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Performance Analysis of Fabricated Helical Coil Heat Exchanger

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Abstract— **In the present days Heat exchangers are the important engineering systems with wide variety of applications including power plants, nuclear reactors, refrigeration and air-conditioning systems, heat recovery systems, chemical processing and food industries. Helical coil configuration is very effective for heat exchangers and chemical reactors because they can accommodate a large heat transfer area in a small space, with high heat transfer coefficients. This paper focus on an increase in the effectiveness of a heat exchanger and analysis of various parameters that affect the effectiveness of a heat exchanger and also deals with the performance analysis of heat exchanger by varying various parameters like number of coils, flow rate and temperature. The results of the helical tube heat exchanger are compared with the straight tube heat exchanger in both parallel and counter flow by varying parameters like temperature, flow rate of cold water and number of turns of helical coil.**

Keywords— **Helical coil tube heat exchangers, Parallel flow, Counter flow, Flow rate of cold water, and Number of turns in helical coil.**

I. Introduction

The flow through a curved pipe has been attracting much attention because helical coiled pipes are widely used in practice as heat exchangers and chemical reactors. The fluid flowing through curved tubes induces secondary flow in the tubes. This secondary flow in the tube has significant ability to enhance the heat transfer due to mixing of fluid. The intensity of secondary flow [1, 2] developed in the tube is the function of tube diameter (D_i) and coil diameter (D). Due to enhanced heat transfer in helical coiled configuration the study of flow and heat transfer characteristics in the curved tube is of prime important.

The several studies have indicated that helical coiled tubes are superior to straight tubes when employed in heat transfer applications. The centrifugal force due to the curvature of the tube results in the secondary flow development which enhances the heat transfer.

This phenomenon can be beneficial especially in laminar flow regime. Naphon [2] investigated the thermal performance and pressure drop of a shell and helical coiled tube heat exchanger with and without helical crimped fins. Naphon et al. [3] summarized the phenomenon of heat transfer and flow characteristics of single-phase and two-phase flow in curved tubes including helically coiled tubes and spirally coiled tubes.

The first attempt has been made by Dean [4,5] to describe mathematically the flow in a coiled tube. A first approximation of the steady motion of incompressible fluid flowing through a coiled pipe with a circular cross-section is considered in his analysis. It was observed that the reduction in the rate of flow due to curvature depends on a single variable, K, which is equal to $2(Re)2r/R$, for low velocities and small r/R ratio. White [6] has continued the study of Dean for the laminar flow of fluids with different viscosities through curved pipes with different curvature ratios (δ). The result shows that the onset of turbulence did not depend on the value of the *Re* or the *De*. He concluded that the flow in curved pipes is more stable than flow in straight pipes. White also studied the resistance to flow as a function of *De* and *Re*. There was no difference in flow resistance compared to a straight pipe for values of *De* less than 11.6.

The fully developed laminar flow and heat transfer, studied numerically, by Zapryanov et al. [7] by using a method of fractional steps for a wide range of *De* (10 to 7000) and *Pr* (0.005 to 2000). The effect of the *Pr* on the heat transfer in helical pipes was studied by Xin et al. [8]. They studied the effect of *Pr* on both the average and local *Nu*. Li et al. [9] numerically investigated turbulent heat transfer in curved pipe for developing flow with water near the critical point. The heat transfer enhancements due to chaotic particle paths were studied by Acharya et al. [10, 11] for coiled tubes and alternating axis coils. The work on pulsating curved tube flow was performed by Guo et al. [11] for fully developed turbulent flow in a helical coiled tube. The two-phase flow of a steam-water mixture in a helical coil was studied experimentally by Guo et al. [12]. Inagaki et al. [14] studied the outside heat transfer coefficient for helically coiled bundle for *Re* in the ange of 6000 to 22,000. The heat transfer studies of a helical coil immersed in a water bath was studied by Prabhanjan et al. [15]. The experimental study of the flow in a helical circular tube was performed by Yamamoto et al. [16]. Arvind et al. [17] studied heat transfer experimentally in the helical coil with the coolants of different viscosity. An analytical and experimental study has carried out by Shokouhmand et al. [18] to optimize the *Re* of laminar viscous flow in a helically coiled tube subjected to constant wall temperature by minimizing entropy generation. Thermal performance and pressure drop *(Δp)* of the helical-coil heat exchangers with and without helically crimped fins was analyzed by Naphon et al. [2]. The heat transfer characteristics of a temperature dependent- property of fluid in shell and coiled tube heat exchangers has studied by Salimpour [19].

II. Geometry and parameters of helical coils

The present analysis considers the following dimensional and operating parameters.

