Numerical Analysis of Thermal and Fluid Flow Behaviour for Different Baffle Profiles in Shell and Tube Heat Exchanger

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Abstract – *Study deals with comparative analysis and optimization based on Analytical and Numerical analysis to determine the Thermal and Fluid flow behaviour of Shell and Tube Heat Exchanger with different baffle profiles. The baffle configurations used are:- Single Segmental baffle profiles, Double Segmental baffle profiles and Helical shaped baffle profile. For analytical analysis, the parameters of model of Shell and Tube heat exchanger are followed by TEMA standards. The design is based on KERN's method of design of Shell and Tube heat exchangers. While during numerical analysis, the fluid domain is simulated by CFD tool ANSYS Fluent R16.0 software. The simulation is solved to predict heat transfer and fluid flow characteristics by using k-ε turbulence model. Results are exhibited in ANSYS-Post software in form of contour plots. Results obtained after simulation shows the Shell and Tube heat exchanger with Helical baffle profile have optimum performance among all three models of heat exchangers. The optimality check is based on the values of Overall heat transfer coefficient (OTC) and Pressure drop (ΔP) in both shell and tube sides.*

Key Words: Baffle profiles, Heat Exchanger, Numerical analysis, TEMA, KERN's method.

1. INTRODUCTION

Heat Transfer from one fluid to another is an important operation is Chemical as well as in Mechanical industries. There are several applications are available for such type of heat transfer. Among them, the most common application to transfer heat from one fluid to another is nothing but the equipment called Heat Exchanger. Heat Exchangers are is a system used to transfer heat between two or many fluids. Heat Exchangers are used in both Heating as well as in cooling process as per the applications. The fluids may be separated by solid wall to prevent mixing of fluid or they may be in contact. The Heat Exchangers are widely used in applications such as Space Heating, Refrigeration, Chemical plants, Sewage Treatment, Refineries etc. Shell and Tube Heat Exchangers are one of the most popular types of exchanger due to the flexibility the designer has to allow for a wide range of pressures and temperatures. They are essential equipment for all the major industries like chemical and petrochemical plants, oil refineries, power plants, metallurgical operations, etc. They are employed for several applications such as heating, cooling, condensation, boiling etc. The reasons for this general acceptance are several. Firstly, this equipment provides a comparatively large ratio of heat transfer area to volume as well as weight. It provides this surface in a form which is relatively easy to construct in a wide range of sizes and which is mechanically rugged enough to withstand the normal shop fabrication stresses, shipping and field erection stresses, and normal operating conditions.

1.1 Need of Modification of Baffles profile

Shell and Tube heat exchanger is widely used in industrial area because of its reliability and flexibility in design. The Baffles play vital role in shell and Tube Heat Exchanger assembly. They gives support to tubes and prevent from vibration also they guides the shell fluid, creates turbulence, mixing of fluid and increases Overall Heat Transfer coefficient. Baffle holds the control on shell side flow. In the traditional Shell and Tube Heat Exchanger there used Single Segmental Baffle profiles. Though there is simplicity in design of Single Segmental baffle profiles, there are some limitations which effects on overall performance of set-up of Shell and Tube Herat Exchanger. The limitations are as follows:-

- Fouling is formed in the stagnation zone near the shell wall and the rear of baffle plates.
- Large pressure drops results from baffles' impeding the fluid flow and the flow separation occurs near the baffle edge. Hence higher pumping power is often needed to offset the higher pressure drop under the same heat load.
- Significant bypass streams and leakage streams due to manufacturing tolerances.
- Short operational lifetime as a result of flow induced tube vibration.

1.2 Methods of Design

Shell side flow is complicated to analysis due to baffles. It is thus desirable to understand the flow field and hence, in turn, be able to predict the heat transfer mechanism over a wide range of heat duty and mass velocities on both the sides. In practice two standard methods are generally used for determining the heat transfer and pressure drop on shell and tube heat exchangers which are (a) **Kern Method** (Kern, 1997) and **(b) Bell-Delaware Method** (Bell, 1963). The Kern method is a more conservative approach, hence not yielding optimum designs. The Bell-Delaware method has been found to be relatively accurate in terms of predictions of pressure drop and heat transfer rates. There used a baffles within a shell generally to hold tubes in position (preventing sagging), both in production and operation. Prevent the effects of steam starvation, which is increased with both fluid velocity and the length of the exchanger.

