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Performance Evaluation of Shell-and-Tube Heat Exchanger with 3-Fluid Sets using CFD and NTU

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Abstract: Energy generation to the present growing population is a crucial challenge for the power sector. Heat exchangers (HE) plays an important role in the industrial development. In this present work an attempt is made to develop a Shell-and- Tube Heat Exchanger (STHE) with segmental baffles using commercial CATIA V5 and Autodesk CFD Simulation Softwares. TEMA standards are considered for design of STHE with baffle-cut of 25%. 3-different sets of fluids are allowed to pass through the shell and tube sides i.e. Methanol - Sea Water (M-S), Distilled Water – Raw Water (D-R) and Kerosene- Crude Oil (K-C). The boundary conditions imposed for analysis are fluid inlet temperatures and velocities. ϵ-NTU is employed for the validation of simulation results and found good agreement between them. Results are plotted for temperature, pressure and velocity contours. The performance of the STHE is shown best for the K-C fluid set among other fluid sets.

Keywords : Autodesk, Catia, CFD, Fluid Flow, STHE.

I. INTRODUCTION

STHEs are widely used Heat Exchangers for heavy industries due to their manufacturing and maintenance flexibilities. A wide variety of configurations are introduced to control the flow rates and to maintain the pressure drops. Maximum pressure drop is achieved by STHEs. A typical single shell and double tube pass STHE is shown in fig.1.

Fig. 1. Shell and Tube Heat Exchanger

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II. LITERATURE SURVEY

Tingting DU and Wenjing DU [1] made an attempt to study the characteristics of STHE with overlapped helical baffles. He demonstrated the numerical CFD with simulation. Sampath Emani et al. [2] processed simulations on STHE with crude oil as fluid to study deposition of asphaltenes particles. Juan Xiao et al. [3] worked on ladder type baffles with coal water slurry to investigate preheating technology.

STHEs with staggered baffles has analyzed by Xinting Wang et al. [4] to find optimal performance of HE. Gugulothu et al. [5] investigated performance of STHE numerically with different mass flow rates at 40^0 helix baffle. Increasing the flow velocities caused the rise in the heat transfer coefficient and more pressure drop.

Usman Salahuddin et al. [6] conducted a review on helical baffles in STHEs and made useful conclusions. Muhammad Mahmood et al. [7] had given a vast review on CFD application for HEs.

Based on the inspiration from the extensive literature review, this work is focused on STHEs with different fluids with different baffle configurations. Finally found baffle spacing 85 mm gives optimum results. So, 12 baffles with TEMA standard parameters this work continued.

III. MATERIALS AND METHODOLOGY

A. Materials

The standard materials are considered for the design of STHE.For the tube and tube sheet high conductivity material considered. For shell body high strength material considered.

Table- I: Materials for STHE

S.No	Component	Material
1.	Shell	Stainless Steel (304)
2.	Tube	Copper
3.	Tube Sheet	Copper

B. Design Parameters

The standard TEMA specifications are followed to design the HE. Kern Method [8] also used to calculate the dimensions of HE components. Conventional standard formulas are used for the HE design

C. Fluid Properties, Boundary Conditions.

The Boundary Conditions considered are Inlet temperatures, Velocities and outlet gauge pressure.

Table- II: Design Parameters for Heat Exchanger

S.No.	Description	Unit	Value
1	Heat Exchanger Length, L	mm	1000
2	Shell Inner Diameter, D_i	mm	100
3	Shell outer diameter, d_o	mm	106
4	Tube Length, l	mm	1000
6.	Tube Outer Diameter, d_o	mm	19.06
7.	Number of Tubes, N_t	-	10
8.	Tube Pitch Triangular, P_t	mm	25
9.	Baffle Cut Portion	%	25
10.	Baffle Spacing, B	mm	85
11.	Side Plate DiameterD_{sp}	mm	100
12.	Side Plate Thickness T_{sp}	mm	3
13.	Baffle Thickness Δ_{BT}	mm	3

Table- III: Properties of Fluids

	M kg/s	T input ^{0}C	ρ kg/m^3	Cp kJ/kgK	μ Pa-s	k W/mK	R_f m^{2}K/W
Shell Side: Methanol	10	95	750	2.84	0.00034	0.19	0.00033
Tube Side: Sea Water	18.8	25	995	4.20	0.00080	0.59	0.00020
Shell side: Distilled Water	10	95	995	4.18	0.00080	0.62	0.00017
Tube Side: Raw water	18.8	25	999	4.18	0.00092	0.62	0.00017
Shell Side: Kerosene	10	95	850	2.47	0.00040	0.13	0.00061
Tube Side: Crude Oil	18.8	25	995	2.05	0.00358	0.13	0.00061