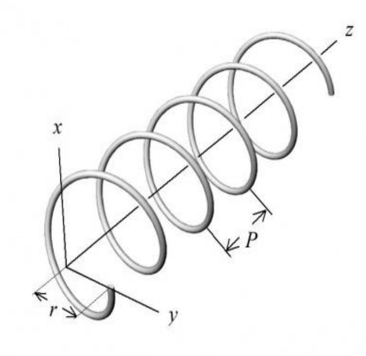

Fig :1 Fluid flow in Helical tubes

Table 1. Dimensional parameters of Helical coil

S.No.	Dimensional Parameters	Dimensions
1	outer diameter of SS cylinder (D)	63.5 mm
2	inner diameter of SS cylinder (D_i)	1.058D mm
3	Thickness of SS cylinder (T)	3-5 mm
4	outer diameter of SS end cap (D_{co})	1.376D mm
5	inner diameter of SS end cap(D_{ci})	1.162D
6	thickness of the end cap(T_c)	6-9 mm
7	Outer diameter of projected tube(D_{to})	0.211D mm
8	Inner diameter of projected tube(D_{ti})	0.145D mm
9	Diameter of connecting tube(D_{cp})	0.2D mm
10	Diameter of CPVC pipe(D_{cpvc})	0.3D mm

Table 2. Operating parameters of Helical coil heat exchanger

Parameter	Cold Water	Hot Water
Mass flow rate Mf	0.0625	0.166
Initial temperature (^oC)	30	100
Outlet Temperature (^oC)	60	70
C_p J/Kg ^oC	4183	4216
Parental Number (PR)	5.68	1.74
Thermal conductivity(K) ($W/m^2\ ^oC$)	383	16.2
Viscosity ($N\text{-}s/m^2$)	0.00082942	0.00028157
Density (kg/m^3)	997.5	961

III. Design Procedure for Helical coil heat exchanger

The analysis of the helical coil heat exchanger is carried out through following procedure:

Step 1

Length of coil needed=L=N×$\sqrt{((2\pi r)^2 + p^2)}$

Here p=20 mm (assume)

$R = 1.5875\times10^{-2}$ m

On substituting L=N×0.101

Step 2

Volume available for fluid flow in annulus

V_f = (π/4)[C²]p×N – (π/4)× $d_O{}^2 \times L$

Here C=0.06 m

D_O =6.35×10^{-3} m

On substituting them

V_f =5.335×10^{-5} × N m^3

Step 3

Shell side equivalent diameter

D_e = (4×V_f)/ (π× d_O ×L)

=(4×5.335×10^{-5} ×N)/(π×6.35×10^{-3} ×N×0.101)

= 0.105 m

Step 4

Mass velocity of fluid

G_S = (M_f)$_{cw}$/ (π/4×C²)

Here M_f =0.166 kg/s

On substituting G_S =58.71 Kg/m²-s

Step 5

Reynolds number

$N_{Re} = D_e \times G_S / \mu_{hw}$

Here μ_{hw} = 281.57×10^{-6}

On substituting N_{Re} =21.89× 10^3 (dimensionless number)

Step 6

Heat transfer coefficient outside the coil

Since N_{Re} >10000 use

$D_e \times h_O$ /K=0.36× $N_{Re}{}^{0.55} \times N_{Pr}{}^{0.333}$ ×(μ/μp)$^{0.14}$

Here K=16.2 W/m^{o}C

N_{Pr} =1.74

μ = 281.57×10^{-6} N-m/s

μ =2.5731×10^{-4} N-m/s

On substituting h_O =16497.74 W/m² ^{o}C

Step 7

Fluid velocity u= (Q/ A_f)

A_f = π/4×D²=2.164× 10^{-5} m²

Q=M/ρ

=0.0625/997.5=60265× $10^{-5} m^3/s$

Therefore u=2.895 m/s

Now *Reynolds number tube side is*

$N_{Re} = \rho_{cw}$ ×u×D/ μ_{cw}

Here ρ_{cw} =997.5

m_{cw} = 829.42× 10^{-6}

then N_{Re} =18.278× 10^3

Step 8

Heat transfer coefficient inside the coil

hio=?