2. OBJECTIVES

The objectives of the current investigation are:-
(1) To Design Shell and Tube Heat Exchanger with single segmental baffles profile by KERN's method followed by TEMA standards.
(2) To carry out analytical analysis of Shell and Tube Heat Exchanger with single segmental baffle profiles.
(3) To carry out Numerical analysis of Shell and Tube Heat Exchanger with Single segmental baffle profiles.
(4) To carry out Numerical analysis of Shell and Tube Heat Exchanger with Double segmental baffle profiles.
(5) To carry out Numerical analysis of Shell and Tube Heat Exchanger with Helical baffle profile.
(6)Generate optimal solution of baffle configuration based on Overall Heat transfer coefficient and pressure drop.

3. ANALYTICAL ANALYSIS

The analytical analysis comprises the design of Shell and Tube Heat Exchanger with single segmental baffles profile followed by TEMA standards. Standard considerations are made based on above methods. The properties based on the mass flow rate and temperature at inlet and outlet in both shell and tubes is given in following table.

Table -1: Fluid Properties

Shell (Hot Fluid)	Tube (Cold Fluid)
$T_{hi} = 67°C$	$T_{ci} = 17°C$
$T_{ho} = 47°C$	$T_{co} = 29°C$
$C_{ph} = 4.182\ kJ/(kg.K)$	$C_{pc} = 4.180\ kJ/(kg.K)$
$\dot{m}_h = 15\ kg/s$	$\dot{m}_c = 25\ kg/s$
$\mu = 5.27 \times 10^{-4}\ Pa.s$	$\mu = 9.09 \times 10^{-4}\ Pa.s$
$v = 1.0144\ m^3/kg$	$v = 1.0028\ m^3/kg$
$k = 0.645\ W/mK$	$k = 0.605\ W/mK$
$h = 225.66\ W/m^2K$	$h = 101.1\ W/m^2K$
Pr = 3.252	Pr = 6.29

Table -2: Material Properties

Part	Material	Density (kg/m3)	Specific Heat (J/(kg.K))	Thermal Conductivity (W/m.K)
Shell	1% Carbon Steel	7801	473	43
Tubes	Brass	8522	385	111
Baffles	Galvanized Steel	8030	470	60

3.1 Analytical Calculations:-

i. Heat Duty:-

$Q = m \times \dot{C_p} \times \Delta T$

$Q = 15 \times 4.182 \times (67 - 47)$

$Q = 1256.1\ kW$

ii. LMTD:-

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

$T_{LMTD} = 33.85\ °C$

For analytical analysis the tube parameters selected as per TEMA standards.

Tube Parameters:-

(a) Considering Velocity of fluid flowing through tubes = $\dot{V} = 2\ m/s$
(b) Tubes Outer diameter:- 1 inch. → $d_o = 25.4\ mm$
(c) Tubes Thickness = 1.5 mm
(d) Tubes Inner Diameter:- $d_i = 22.4\ mm$
(e) Tube Pitch:- $1\frac{1}{4}\ inch$ Square Pitch → $P_T = 31.75\ mm$

To find no. of tubes and shell diameter:-

$$m_c = \rho \times A \times \dot{V} \times \frac{N_T}{N_P}$$

$$25 = 997.2 \times \left(\frac{\pi}{4} \times 0.0224^2\right) \times 2 \times \frac{N_T}{1}$$

$N_T = 31.77 \approx 32$

From Tube - Shell layout table for 1-pass, 1 inch. OD tube with $1\frac{1}{4}$ inch square pitch, corresponding to 32 no. of tubes:-

Shell Inner Diameter:- D_s = 10 $inch.$ = 254 mm
Baffle spacing = B = 300 mm
Length of tubes = 1500mm
No. of Baffles = 4

Corrected velocity:-

$$25 = 997.2 \times \left(\frac{\pi}{4} \times 0.0224^2\right) \times \dot{V} \times \frac{32}{1}$$

$\dot{V} = 1.8\ m/s$

To perform the analytical analysis there required calculating the Overall heat transfer coefficient and pressure drop within both parts i.e. shell and tubes in the STHEX. There used the standard empirical formulae followed by the Reynolds number (Re) and Prandlt number (Pr). The properties of fluid within shell are taken from standard property chart at bulk mean temperature ($T_b = 57°C = 330.15K$) and wall film temperature ($T_w = 61.65°C = 334.8K$) as follows.

