Experimental Investigation Of Thermal Performance Of Helical Cone Coil Heat Exchanger

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Abstract

A variety of industries use coiled tube heat exchangers for the heating and cooling of liquids and gases. Helically and spirally coiled tubes are utilized for single-phase, evaporating, and condensing flows. The aim of this research was to study the heat transfer characteristics of a helical cone coil heat exchanger and to obtain heat transfer rate, heat transfer coefficients and effectiveness. It was also intended to compare these results with the available results of helical coil heat exchangers. To accomplish this experimental set up of helical cone coil heat exchanger was developed. Helical cone coil was manufactured for slant edge angle 70°. In experimentation, hot water is allowed to flow through the coil and cold water was flowing through the shell respectively. Variation of mass flow rate of coil fluid and shell fluid was considered in the range of 0.02 to 0.10 kg/s respectively. Cold water exit temperature, rate of heat transfer, heat transfer coefficients, effectiveness and modified effectiveness were obtained for variation of mass flow rate of shell fluid and coil fluid. Further these results were compared with results of researchers. It is found out that as hot water mass flow rate increases cold water exit temperature and rate of heat transfer increases. When mass flow rate of cold water increases from 0.05 kg/s to 0.1 kg/s, effectiveness is found to decrease for increase in hot water mass flow rate. Also modified effectiveness is found to decrease as ratio of mass flow rates of both fluids increases. Tube side heat transfer coefficients and Nusselt numbers are found to increase when hot water mass flow rate increases. Results obtained in this study are in agreement with results of researchers.

Keywords: helical cone coil heat exchanger, inside heat transfer coefficients, effectiveness, logarithmic mean temperature difference