IV. MATHEMATICAL ANALYSIS

Max. heat transfer $Q_{max} = C_{min}(T_{hi} - T_{ci})$ W (1)

Heat transfer area $A = L\pi d_o N_t$ m^2 (2)

A. Tube Side Calculations

Tube side velocity

$V_t = (m_t/(\rho_t d_i^2 \times \pi/4)) \times (n/N_t)$ (3)

Reynolds number $R_{et} = ((\rho_t V_t d_i)/\mu_t)$ (4)

Prandtl number $Pr_t = (\mu_t c_{pt})/k_t$ (5)

Convective heat transfer coefficient

$h_t = 0.027 \times k_t/d_i \times Re_t^{0.8} \times Pr_t^{(1/3)} \times (\mu_t/\mu_w)^{0.14}$ (6)

B. Shell Side Calculations

Equivalent diameter

$d_e = 4(0.43 \times P_t^2 - (0.5) \times \pi \times (d_0^2)/4)/(0.5\pi d_0)$ (7)

Area of shell $A_s = d_s \times B \times (P_t - d_0/P_t)$ (8)

Shell side velocity $V_s = m_s/(A_s \rho_s)$ (9)

Reynolds number $R_{es} = (\rho_s V_s d_e)/\mu_s$ (10)

Prandtl number $Pr_s = (\mu_s c_{ps})/k_s$ (11)

Convective heat transfer coefficient

$h_s = 0.36 \times (k_s/d_e) \times R_{es}^{0.55} \times Pr_s^{(1/3)} \times (\mu_t/\mu_s)^{0.14}$ (12)

Overall heat transfer coefficient

$U = 1/(1/h_s + R_{fs} + (d_o/d_i) \times (R_{ft} + 1/h_t))$ (13)

Number of Transfer Units $NTU = UA/C_{min}$ (14)

Effectiveness

$\epsilon = 2(1+c+(1+c^2)^{0.5} \times ((1+e^{(-N(1+c^2))^{0.5}})/(1-e^{(-N(1+c^2))^{0.5}})))^{(-1)}$ (15)

Actual heat transfer = $Q_{act} = \epsilon \times Q_{max}$ (16)

C. CFD Equations

The Governing equations for the CFD analysis are

Continuity equation: $\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho u) = 0$ (17)

Momentum Equation:

Stress components in x – direction (18)

$$\frac{\partial Du}{Dt} = \frac{\partial(-p+\tau_{xx})}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

Y – Component of the momentum equation (19)

$$\frac{\rho Dv}{Dt} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(-p+\tau_{yy})}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{My}$$

Z – Component of the momentum equation (20)

$$\frac{\rho Dw}{Dt} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial(-p+\tau_{zz})}{\partial z} + S_{Mz}$$

Energy Equation

Rate of increase of energy = Net rate of heat added to fluid particle + Net rate of work done on fluid particle (21)

V. MATHEMATICA/L ANALYSIS

Manufacturing of STHEs involves a huge investment cost, therefore CAE is the best alternative for the testing of HEs. Here CATIA V5 software is used for modelling of STHE. The CFD analysis part is carried out by Autodesk CFD 2015. The machine used for the analysis is intel i7-7th generation quad core processor with 8 GB RAM. The average time for each case simulation is 6 hrs.

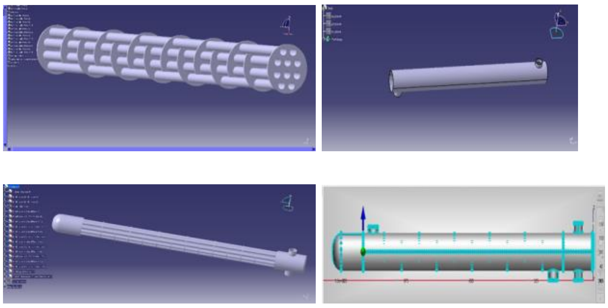

Fig. 2.Modelling and Meshing

VI. RESULTS

A. Methanol - Seawater (M-S)

The shell side and tube side fluids are Methanol & Seawater . The solution is converged at 489th iteration.

a. Temperature Contour

As the inlet temperatures of the HE are fixed, the outlet temperature of the Methanol & Sea Water are 29.61 ^{0}C & 32.98 ^{0}C respectively.