- Shell Wall Temperature = $T_w = 61.65°C = 334.54\ K$
- Coefficient of Viscosity at T_w= $\mu_w = 4.66 \times 10^{-4}\ Pa.sec$
- Bulk Mean Temperature= $T_b = 57°C = 330.15\ K$
- Coefficient of Viscosity at T_b= $\mu_b = 5.27 \times 10^{-4}\ Pa.sec$

By empirical relations followed by KERN's method,

- $D_e = \frac{4\left(P_T{}^4 - \left(\frac{\pi}{4}\right) \times d_o\right)}{\pi \times d_o} = 0.02513\ m$
- $C = P_T - d_o = 0.00635\ m$
- $B = 0.3\ m$
- $A_s = \frac{D_s \times C \times B}{P_T} = 0.01524\ m^2$

- $G_s = \frac{\dot{m}}{A_s} = 984.25\ kg/m^2s$
- $R_{es} = \frac{G_s \times D_e}{\mu_f} = 48027$

iii. Shell side Heat transfer coefficient calculations:-

$$\frac{h_0 \cdot D_e}{K} = 0.36 \cdot \left(\frac{D_e \times G_s}{\mu_f}\right)^{0.55} \times \left(\frac{\mu_f \times C_p}{K}\right)^{\frac{1}{3}} \times \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

$h_0 = 5258.77\ W/m^2K$

iv. Tube side Heat Transfer coefficient:-

Reynold's No. equation is given as,

$$R_e = \frac{\rho \cdot \dot{V} \cdot d_i}{\mu_f}$$

$R_e = 44232.23$ And $P_r = 6.29$

From correlation chart,

Coefficient of Friction for $(2300 < R_e < 5 \times 10^6)$

$f = (1.58 \times \ln(R_e) - 3.28)^{-2}$

$f = 5.389 \times 10^{-3}$

Nusselt no. is given as:-

$$N_u = \frac{(f/2) \cdot R_e \cdot P_r}{1.07 + 9(f/2)^{1/2} \cdot (P_r - 1) \cdot P_r^{(-1/4)}}$$

$N_u = 296.19$

$$N_u = \frac{h_i \times d_i}{k}$$

$h_i = 7991.01\ W/m^2K$

3.2 Overall Heat Transfer coefficient:-

From the values of heat transfer coefficient of both shell and tube sides, there calculated the overall heat transfer coefficient for both clean and fouled surface with taking fouling factor as $R_{ft} = 0.000352\ m^2K/kW$ by the correlations as follows

For cleaned surface:-

$$\frac{1}{U_c \cdot \pi \cdot d_o \cdot L} = \left(\frac{1}{h_i \cdot d_i} + \frac{1}{h_o \cdot d_o} + \frac{\ln(d_o/d_i)}{2K_{Tube}}\right) \times \frac{1}{\pi \times L}$$

$$\frac{1}{U_c \cdot d_o} = \left(\frac{1}{h_i \cdot d_i} + \frac{1}{h_o \cdot d_o} + \frac{\ln(d_o/d_i)}{2K_{Tube}}\right)$$

$U_c = 3258.48\ W/m^2K$

For Fouled Surface:-

From fouling factor correlations,

$R_{ft} = 0.000352\ m^2K/kW$

Overall heat transfer coefficient for fouled surface is taken as,

$$\frac{1}{U_f} = \frac{1}{U_c} + R_{ft}$$

$U_f = 3255.03\ W/m^2K$

3.3 Pressure Drop

Pressure drop within shell and tubes calculated by formulae defined in KERN's Method in both shell and tube side.

i. Shell Side Pressure drop:-

$$\Delta P_s = \frac{f \times G_s^2 (N_b + 1) \times D_s}{2 \times \rho \times D_e \times \phi_s}$$

$\Delta P_s = 133.60\ Pa = 0.13360\ kPa$

ii. Tube side pressure drop:-

$$\Delta P_t = \left(4f \times L \times \frac{N_p}{d_i} + 4N_p\right) \times \frac{\rho \times \dot{V}^2}{2}$$

$\Delta P_t = 8.64\ kPa$.

4. NUMERICAL ANALYSIS

4.1 Physical model design:-

Three-dimensional geometrical model of Shell and Tube Heat Exchangers for different baffle profiles has been created on modeling software SOLIDWORKS 13 on the basis of described design parameters as follows.

