Comparative Thermal Analysis of Shell and Tube Heat Exchanger using Bell Coleman Method and CFD

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***Abstract*— Design, analysis and optimization of shell and tube heat exchanger using Bell Coleman Method and CFD. Design variables: tube outer diameter, tube pitch, tube length, number of tube passes, no of shell, shell head type, shell layout, baffle spacing and baffle cut are taken for optimization. Bell's method is used to find the heat transfer area for a given design configuration. The optimal analysis be the one tube, sectional one tube and sectional heat exchanger.**

Keywords—***Bell Coleman Method, One tube, sectional tube, sectional heat exchanger, shell and tube heat exchanger, Computational Fluid Dynamics.***

I. INTRODUCTION

A. Background Study

Heat exchangers are widely used in heat transfer from one to another fluid. It is used equipment in various industries such as process, power generation, and transportation and refrigeration industry.

B.Shell and tube heat exchanger

The basic principle of operation is fluid flow in shell and tube side with different temperature.The fluids can be either liquids or gases on either the shell or the tube side. In this system the large surface area used to heat transfer is the tube wall leading to use many tubes.

II. DESIGN BY USING BELL COLEMAN METH

Nomenclature

Q = Total Heat Generated
Wc = Cold fluid flow rate (Water)
Cc = Specific Heat of cold fluid
Tco = Cold fluid outlet
Tci = Cold fluid inlet
Wh = Hot fluid flow rate (steam)
Ch = Specific Heat of hot fluid
Thi = Hot fluid inlet
Tho = Hot fluid outlet
LMTD = Log Mean Temperature Difference
Ft = Temperature Difference Factor
Fc = Caloric Temperature Factor
ID = Internal Diameter
B = Baffle Spacing
Gs = Mass velocity
As = Shell Side flow area
Pt = Tube pitch
BWG = Birmingham Wire Gauge
Re = Reynolds number
De = Effective Diameter
C = Specific Heat
μ = Viscosity at the caloric temperature
μ_w = Viscosity at the tube wall temperature
K = Thermal Conductivity
Gt = Tube Side Mass velocity
At = Tube Side flow area
h_0 = Corrected coefficient
Uc = Clean overall coefficient
U_D = Design Overall Coefficient
R_d = Dirt Factor
d_e = Equivalent Diameter
ΔPs = Pressure Drop in Shell Side
f = Friction factor sqft/sq in
(N+1) = Number of Baffles in the Shell
ΔPt = Tube side Pressure Drop
n = number of passes
ΔPr = Return Crosses Pressure Drop
ΔP_T = Total pressure drop of entire tube

A. Heat Balance:-

Tube Side
Wc=20TPH=5.556kg/s, 1TPH=2205lb/hr
Wc=20×2205=44100 lb/hr = 5.55 Kg/s
Cc(Water)=1Btu/lb^0 f
Tco= 176˚f =80 ^{0} C , Tci = 86 ^{0} f = 30 ^{0} C
Q=Wc ×Cc×(Tco-Tci)
Q=44100 ×1×(176-86)
Q=3969000 Btu/hr = 1163199.07 Watt
Wh=4TPH= 1.11kg/s, 1TPH=2205lb/hr
Wh=4×2205=8820 lb/hr = 1.1113 Kg/s
Ch(Steam at 572 ^{0} f = 300 ^{0} C)=1.3 Btu/lb^{0}f
Thi=572 ^{0}f = 300 ^{0} C , Tho=?
Q=3969000Btu/hr = 1163199.07 Watt
Q = Wh ×Ch×(Thi-Tho)
3969000 = 8820×1.3×(572-Tho)
Tho = 225.846 ^{0} f = 107.69 ^{0}C

B.LMTD (Δt):-

Δt2=Thi-Tco=572-176=396 ^{0} f
Δt1=Tho-Tci=225.84-86=139.84 ^{0}f = 59.91 ^{0} C

$$\text{LMTD}(\Delta t) = \frac{\Delta t2 - \Delta t1}{\text{In } \Delta t2/\Delta t1}$$

$$= \frac{396 - 139.84}{\text{In }(396/139.84)}$$

$$\text{LMTD}(\Delta t) = 246.09\ ^{0}f = 118.93\ ^{0}C$$

C. Shell Side Detail:-

1) Flow Area (As)