Calculate Colburn factor first

From graph jH=70

But jH=hi×(D/K)×Npr $^{-0.333}$

Here K=383 W/m°C

Npr=5.68

On substituting and subjecting hi we get

h_i =9.11× W/m² ° C

Step 9

Heat transfer coefficient based on the outside diameter of coil

hio = h_i ×D/ do

On substituting D & do we get

hio=7.53× W/m² °C

Step 10

Overall Heat Transfer Coefficient

First calculate Coil wall thickness x

X=(do -D)/2

=0.55× 10^{-3} m

1/U=1/ho +1/hio+(x/Kcu)+Ra +Rt

Here Ra = Rt =0.0001754

On substituting , hio, , x, , , we get

U-2424.40 W/m² ° C

Step 11

Logarithmic mean temperature difference

θm={(100-30)-(70-60)}/ln {(100-30)/ (70-60)}

=30.83 °C

Now corrected LMTD= θc=correction factor × θm

=0.99×30.83

θc =30.52 °C

Step 12

Heat load Q

Q=Mhw ×Cp×δT

=0.166×4216× (100-70)

=20.916 KW

Step 13

Required contact area A

A=Q/(Ui×θc)

On substituting Q, Ui, θc we get

N=0.280/(π×6035× 10^{-3} ×N×0.101)

Therefore N=12.5~12

Practically range between Nor N±4

Step 14

Distance between inlet and outlet pipe

This is the minimum length required to accommodate helical coil

H=12×20× + (6.35× 10^{-3})

= 0.2463 m ~0. 3 m

Thickness of insulation required:

Rc=k/ho

=16.2/16497.74

=0.98 mm which is less than the radius of the cylinder. So insulation is not necessary. But due to assumptions made to prevent heat loss nominal thickness of 3-5 mm of insulating material is wrapped around the cylinder.

Fig. 2 Fabricated Helical Coil Heat Exchanger

Fig.3.Copper helical coil

IV. Results and Discussions

The effectiveness and overall heat transfer coefffecient is calculated and presented in a Table 4.1, 4.2 and 4.3. for straight pipe (both parallel and counter),Helical coil parallel and helical coil counter flow respectively.

Table 3. Effectiveness and Overall Heat Transfer Coeffecient for Straight Heat Exchanger

Max Temp °C	Flow Rate	Flow	Qh(KW)	Qc(KW)	Ui(W/m^2 °C)	€
50	15	P A R A L L E L	3.0545	0.807	27811.93	0.263
50	45		2.1	1.4	17943.95	0.316
60	15		2.584	1.225	12885.39	0.241
70	45		3.267	2.470	11297.05	0.256
70	30		1.938	1.6	6322.688	0.205
80	30		9.1	2.52	27499.54	0.25
90	15		1.4	2.31	2781.558	0.186
50	15	C O U N T E R	1.527	1.292	12743.33	0.498
50	45		1.68	1.633	14936.94	0.378
60	15		2.907	2.8	15133.76	0.310
70	45		2.8	2.717	9455.539	0.291
70	30		1.938	1.718	6291.429	0.260
80	30		1.8	1.593	4445.799	0.259
90	15		4.667	2.1	9685.875	0.377

Table 4. Effectiveness and Overall Heat Transfer Coeffecient For Helical Pipe (Parallel)

Max Temp °C	Flow Rate	Flow	Qh(KW)	Qc(KW)	Ui(W/m^2 °C)	€	Max Temp °C
16	70	15	P A R A L L E L	2.5872	2.331	11675.63	0.417
16	80	15		3.0618	3.36	12196.17	0.465
16	60	30		4.662	2.6271	37873.4	0.517
16	90	45		4.851	4.47678	10755.62	0.371
16	50	30		0.96894	1.67832	10361.2	0.631
12	50	15		1.04958	1.512	1164.042	0.474
12	60	45		2.0538	3.65148	1420.834	0.483
12	70	45		1.52712	2.28816	720.5213	0.424
12	80	30		3.14874	1.53846	1233.39	0.244
12	90	15		0.64596	2.3751	190.9627	0.345
8	60	15		1.19952	1.9068	1097.404	0.345
8	70	30		0.58044	1.77408	351.7282	0.283
8	50	45		0.89964	1.22304	1306.032	0.368
8	80	45		1.29192	2.44608	655.3964	0.391
8	90	30		3.2298	2.2491	2158.06	0.372

Table 5. Effectiveness and overall heat transfer Coeffecient for helical heat exchanger (counter)

Max Temp °C	Flow Rate	Flow	Qh(KW)	Qc(KW)	Ui(W/m^2 °C)	€	Max Temp °C
16	70	15	C O U N T E R	2.587	2.486	1112.698	0.421
16	80	15		3.881	3.574	704.7993	0.500
16	60	30		2.331	2.271	552.0947	0.543
16	90	45		10.458	5.513	1228.347	0.388
16	50	30		2.585	1.554	1878.346	0.671
12	50	15		1.909	1.243	979.5355	0.491
12	60	45		4.133	3.906	1466.629	0.517
12	70	45		2.673	2.482	640.0294	0.361
12	80	30		3.150	1.960	572.9315	0.311
12	90	15		3.554	3.287	567.5365	0.370
8	60	15		2.100	1.909	976.1179	0.357
8	70	30		1.960	1.777	603.2877	0.389
8	50	45		1.800	1.575	1597.494	0.474
8	80	45		2.908	2.275	712.8407	0.377
8	90	30		3.231	2.550	683.2348	0.399
16	70	15		2.587	2.486	1112.698	0.421

Parametric Analysis

The effect of flow rate, temperature, number of turns on effectiveness and overall heat transfer coefficient is analyzing and comparing with linear copper pipe through the following figures.