Table-3 Parameters of Parts of STHEX

Sr. No.	Part	Parameters
1.	Shell	Inner Diameter = 254 mm Thickness = 3.5 mm
2.	Tubes	No. of tubes = 32 OD of tubes = 25.4 mm Thickness = 1.5 mm Effective Length = 1500 mm Tube Pitch = 31.75 mm
3.	Baffles	Cut Ratio = 20 % Thickness = 3.5mm No. of Baffles: = 4 Baffle Pitch = 300 mm

The tube sheet is drawn below on the basis of parameters of STHEX. According to standard data table, no. of tubes with their diameter, pitch and inner diameter of shell are taken. Nozzle for inlet and outlet in shell are placed according to the nozzle design parameter. Thickness is considered to determine the effective heat transfer through wall of shell.

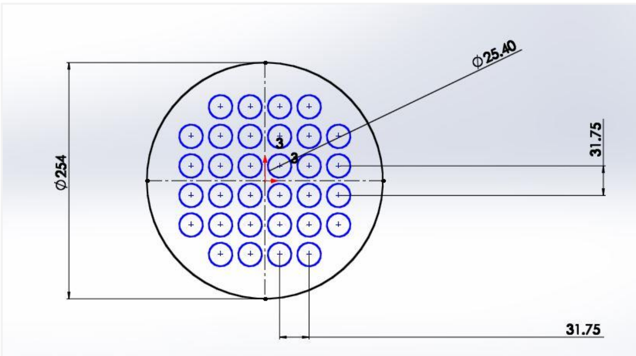

Fig.-1 Tube Sheet drawing

4.2 Baffle profiles Design

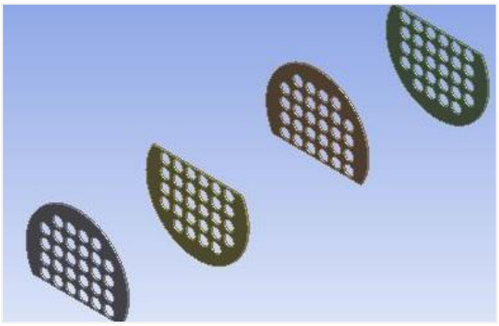

Fig.-2 SS Baffle Profile

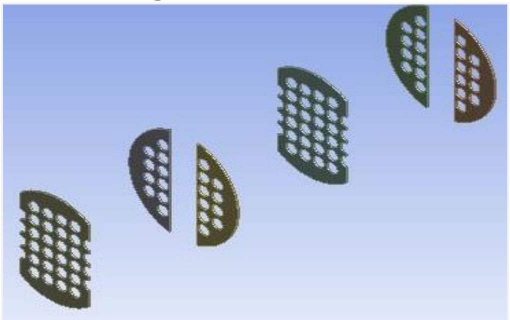

Fig.-3 DS Baffle Profile

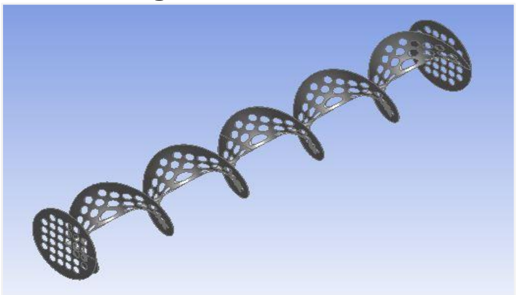

Fig.-4 Helical Baffle Profile

4.3 Physical Model Assembly Design

The physical model design comprises the three types of models by different baffles profiles. All three models create turbulence with different flow patterns. The flow pattern effects on pressure drop as well as the overall heat transfer coefficient. The assembly design of STHEX with corresponding baffle design as shown in following figures.