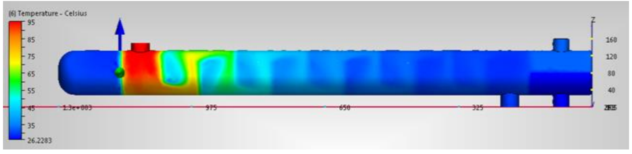

Fig. 3.Temp Distribution across STHE with M-S as Fluids.

b. Velocity Contour

Velocity magnitude profile is used to examine the flow distribution across the HE.

From the results it is clear that the velocity of the methanol is decreased where the sea water velocity increases slightly.

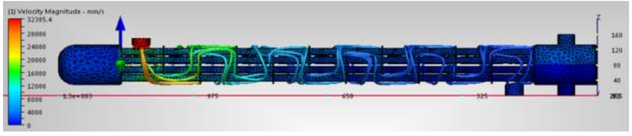

Fig. 4.Velocity Contour of M-S Fluids

a. Pressure Contour

The outlet pressure of STHE is taken as zero Pascal (boundary condition), the maximum pressures are 669596 N/m^2 and 1394120 N/m^2 respectively at shell and tube side .

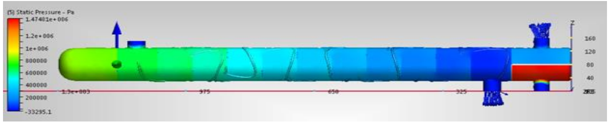

Fig. 5.Pressure Contour of M-S Fluids

B. Distilled Water – Raw Water (D-R)

With the same parameters, now the introduced working fluids are Distilled water and Raw water. The solution is converged at 561th iteration.

a. Temperature Contour

The outlet temperatures obtained for fluids D-R are 39.25^{0}C and 35.23^{0}C respectively.

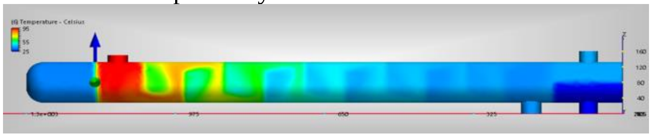

Fig. 6.Temperature Distribution across STHE with D-R as fluids

b. Velocity Contour

The maximum velocity occurs in the tube side is 19.401 m/s and velocity in the shell side is 8.371 m/s.

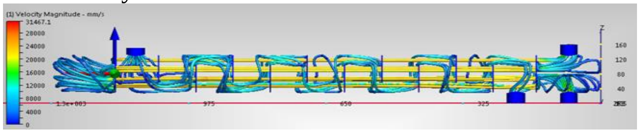

Fig. 7.Velocity Contour of D-R fluids

c. Pressure Contour

The maximum pressure obtained at the shell side is 960990 N/m^2 and tube side is 1263690 N/m^2.

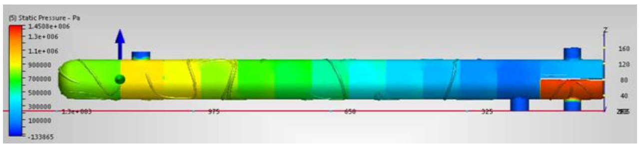

Fig. 8.Pressure Contour of D-R fluids

C. Kerosene – Crude Oil (K-C)

The working fluids in the STHE are Kerosene and Crude oil. The solution is converged at 302th iteration.

a. Temperature Contour

The outlet temperature obtained are 34.94^0 C and 40.98^0 C for K-C fluids.

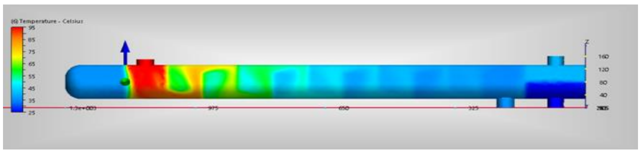

Fig. 9.Temperature Distribution across STHE with K-C fluids

b. Velocity Contour

The results shown that velocity occurs in the tube side and shell side are steady.

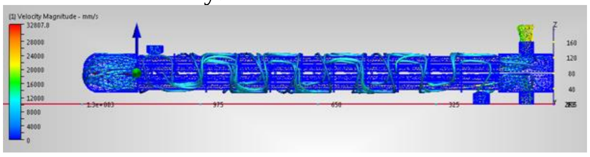

Fig. 10. Velocity Contour of K-C fluids

c. Pressure Contour

The maximum pressure obtained at the shell inlet is 818462 N/m^2 and tube inlet is 1263690 N/m^2.