4.2.1 Effect of flow rate on overall heat transfer coefficient and effectiveness

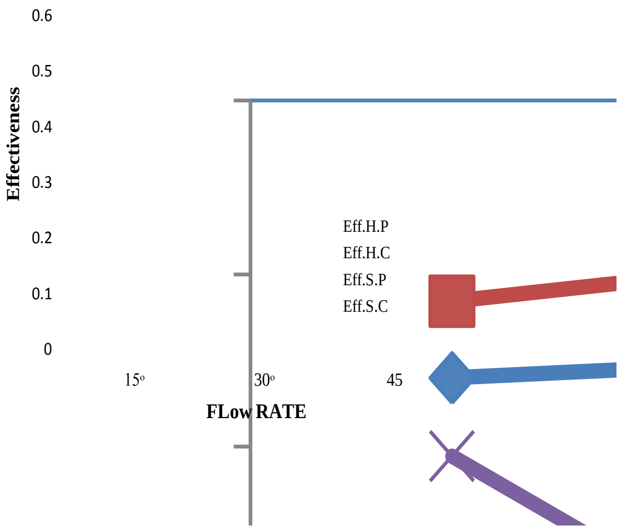

Fig 4: Flow rate Vs Effectiveness

As the flow rate increases in parallel flow configuration of Helical copper pipe effectiveness increases slightly up to 30^0 (position of the valve) and starts declining gradually. Where as in straight pipe parallel configuration as flow rate increases its effectiveness increase gradually till 30° gradually and rises sharply after 30°.As flow rate of cold water increases it gets less contact time with hot water.So Effectiveness starts declining. Max effectiveness obtained was 0.45 in helical and it was 0.29 in a straight pipe which is noticed in fig.4

In counter flow arrangements of helical copper pipe it can be observed that the effectiveness of helical configuration is higher than the rest of the configuration. In counter flow also as flow rate increases effectiveness increases up to 30° and later it starts declining. As flow rate of cold water increases it gets less contact time with hot water.So Effectiveness starts declining. Max effectiveness was found to be 0.52 in helical arrangement and Effectiveness of straight pipe decreases initially till 30° and starts increasing after 30^0.

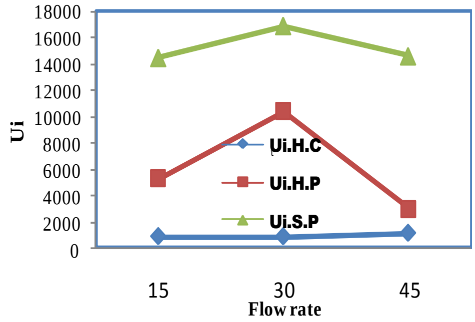

Fig 5. Flow rate Vs Overall Heat Transfer

From figure 5 one can observe that

As the flow rate increases in parallel configuration Ui rises slowly till 30° and starts declining after 30°. But in the straight it raises till 30° (and starts declining after 30°.In counter flow configuration as flow rate increases Ui is almost constant till 30° and later its value raises slightly. Similar in a straight configuration as flow rate increases Ui decreases till 30° and rises sharply after 30°.

Effect of Temperature on Ui and effectiveness

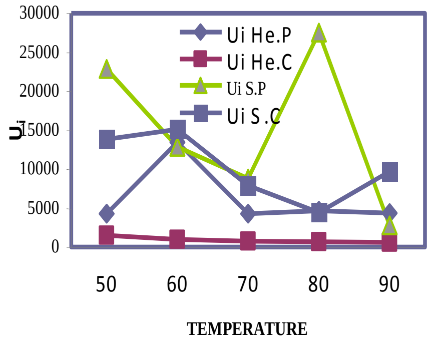

Fig 6. Temperature Vs Overall Heat Transfer

Temperature is the next most important parameter influencing the performance of heat exchanger. From fig. 6 one can conclude that

In the parallel configuration of helical pipe as temperature increases Ui increases sharply and starts decreasing and finally maintains constant Ui after a certain period of time. But in counter also initially it starts decreasing and maintains constant Ui quickly. The overall heat transfer is more in case of parallel than the counter of Helical arrangement.