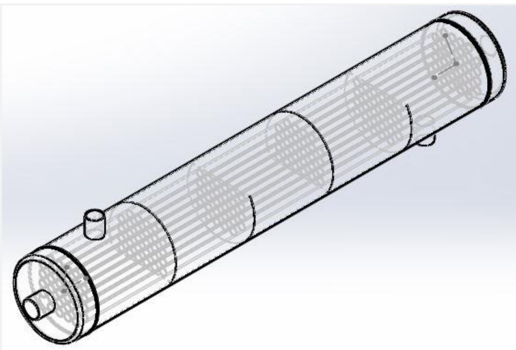

Fig.-5 STHEX with Single segmental baffles

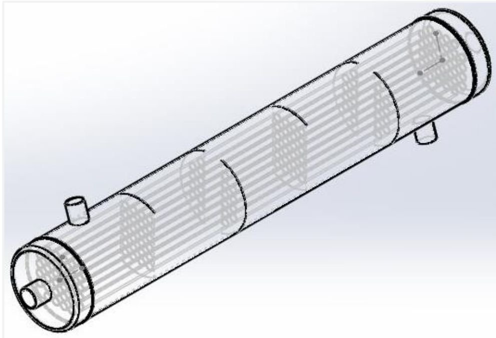

Fig.-6 STHEX with Double segmental baffles

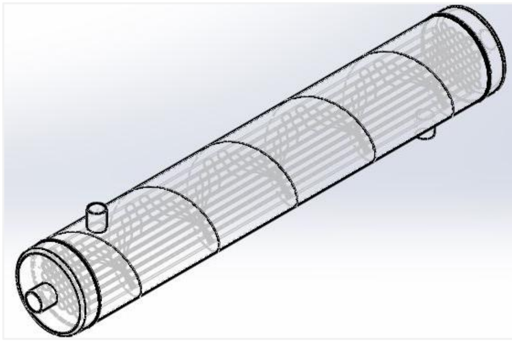

Fig.-7 STHEX with Helical baffle profile

4.4 Meshing

The 3D models of Shell and Tube Heat Exchanger are meshed by ANSYS Fluent 16.0 meshing modular. The meshed quality of the models is solely done using quarts, which improved the accuracy of simulation. The appropriate value of sizing is given to individual parts.

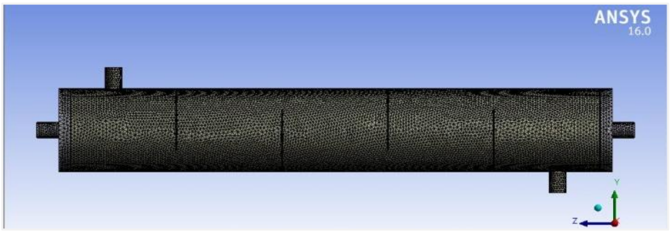

Fig.-8 Meshing of shell fluid domain

The Meshing model of Shell and Tube Heat Exchanger with Single segmental baffles, which compromises mostly tetrahedron elements with average quality around 0.8, average skewness around 0.2. There are around 4,71,321 Nodes and 19,54,146 elements formed in the meshing. The orthogonality is 0.02. In the Meshing model of Shell and Tube Heat Exchanger with Double segmental baffles, which compromises mostly tetrahedron elements with average quality around 0.81, average skewness around 0.19 . There are around 4,52,327 Nodes and 18,50,215 elements formed in the meshing. The orthogonality is 0.021. While the Meshing of STHEX with helical baffle has complicated geometry, thus there defined tri elements for baffle profile. There are around 4,20,127 Nodes and 16,52,953 elements formed in the meshing.

4.5 MATHEMATICAL MODELLING

The process is taking place due to conservation mass, momentum and energy. Turbulence is also one of the governing equations. Here $k - \varepsilon$ used as turbulence model. K-epsilon (k-ε) turbulence model is the most common model used in CFD analysis. This model is used to simulate mean flow characteristics for turbulent flow conditions. It is a two equations model that provides a broad explanation of turbulence by means of two transport equations. Below are the governing equations used for 3D steady state.

i. Continuity Equation:-

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

ii. Momentum Equations:-

X-Momentum:-

$$\frac{\partial(\rho \cdot u)}{\partial t} + \nabla(\rho \cdot \overline{u} \cdot u) = -\frac{\partial p}{\partial x} + \mu\nabla^2 u$$

Y-Momentum:-

$$\frac{\partial(\rho \cdot v)}{\partial t} + \nabla(\rho \cdot \overline{u} \cdot v) = -\frac{\partial p}{\partial x} + \mu\nabla^2 v$$

Z- Momentum:-

$$\frac{\partial(\rho \cdot w)}{\partial t} + \nabla(\rho \cdot \overline{u} \cdot w) = -\frac{\partial p}{\partial x} + \mu\nabla^2 w$$

iii. Energy Equation:-

$$\frac{\partial(\rho C_p T)}{\partial t} + \nabla(\rho \cdot \overline{u} \cdot C_p T) = \nabla(k\nabla \cdot C_p T) + q_v$$

iv. Turbulent Kinetic Energy Equation:-

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \tau_{ij}\frac{\partial u_i}{\partial x_i} - \rho\varepsilon + \mu_t P_B + \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_i}\right]$$

v. Turbulent Dissipation Energy Equation:-

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \omega}{\partial x_i}\right] + S_\varepsilon$$