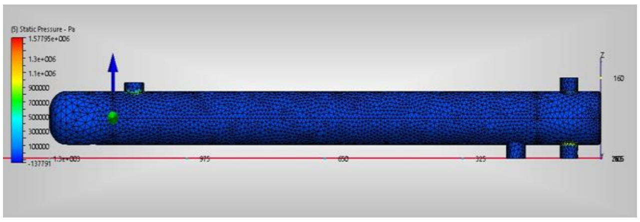

Fig. 11. Pressure Contour of K-C fluids

VII. DISCUSSIONS

The performance of the STHE is discussed based on the results obtained for 3-different sets of fluids. The following table shows the outlet temperature comparison for different fluid sets.

Table- IV: Temperature Results for Three Different Set of Fluids

S.No	Fluids		Shell Side Temperature (^{0}C)		Tube side Temperature (^{0}C)	
	Shell side	Tube side	Inlet	Outlet	Inlet	Outlet
1.	Methanol	Sea water	95	29.61	25	32.98
2.	Distilled water	Raw water	95	39.25	25	35.23
3.	Kerosene	Crude oil	95	34.94	25	40.98

A. Temperature Distribution for M-S fluids

The shell side and tube side fluids are entering at 95^{0}C & 25^{0}C and exiting at 29.61^{0}C & 32.98^{0}C. The tube side cold fluid has two passes. In 1st pass fluid temperature gains from 25^{0}C to 51.73^{0}C and in 2nd pass temperature drops from 51.73^{0}C to 32.98^{0}C.

This show that the cold fluid is hotter than cold fluid at the exit. It happens because of heat capacity of fluids.

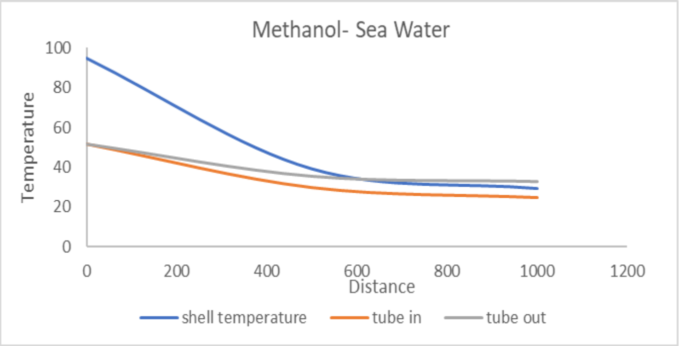

Fig. 12. Distance (mm) vs Temperature (^{0}C) for M-S fluids. The distance shown in two passes for tube and one pass for shell

B. Temperature Distribution for D-R fluids

As the inlet temperatures are fixed, the outlet temperatures for shell & tube side are 39.25^{0}C & 35.23^{0}C. The cold fluid has two passes. In 1st pass its temperature reaches from 25^{0}C to 66.31^{0}C and in 2nd pass temperature again decreases from 66.31^{0}C to 35.23^{0}C.

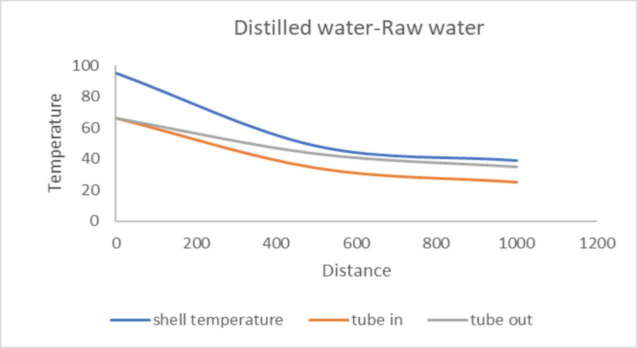

Fig. 13. Distance (mm) vs Temperature (^{0}C) for D-R fluids

C. Temperature Distribution for K-C fluids

The outlet temperature for shell and tube side fluids are, 34.94^{0}C & 40.98^{0}C. The cold fluid has two passes in one pass its temperature reaches from 25^{0}C to 76.55^{0}C and in second pass temperature again decreases from 76.55^{0}C to 40.98^{0}C