$$As = \frac{ID \times C \times B}{144 \times Pt}\ Ft^2$$

Where ID,C,B,Pt are in inches
ID of shell =15.25 inch =381.25mm=1.27 ft
C = Pt – OD of tube =1.25-1=0.25 inch =6.25 mm
B=(0.2 to 1) ID=15.25 inch=381.25 mm

$$As = \frac{15.25 \times 0.25 \times 15.25}{144 \times 1.25}\ Ft^2$$

$$As = 0.323\ ft^2 = 0.0300076\ m^2$$

2) Mass Velocity

$$Gs = Wh/As \quad lb/hrft^2$$

$$= \frac{2205 \times 4}{0.323}$$

$$Gs = 27306.50\ lb/hrft^2 = 37.0339\ Kg/s\ m^2$$

3) Reynolds Number

$Re = De \times Gs / \mu$
Where $De = de/12 = 0.99/12 = 0.0825$
$\mu = Cp \times 2.42$ lb/ft-hr
$= 0.015 \times 2.42$
$\mu = 0.0363$ lb/ft-hr $= 0.0363$ Kg/m hr
$Re = De \times Gs / \mu$

$$= \frac{0.0825 \times 27306.50}{0.0363}$$

$Re = 62059.09$

7) $J_H = 100$

8) $K = 0.3117$ Btu/hr-ft^2 (^{0}f/ft) = 53.9109 KW/m$^{2\,0}$C

9) $ho/\phi_s = J_H \times K/De \times (c\mu/k)^{1/3}$ Btu/ft-hr - ^{0} f

$$= 100 \times \frac{0.3117}{0.0825} \times \left(\frac{1.36 \times 0.0363}{0.3117}\right)^{1/3}$$

$ho/\phi_s = 204.54$ Btu/ft-hr - ^{0} f = 354 watt/m ^{0}K

11) Tube Wall Temperature (Tw)

$$Tw = Tc + \frac{ho/\phi_s}{ho/\phi_s + hio/\phi t}(Tc - tc)$$

$$Tw = 322.76 + \frac{204.54}{204.54 + 62.124}(322.76 - 116.6)$$

$Tw = 480.891\ ^{0}f = 249.384\ ^{0}C$
$\mu_w = 0.018 \times 2.42$
$\mu_w = 0.04356$
$\phi_s = (\mu/\mu_w)^{0.14}$
$= (0.0363/0.04356)^{0.14}$
$\phi_s = 0.9747$

12) Corrected Coefficient

$h_0 = (h_o/\phi_t) \times \phi_t$ Btu/hr-ft^2 ^{0}f
$= 204.54 \times 0.9747$
$h_o = 199.365$ Btu/hr-ft^2 ^{0}f $= 1131.29$ w/m^2 K

D. Tube side Detail:-

1) Flow Area (As)

$$At = \frac{Nt \times a_t}{144 \times n}\ Ft^2$$

Where At is in inches
ID of tube =0.834 inch = 20.85mm
Thickness of tube = 0.083 inch =2.075 mm
OD of tube =1inch=25mm
Length of tube =72 inch=1800 mm
BWG=14
$a_t = 0.268$ inch^2

$$At = \frac{81 \times 0.268}{144 \times 1}\ Ft^2$$

$$At = 0.15075\ ft^2 = 0.014005\ m^2$$

2) Mass Velocity

$$Gt = Wc/At \quad lb/hrft^2$$

$$= \frac{2205 \times 20}{0.15075}$$

$$Gt = 58507.46\ lb/hrft^2 = 8507.46\ Kg/s\ m^2$$

3) Reynolds Number

$Re = Dt \times Gt / \mu$
Where $Dt = 0.834$ inch
$Gt = 58507.46$ lb/hrft^2

$\mu = Cp \times 2.42$ lb/ft-hr
$= 0.6 \times 2.42$
$= 1.452$lb/ft-hr

$$Re = Dt \times Gt / \mu = \frac{0.834 \times 58507.46}{1.452}$$

Re = 33605.52

1) $J_H = 110$

5) K= 0.3543 Btu/hr-ft^2 (^{0}f/ft) =0.6127 w/m ^{0}K

6) $hi/\phi_t = J_H \times K/Dt \times (c\mu/k)^{1/3}$ Btu/ft-hr - ^{0} f

$$= 110 \times \frac{0.3543}{0.834} \times \left(\frac{0.99 \times 1.452}{0.3543}\right)^{1/3}$$

hi/ϕ_t = 74.49 Btu/ft-hr - ^{0} f = 128.83 w/m ^{0}K

7) $\frac{h_{io}}{\phi_t} = \frac{hi}{\phi_t} \times \frac{ID}{OD}$ Btu/ft-hr - ^{0} f

$$\frac{h_{io}}{\phi_t} = 74.49 \times 0.834$$

$\frac{h_{io}}{\phi_t}$ = 62.124 Btu/ft-hr - ^{0} f =107.52 w/m ^{0}K

E. Pressure drop:-

Shell side

1) $$\Delta Ps = \frac{f \times Gs^2 \times Ds \times (N+1)}{5.22 \times 10^{10} \times De \times S \times \phi_s}$$