As temperature increases in straight pipe Ui start decreasing till 70 and rises sharply after 70 °. It follows a cycle i.e. Periodic rise and fall of Ui .Similarly in counter arrangement as temperature increases Ui decreases gradually.

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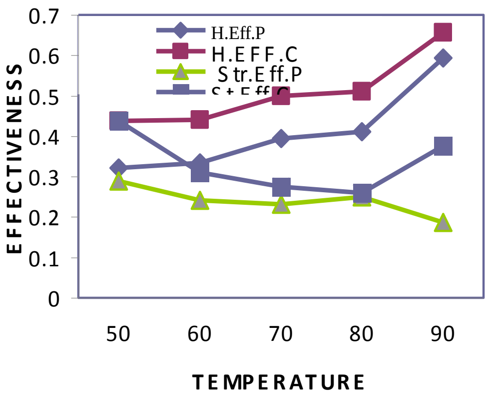

Fig 7. Temperature Vs Effectiveness

From Fig.7 one can observe that

For the points plotted on Temperature Vs Effectiveness if a best outfit curve is drawn, one can notice some interesting and worthy points. When temperature increases there is a gradual rise in the Effectiveness. But in case of Straight pipe configuration one can notice a gradual drop in the effectiveness with the rise in the temperature.

Effectiveness is more in case of counter than parallel configuration (Straight / Helical configuration). When a best outfit curve is drawn one can notice a fact that the maximum effectiveness obtained was around 0.7 which is considered as one of the best result that is expected. On the other hand in straight pipe configuration effectiveness starts decreasing with an increase in temperature.

Effect of number of turns on Effectiveness and U_i

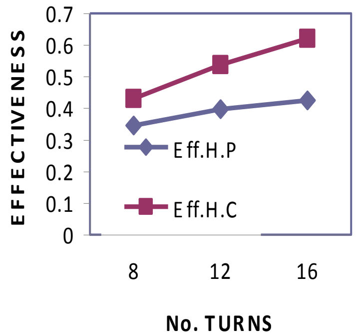

Fig 8. Turns Vs Effectiveness

This also plays a vital role in deciding the overall performance of Heat exchanger. From fig.8 one can observe that for the same length with different pitch i.e. change in number of turns as pitch increases effectiveness decreases. Minimum pitch to be maintained (4d-5d).Counter arrangement showed good result.

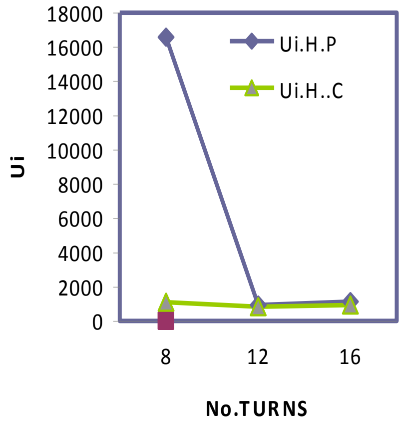

Fig 9. Turns Vs Ui

In counter arrangement Overall Heat transfer is almost constant but in parallel arrangement it drops drastically with an increase in the number of turns as shown in Fig 9.

5. Conclusion

Based on the results obtained by conducting the experiments on helical (parallel and counter flow) and straight (parallel and counter flow) tube,the following are the conclusions drawn:

- The helical pipe is having the greater surface area which allows the fluid to be in contact for greater period of time period so that that there is an enhanced heat transfer compared to that of straight pipe.
- The inside over all heat transfer coefficient for helical pipe is approximately 0.35 of that straight pipes.
- The temperature of cold water coming from the helical tube in counter flow arrangement is (38°C - 52 °C) i.e. a rise in the temperature of water is between 7 °C to 21 °C.It implies that for the same surrounding area the helical pipe absorbed is more than that of straight copper tube.
- The effectiveness of pipes either helical or straight in counter flow is greater than parallel configuration.
- From the above one can realize the fact that for the same space or volume in industry the helical heat exchangers are more efficient than normal straight heat exchangers.
- The influencing parameters on effectiveness and overall heat taransferr coefficient in the dectreasing order are: Flow rate, Hot water inlet temperature and number of turns.
- Maximum effectiveness in parallel configuration of Helical type is 0.631.
- Maximum effectiveness in counter configuration of Helical type is 0.671.
- Maximum effectiveness in parallel configuration of straight type is 0.316.

- Maximum effectiveness in counter configuration of straight type is 0.498.

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