5. RESULTS AND DISCUSSION

5.1 Contours of STHEX with SS baffles profile

a. Shell side velocity contour:-

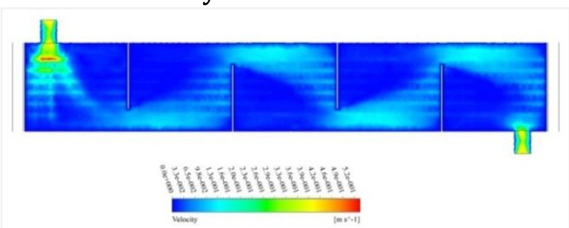

Fig.-9 Shell side velocity contour

b. Shell side pressure contour:-

Pressure variation can be seen due to the resistance by baffle profile. The pressure drop within shell is considerable and found near about 0.14kPa

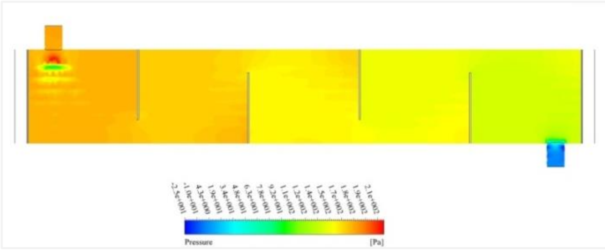

Fig.-10 Shell side Pressure contour

c. Shell side Temperature contour:

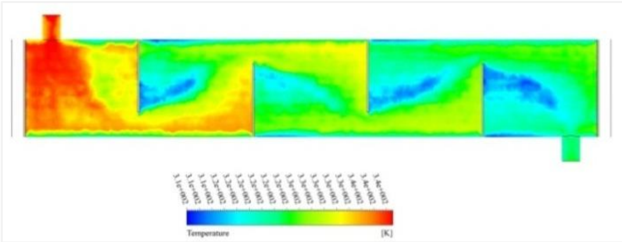

Fig.-11 Shell side Temperature contour

There observed the variation in pressure from inlet to outlet of shell, which is due to the turbulence flow generated because of the baffle profile. There is considerable pressure drop from inlet to outlet. There is considerable change in temperature from inlet to outlet i.e. from 67°C to51.19°C.

5.2 Contours of STHEX with DS baffles profile

a. Velocity contour and flow pattern:-

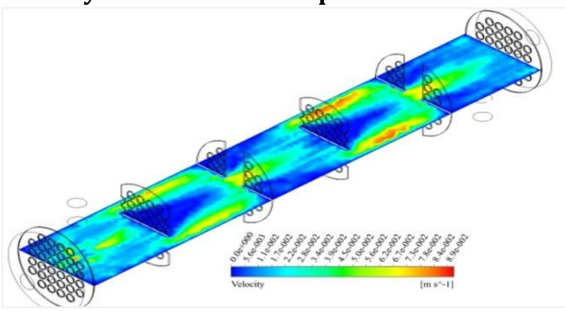

Fig.-12 Shell side velocity contour

Variation in pressure is due to the turbulence created by the DS baffle profile in STHEX.

b. Shell side pressure contour:-

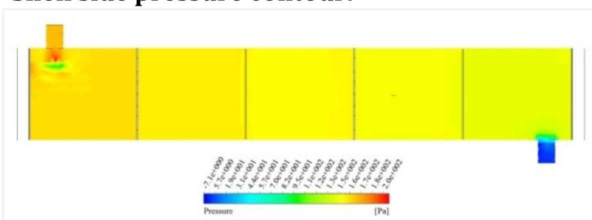

Fig.13 Shell side Pressure contour

c. Shell Side Temperature contour:-

Temperature values are changed gradually followed by the baffle profile. Inlet temperature is 67°C while outlet temperature reached to 50.18°C. Initially the pressure is high i.e. at inlet which is lowered due to baffles. The flow pattern can be observed in the velocity contour.