S=0.91 for steam at 300 ^{0} C

Ds = ID/12 ft

= 15.25/12

Ds = 1.27 ft =0.38709 m

Number of crosses (N+1) = 12L/B

= 12×6.66/15.25

Number of crosses (N+1) = 5.241

Gs=27306.50

De=0.0825 ft

ϕ_s=0.973

$$\Delta Pt = \frac{0.00018 \times 27306.50^2 \times 1.27 \times 5.241}{5.22 \times 10^{10} \times 70 \times 0.0825 \times 0.91 \times 0.973}$$

ΔPt = 0.00479 lbf/ft^2 = 0.0002018 Kg/m^2

Tube Side

1) $$\Delta Pt = \frac{f \times G_t^2 \times L \times N}{5.22 \times 10^{10} \times D_t \times S \times \phi_t}$$

S=1 for water

$$\Delta Pt = \frac{0.00017 \times 58507.46^2 \times 6.666 \times 81}{5.22 \times 10^{10} \times 70 \times 10^{-3} \times 1 \times 1.2141}$$

ΔPt = 0.07154 lbf/ft^2 = 0.003014 Kg/m^2

2) Return Crosses

$$\Delta Pr = \frac{4 \times n}{S} \times \frac{v^2}{2g}$$

n = Number of passes= 1, $\frac{v^2}{2g} = 0.04$

$$\Delta Pr = \frac{4 \times 1}{1} \times 0.04$$

ΔPr = 0.160 = 0.006742 kg/m^2

3) Total pressure Drop of Entire Tube

$\Delta P_T = \Delta Pt + \Delta Pr$

= 0.07076 + 0.160

ΔP_T = 0.23076lbf/ft^2 = 0.009721 kg/m^2

III. ANALYSIS BY USING CFD

CFD is a sophisticated computationally-based design and analysis technique. CFD software gives you the power to simulate flows of gases and liquids, heat and mass transfer.CFD is one of the branches of fluid mechanics that uses numerical methods and algorithm can be used to solve and analyse problems that involve fluid flows and also simulate the flow over a piping, vehicle or machinery.

Three different models have been presented in this paper as follow.

A. One tube with full length

Parameter	Dimension
Tube Length	1800 mm
Tube Diameter	21 mm
Mass flow in Tube	0.069 Kg/cm2

Table1:-Detail dimension of tube with full length

B. Sectional tube

Parameter	Dimension
Tube Length	668.5 mm
Tube Diameter	21 mm
Mass flow in Tube	0.069 Kg/cm2

Table2:-Detail dimension of sectional tube

C Sectional heat exchanger

Shell side Detail:-

Sr.No	Parameter	Unit	Dimension	
1	Shell Diameter	mm	381.25	
2	Shell Length	mm	768.5	
3	Baffle Spacing	mm	381.25	
4	Shell inlet fluid		Steam	
5	Inlet Temperature	^{0}C	300	
6	Shell side mass flow	Kg/s	1.11	4TPH
7	Shell length	mm	888.5	

Table3:-Detail dimension of Shell side

Tube side Detail:-

Sr. No	Parameter	Unit	Dimension	
1	Tube ID	mm	21	
2	Tube OD	mm	25	
3	Tube pitch	mm	31.25	
4	Tube length	mm	668.5	
5	Arrangement of tube bundles		Square	
6	Number of tubes		81	
7	Tube in the fluid		Water	
8	Mass flow rate per tube	Kg/s	0.069	
9	Mass flow rate of total tube side	Kg/s	5.5	20TPH
10	Inlet temperature of tube	^{0}C	30	
11	Outlet temperature of tube	^{0}C	80	

Table 4:-Detail dimension of Tube side

IV. MESHING OF MODEL IN ICEM

In this model used global mesh size be 4element,all triangular mesh type and mesh method patch dependent for surface. Fluids (water) mesh type be tetra mixed and mesh type Quick Delaunay used.The Total mesh count of one tube with full length is 17000, sectional tube is 6000 and sectional heat exchanger is 6 million.