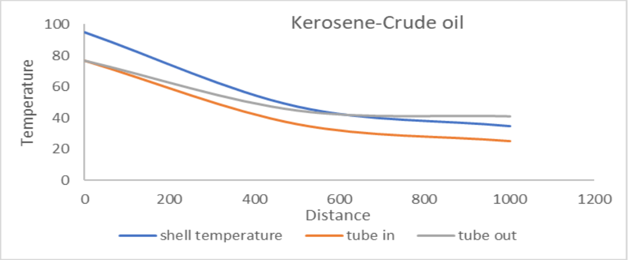

Fig. 14. Distance (mm) vs Temperature (^{0} C) for K-C fluids

D. Temperature Comparison for Shell Side

The Fluid which is entering from Shell Side with inlet temperature as 95°C and outlet as 29.61°C minimum for methanol. The temperature difference for methanol, distilled water and kerosene is 65.39°C, 55.75°C, and 60.06°C respectively. Thus we obtained maximum temperature difference for methanol. Since heat exchangers are used for heat exchanging purpose thus the fluid which lost more heat is said to be better.

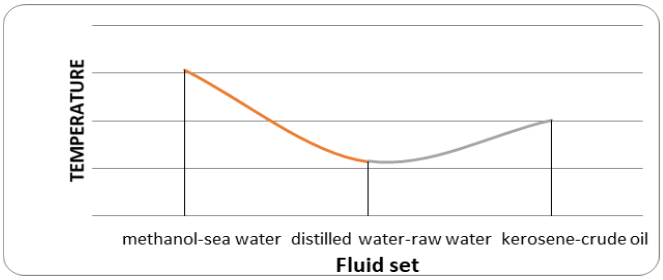

Fig. 15. Fluid set vs Temperature (^{0}C) at shell side

E. Temperature Comparison for Tube Side

The Fluid which is entering from Tube Side with inlet temperature as 25°C and outlet as 32.98°C minimum for sea water.the temperature difference for sea water, raw water and Crude oil is 7.98°C, 10.23°C, and 15.98°C respectively. Thus we obtained minimum temperature difference for sea water.

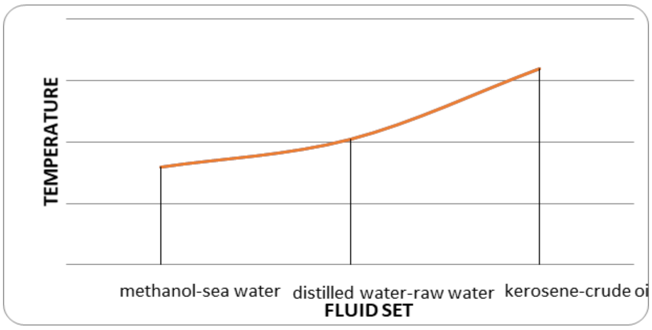

Fig. 17. Fluid set vs Temperature (^{0} C) at tube side

F. Validating the Results

The outlet temperatures for shell and tube side of a shell and tube heat exchanger obtained by NTU Method & CFD Simulations are shown in the below. The simulation values shown good agreement with the mathematical results. Also the fluid sets shown good increament in the heat transfer rate. This shows the sthe works better with the 3rd fluid set.

Table- V: Temperature Results by NTU method and CFD Simulations

S.No	FLUIDS		NTU method results Outlet temperature (^{0}C)		CFD Simulation results Outlet temperature (^{0}C)	
	Shell side	Tube side	Shell side	Tube side	Shell side	Tube side
1	Methanol	Sea water	33.57	37.62	29.61	32.98
2	Distilled Water	Raw water	44.24	41.23	39.25	35.23
3	Kerosene	Crude oil	36.64	38.92	34.94	40.98

VIII. CONCLUSION

A novel STHE paper is designed and analyzed with commercial softwares, and validated with ϵ-NTU method. Three sets of fluids are evaluated and various contours of temperature and velocity across the double pass Shell and Tube Heat Exchanger are found.

From results it is clear that shell side fluid temperature decreases from shell inlet to outlet in single pass by gaining coldness from cold fluid and for tube the temperature increases to a greater extent in first pass and then decreases in second pass.

For the same process parameters for three set of fluids, the results obtained are

(1) In the methanol-sea water fluids, methanol has temperature loss from 95°C to 29.61°C and sea water has gained temperature from 25°C to 32.98°C.

(2) In the distilled water-raw water fluids, distilled water has temperature loss from 95°C to 39.25°C and raw water has gained temperature from 25°C to 35.23°C.

(3) In the kerosene-crude oil fluids, kerosene has temperature loss from 95°C to 34.94°C and crude oil has gained temperature from 25°C to 40.98°C.

The results obtained from CFD Simulation are in good agreement with the mathematical calculation done by NTU method with a variation of 9-14%. The performance of the STHE is found better rate when methanol and sea water as working fluids.

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