318.0	323.1	328.1
Case6	0.309	Steel AISI 4340	318.2	324.0	328.0

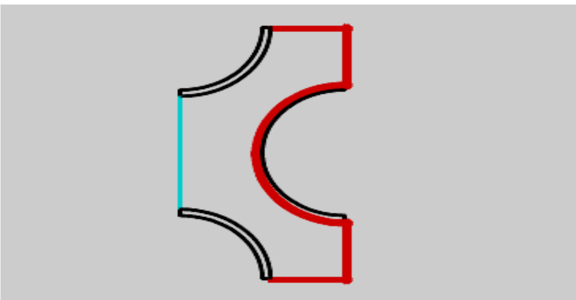

Fig. 5: Boundary Consideration of Shell and Tube for Temperature measurement.

<u>Case 1</u>

In 'Figure 6 & 7' simulation was done for three different mass flow rates and water for both parallel flow and counter flow condition. Parameters adopted for comparison are heat transfer coefficient. For a given flow, rate of hot fluid is 0.05 m/s with pipe material steel AISI 4340 the temperature difference achieved 6.9 K.

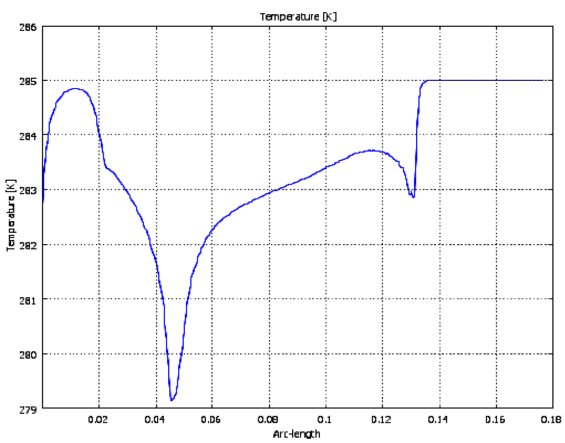

Fig. 6: Temp and Arc length.

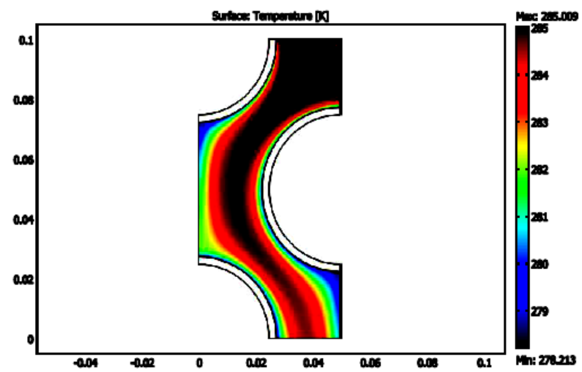

Fig. 7: Surface Plot of Temperature.

<u>Case 2</u>

In order to validate the simulation results important factors like Nusselt number (Nu) was calculated using the correlation for tube. Heat transfer coefficient corresponding to the counter flow is higher than that for parallel flow. This is because the better mixing of fluid particles provided by insert and increase in contact time. In annular insert, it is observed that the heat transfer coefficient varied for counter flow as well as parallel flow. In this case, hot fluid taken in annulus section and cold in inlet pipe. The given flow rate of hot fluid 0.02 m/s with pipe material Aluminum, the temperature difference achieved 9.1 K.

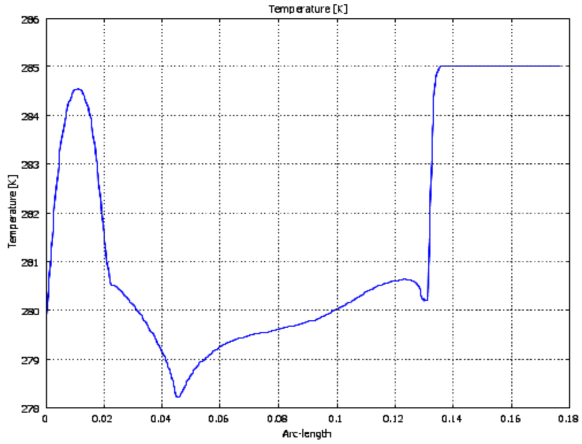

Fig. 8: Temp vs Arc length curve.