A. One tube with full length

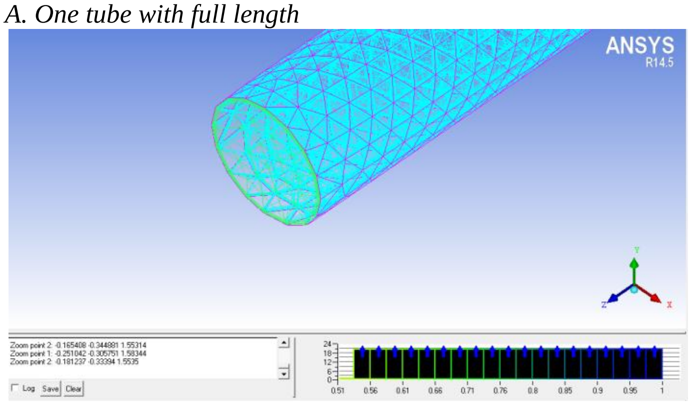

Fig1:- Single tube Full Length with mesh

B.Sectional tube

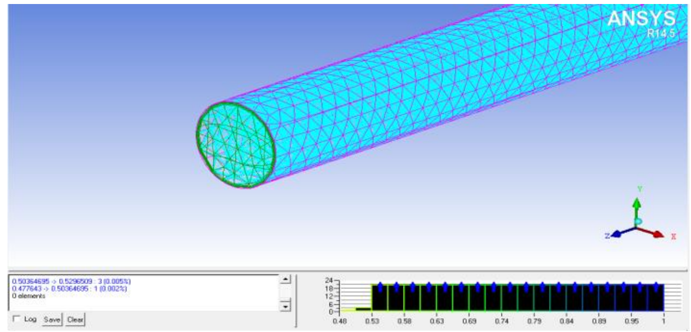

Fig2:- Sectional tube with mesh

C. Sectional heat exchanger

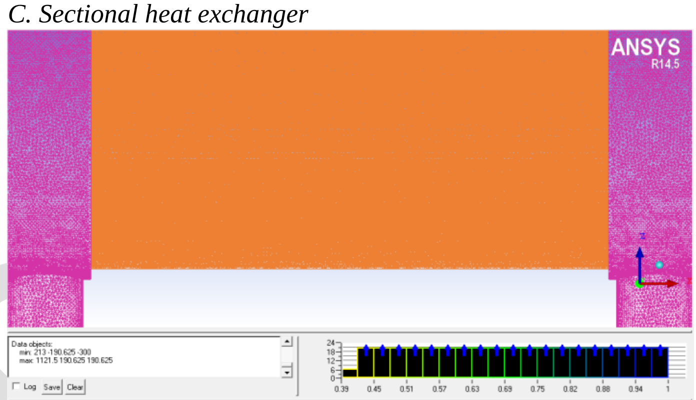

Fig3:- Sectional heat exchanger with mesh

V. FLUENT

Fluent is the pre-processing and solution devices give the input data (property data), initial and boundary condition. And solve algebraic equations.