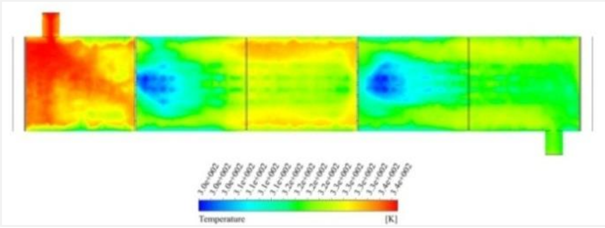

Fig.14 Shell side Temperature contour

5.3 Contours of STHEX with Helical baffles profile

a. Shell side velocity contour:-

The velocity contour shows the flow pattern within shell followed by the helical profile of baffles. The baffle gives direction to flow as well as the create turbulence for mixing of fluid.

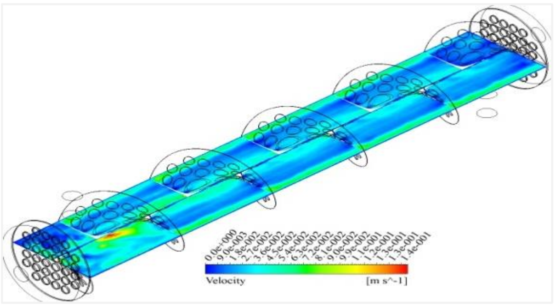

Fig.-15 Shell side velocity contour

b. Shell side pressure contour

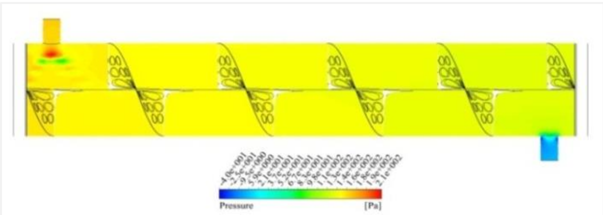

Fig.-16 Shell side Pressure contour

c. Shell side Temperature contour:-

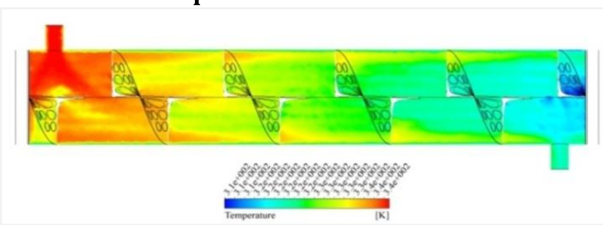

Fig.-17 Shell side Temperature contour

The range of temperature from inlet to outlet is 67°C to 51°C. There observed pressure distribution in shell fluid domain is followed by the baffle profile. As the helical shape of baffles generated turbulence, there the pressure is gradually decreasing.

5.4 Tube side pressure drop:-

The contour of pressure drop within tubes is near about same in all three cases. The pressure drop in tubes cased due to the surface roughness of tubes. From inlet to outlet the average value of pressure drop is 10.193 kPa.

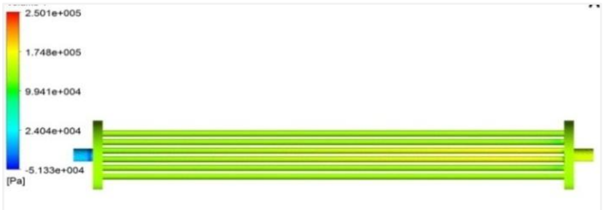

Fig.-18 Tube side Pressure contour

5.5 Graphical Representations of Results:-

From the graphical representation there elaborated the comparative analysis on the basis of values and found the optimal results.