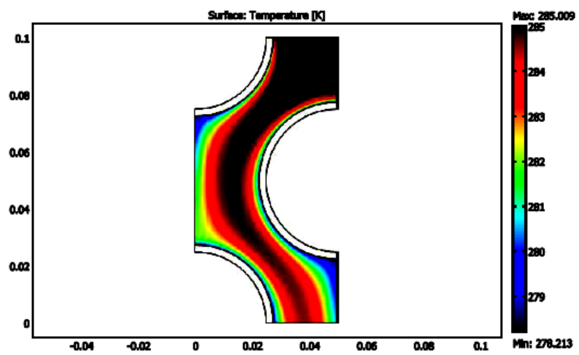

Fig. 9: Surface Plot of Temperature.

Case 3

For lower mass flow rate pressure drop varies linearly whereas on increasing the mass flow rate pressure drop varies exponentially. The pipe material is Steel AISI 4340 and the temperature profile is made graphically.

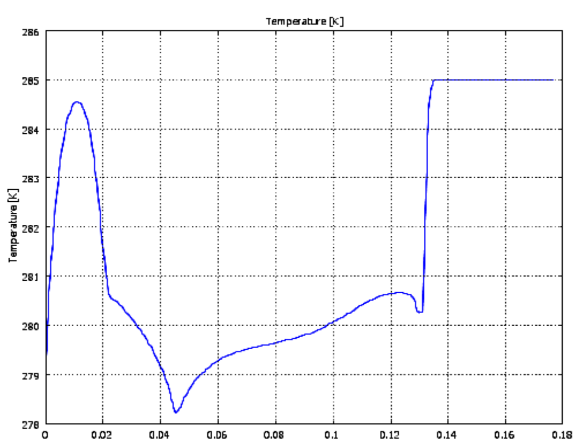

Fig. 10: Temp vs Arc length curve.

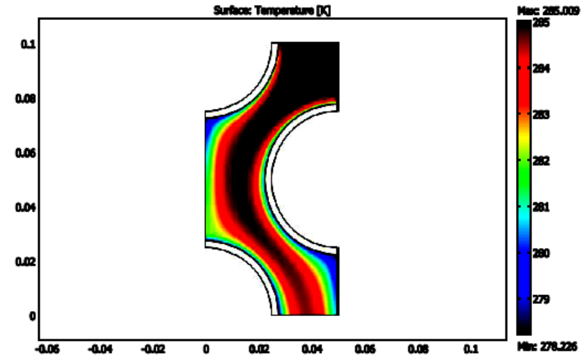

Fig. 11: Surface Plot of Temperature.

Conclusion & future work

The design of Shell and Tube type Heat Exchanger i.e. thermal and mechanical design is carried out using ASME standards both manually and using software. On the basis of above study it is clear that a lot of factors affect the performance of the heat exchanger and the optimization obtained by the formulas depicts the cumulative effect of all the factors over the performance of the heat exchanger. It is observed that by changing the value of one variable by keeping the rest variable as constant we can obtain the different results. Based on that result we can optimize the design of the shell and tube type heat exchanger. After the above discussion it is easy to say that the shell & tube type heat exchangers has been given a great respect among all the classes of heat exchangers due to their virtues like comparatively large ratios of heat transfer area to volume and weight and many more. Moreover well designed as well as described methods are available for its designing and analysis. The literature survey also shows the importance of this class of heat exchangers. It is also shown by the literature survey that the Computational Fluid Dynamics and other software like ANSYS etc. have been successfully used and implemented to secure the economy of time, materials and efforts. However, it is also seen that there does not exists direct relation between the turbulence and effectiveness.

This COMSOL Multiphysics is very helpful in determining the optimum dimensions. It solves using iteration of many random values thereby giving more accurate results.

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