VI. RESULT AND DISCUSSION

A. One tube with full length

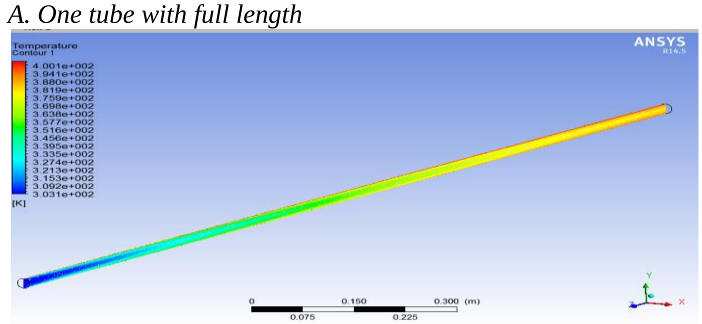

Fig 4:-Single Tube Full Length Temperature Contour

B. Sectional tube

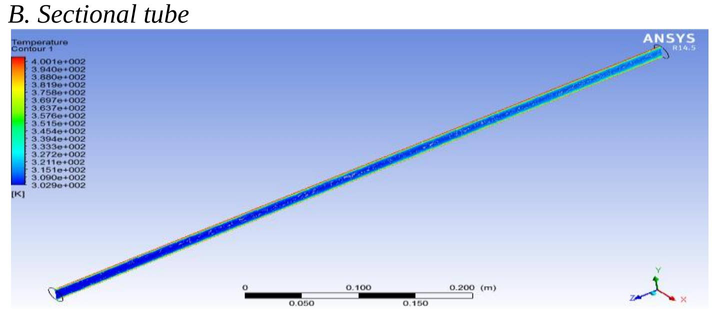

Fig 5:-Sectional tube Temperature Contour

C. Sectional heat exchanger

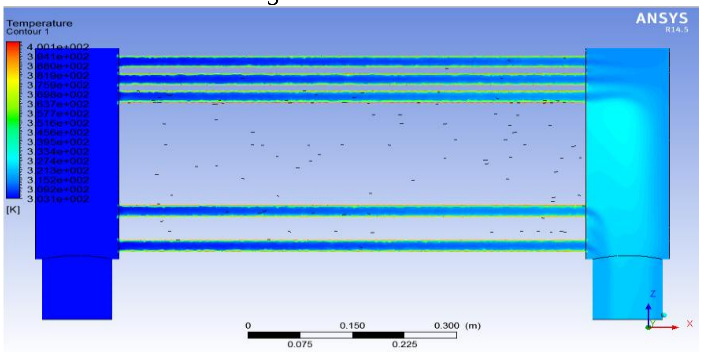

Fig 6:-Sectional heat exchanger Temperature Contour

D. Streamline diagram of sectional heat exchanger

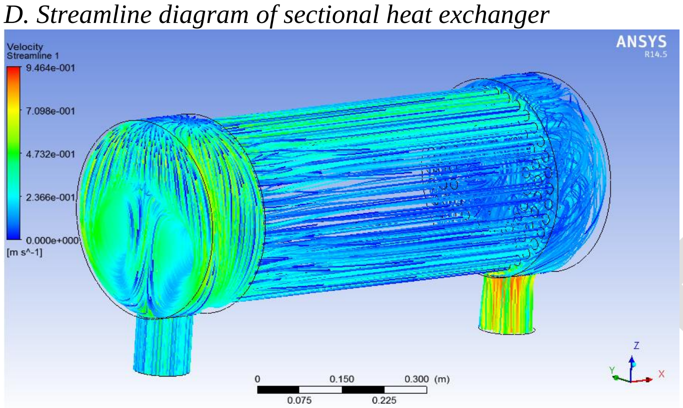

Fig 7:-Streamline diagram of sectional heat exchanger

One tube Full Length		
Content	Theoretical	Analytical(CFD)
Inlet fluid temp	30 ^{0}C (303K)	30 ^{0}C (303 K)
Outlet Fluid temp	80 ^{0}C (353K)	108 ^{0}C (381 K)
Wall temp	134.85^{0}C (407.85K)	130^{0}C (403 K)
Sectional One Tube		
Inlet fluid temp	30 ^{0}C (303 K)	30 ^{0}C (303 K)
Outlet Fluid temp	-	66 ^{0} C (339K)
Wall temp	134.85^{0}C(407.85K)	130^{0}C (403 K)
Sectional Heat Exchanger		
Inlet fluid temp	30 ^{0}C (303K)	30 ^{0}C (303 K)
Outlet Fluid temp	-	66 ^{0} C = 339K
Wall temp	134.85 ^{0}C(407.85K)	130^{0}C (403 K)

Table 5 :-Result Comparison of one tube full length,Sectional one tube and sectional heat exchanger.

VII. CONCLUTION

The present work represent the result of shell and tube heat exchanger by theoretical(Bell Coleman Method) and analytical(CFD)In theoretical calculation inlet water temperature is 30^0 C and outlet temperature is 80^0 C with wall temperature 134.85^{0}C.In analytical method (CFD) results shows three cases, one is full length tube, second is sectional tube and last is sectional heat exchanger.

In analysis of CFD the results for one tube full length inlet temp is 30^0 C and outlet temperature 108^{0}C. For sectional tube inlet temp is 30^0 C and outlet temperature 66^0 C. Similarly for sectional heat exchanger inlet is 30^0 C and outlet temperature 66^0 C. With wall temperature of 130^{0}C.The results of sectional tube and sectional heat exchanger is same. The full length tube outlet water temperature also gives required temperature.

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