a. Shell Side pressure drop:-

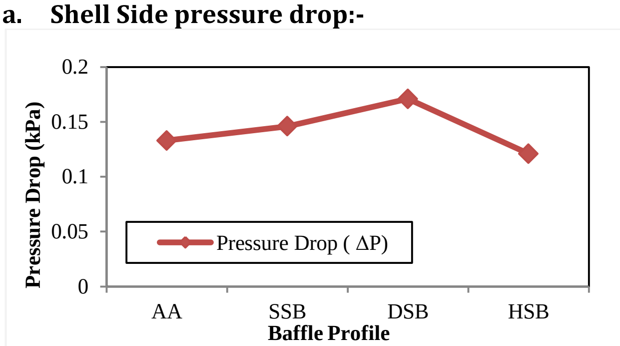

Fig.-19 Graph-Shell side pressure drop

b. Tube side pressure drop:-

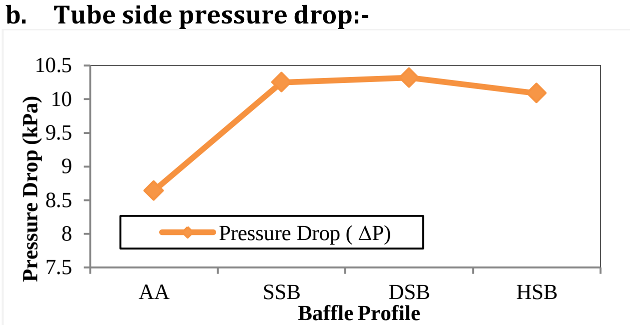

Fig.-20 Graph-Tube Side pressure drop

c. Overall Heat Transfer coefficient:-

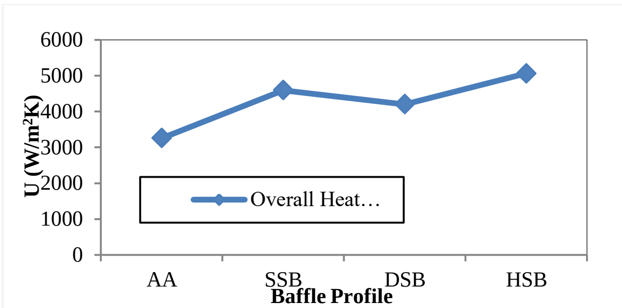

Fig.-21 Graph-Overall Heat Transfer coefficient

Overall heat transfer coefficient value calculated in analytical analysis. Then in numerical analysis, for STHEX with single segmental baffle has value of U is around 4592.6 W/m^2K. The U value for double segmental baffle is around 4198.49 W/m^2K while for helical baffle has maximum value of U i.e. 5059.9 W/m^2K. The values are based on the turbulence created due to baffle profiles in all three models. There is difference between the numerical and analytical value, which is under accepted limit.

5. CONCLUSION

Design of Shell and Tube Heat exchanger with single segmental baffles profile is done followed by TEMA standards and analytical analysis done by KERN's method. The numerical analysis is done over the models of Shell and Tube Heat Exchanger with different baffle profiles such as Single segmental baffle profile, Double segmental baffle profile and Helical baffle profile to determine the thermal and fluid flow behaviour. The results are compared with the analytical analysis. There observed Helical baffle profile has maximum value of overall heat transfer coefficient (U) while double segmental baffle profile have lowest value of U. In case of pressure drop, the value of ΔP is highest in case of Shell and Tube heat exchanger with double segmental baffle profile while, the value of ΔP is lowest in case of helical shaped baffle profile. Thus the STHEX with helical baffle profile gives optimum results among all three models of Shell and Tube Heat Exchanger.

NOMENCLATURE

Letters	Specification
T_{ci}	Inlet Temperature of Cold fluid
T_{co}	Outlet Temperature of Cold fluid
T_{hi}	Inlet Temperature of Hot fluid
T_{ho}	Outlet Temperature of Hot fluid
C_{pc}	Specific Heat Capacity of Cold fluid
C_{ph}	Specific Heat Capacity of Hot Fluid
$\dot{m}_h$	Mass flow rate of Hot fluid
$\dot{m}_c$	Mass flow rate of Cold Fluid
h	Heat transfer coefficient
v	Specific volume
k	Thermal conductivity
μ	Coefficient of viscosity
P_r	Prandtl Number
N_u	Nusselt Number
R_e	Reynold's Number
D_s	Diameter of Shell
d_i	Inner Diameter of Tube
d_o	Outer Diameter of Tube
N_T	Number of Tubes
N_b	Number of Baffles
T_w	Shell wall Temperature
T_b	Bulk mean Temperature
A_S	Surface area
h_i	Heat transfer coefficient Tube side fluid
h_o	Heat transfer coefficient of Shell side fluid
ΔP_s	Shell side pressure drop
ΔP_t	Tube side pressure drop
U_c	Overall heat transfer coefficient of cleaned surface
U_f	Overall heat transfer coefficient of fouled surface
U_o	Overall heat transfer coefficient
R_{ft}	Fouling Factor
B	Baffle spacing
T_{LMTD}	Logarithmic Mean Temperature Difference
$\dot{V}$	Velocity of fluid
f	Coefficient of friction
L	Length of tubes

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