1. Introduction:

Helical coiled tubes are used in a variety of applications where enough space is not available for straight pipe and heat transfer enhancement due to secondary flow is taken into consideration. In conical coils as curvature increases main fluid flow (axial fluid flow) increases and secondary fluid flow becomes intensive when tube curvature is increased. Patil P. et al [1] explained advantages of helical coil heat exchanger over double pipe heat exchanger and discussed designing procedure of helical coil heat exchanger. Ali M. et al [2] experimentally studied natural convection heat transfer from vertical helical coil tubes. For a particular coil tube diameter (d_o), coil diameter (D) were fixed and number of turns (N=5, 10) and pitch (P=1.5, 2, 3, 3.5 times d_o) were varied. Prabhanjan D. et al [3] experimentally studied the relative advantage of using a helically coiled heat exchanger versus a straight tube heat exchanger for heating of coil liquids. Heat transfer coefficient for helical coil was 1.16 and 1.43 times larger than for straight pipe heat exchanger. Aravind G. et al [4] experimentally studied heat transfer between coolant in coil and water, soap solutions and carboxymethyl cellulose (CMC) used as bath liquids. Overall heat transfer coefficients for soap and CMC solutions were found to be below that of water. Rose J. [5] explained traditional Wilson plot and laminar film condensation and drop wise condensation on an internally cooled horizontal tube was discussed. Also comments were made on accuracy of temperature measurement. Rennie T. et al [6] numerically modeled double-pipe helical heat exchanger for laminar fluid flow and heat transfer characteristics under different fluid flow rates and tube diameters. Validation of the simulations was conducted by comparing the Nusselt numbers in the inner tube with those found in literature; the results fell within the range found in the literature. Vimal K. et al [7] studied tube in tube helical heat exchanger at the pilot plant scale to investigate the hydrodynamic and heat transfer characteristics. Heat transfer coefficients in inner and outer tube were determined using Wilson plots. Parker J. et al [8] developed laboratory set up of helical coil heat exchanger to calculate Nusselt number, heat transfer coefficient, friction factor and pressure drop for the helical coil. Seara J. et al [9] reviewed Wilson plot method dealing with the determination of convection coefficient based on measured experimental data. Naphon P. et al [10] experimentally and numerically (Fluent software) studied horizontal spiral coil tube. The effects of curvature ratios on coil exit temperature, heat transfer rate, Nusselt number and pressure drop were studied. Naphon P. [11] experimentally investigated thermal performance of helical coil heat exchanger with and without helically crimped fins. Range of mass flow rates for cold and hot water were 0.10 – 0.22 kg/s and 0.02 – 0.12 kg/s respectively. The range of inlet temperatures of cold and hot water were 15- 25°C and 35 – 45°C respectively. Jayakumar J. et al [12] fabricated a set up to study fluid to fluid heat transfer in a helically coiled heat exchanger. Heat characteristics were also studied using CFD code FLUENT, considering fluid to fluid boundary conditions. Vimal K. et al [13] studied numerically tube-in-tube helically coiled (TTHC) heat exchanger and heat transfer characteristics for different fluid flow rates in the inner as well as outer tube. The Nusselt number and friction factor values in the inner and outer tubes were compared with the experimental data reported in the literature. Shokouhmand H. et al [14] carried out experimental investigation to study shell side and tube side heat transfer coefficients for three helical coil heat exchangers with different coil pitches and curvature ratios. Kharat R. et al [15] studied outside flow of flue gases over concentric helical coils and developed correlation. Moawed M. [16] studied experimentally, the forced convection from the outside surface of helical coiled tubes with constant wall heat flux (electric heating). Air was present at outside surface of tubes. Ghorbani N. et al [17] carried out experimental investigations for mixed convention of helical coil heat exchanger. Tube diameter d_o, coil diameter D, pitch P and number of turns N were varied. Height H and shell dimensions were kept constant. Correlation was obtained for modified effectiveness considering ratios of mass flow rates. Ghorbani N. et al [18] studied the same experimental setup and obtained an insignificant effect of the tube diameter on shell side heat transfer coefficient h_o. h_o decreased rapidly as coil surface area increased. Hminic G. et al [19] studied heat transfer characteristics of a double tube helical heat exchanger using nanofluids of CuO and TiO_2 nanoparticles with diameter of 25 nm dispersed in water with volume concentration of 0.5-3 volume %. Heat transfer rate of nanofluid was approximately 14% greater than of pure water. Jamshidi N. et al [20] investigated numerically (CFD package-FLUENT) performance of helical coil by using water and water/ Al_2O_3 nanofluids. The numbers of simulations were determined by use of Taguchi method according to a number of design parameters. Zhao Z. et al [21, 22] experimentally and numerically studied heat transfer in convection cooling section of pressurized coal gasifier with the membrane helical coil and membrane serpentine tubes under high pressure. The heat transfer coefficients of heat exchanger with membrane helical coils were greater than that of the membrane serpentine tube heat exchanger under the same conditions. Ferng Y. et al [23] carried out numerical simulations with CFD package to investigate effects of Dean Number and pitch size. Three values of Dean Number and four sizes of pitch were considered. Naphon P. [24] experimentally and numerically (Nastran /CFD software) investigated horizontal spiral coil with curvature ratio = 0.02. Cold water and hot water were used as tube and bath fluid respectively. Yan K. et al [25] investigated the heat transfer characteristic of conical spiral tube with a numerical simulation method. Heat transfer coefficient of the circular section of the conical tube was found to be larger than the elliptical section. As curvature increases main fluid flow (axial fluid flow) increases and maximum flow speed was obtained equal to 0.1642 m/s when flow speed at inlet was set at 0.1 m/s. The secondary fluid flow became intensive as tube curvature increased and this secondary flow was found to be more intensive for circular cross section than elliptical. Elazm M. et al [26] studied experimental and numerical comparison between the performance of helical cone coils and ordinary helical coils. Two helical cone coils with varying cone angles were manufactured. The heat transfer characteristics of the helical cone coil were found to be better than the heat transfer characteristics of ordinary coils. Geneic S. [27] experimentally studied helical coil heat exchanger with concentric helical tube [HECHT]. Shell side heat transfer coefficient was strongly influenced by geometric/ construction parameters such as winding angle, radical pitch, and axial pitch. Pawar S. et al [28] manufactured two straight helical coils with same length and curvature ratios as 0.1136 and 0.0833. These were tested for laminar and turbulent flow under constant shell side fluid bath. Ashkan A. et al [29] studied the effectiveness of straight helical coil heat exchanger. Based on the results two correlations were proposed for wide ranges of ratio of mass flow rates. Jamshidi N. et al [30] studied geothermal heat exchanger where heat exchangers. It was observed that, for increased pitch, the Nusselt number decreased. Daghigh R. et al [31] studied coils having three shapes, including cylindrical-spiral, conical spiral and conical-cylindrical- spiral coils using working fluids consisting of water and nanofluids as MWCNT, CuO&TiO_2. It was found out that conical-cylindrical- spiral coils had a better thermal performance than other coils. Palanisamy K. et al [32] studied horizontal helical cone coil heat exchanger using Multi wall carbon nanotubes/ water nanofluids. Nanofluids 0.1 %, 0.3% and 0.5% volume concentrations were supplied through tube and hot water was allowed to shell side at constant value of 0.15 kg/s. Heyhat et M. et al [33] developed cone coils and the outer surface of the coil was heated and SiO_2 / water nanofluids were passed through the tubes. It was found out that cone angle is more effective for heat transfer enhancement than coil pitch. Ali. M. et al [34] numerically investigated double pipe cone coils to obtain annulus side Nusselt number and friction factor. Results showed that, as cone angle was increased in the range from 0° to 90°, friction factor and the Nusselt number increased by 15.51% and 31.71% respectively. Sheeba A. et al [35] studied double pipe cone coils experimentally for 72° cone angle and numerically varied cone angle from 30° to 90°. It was observed that up to 72° overall heat transfer coefficient increased and after that it was decreased. Khalid A. [36] carried out numerical simulation of cone coil and studied heat transfer and fluid flow in the annulus section of tube in tube conical heat exchanger. It was found that minimum values of cone angle (range-0°,45°,90°,135°) maximized exergy efficiency. Maghrabiee H. et al [37] studied a single straight helical coil in which the position of the coil is changed from horizontal to vertical position. Also, the dean number varied from 1540 to 3860. It was found out that the effectiveness of vertical direction is more than horizontal position. Chok phoemphunet S. et al [38] studied coil tube exchangers positioned inside the free board zone such that air was allowed to flow through the coil and flue gasses made to flow around the coil from bottom. It was depicted that, compared to counter flow, for parallel flow outlet temperature of air is higher by 7 - 17°. Omri M. et al [39] studied experimentally helical coil and using distilled water based CuO-Gp (80-20%) hybrid nanofluid was analyzed in laminar flow regime. It was observed that heat transfer coefficient improvement is high at the entrance region. Hasan M. et al [40] numerically studied helical coils with 3 ribbed head profiles (2 head ribbed, 3head ribbed, 4 head ribbed) and three coil revolutions (10, 20 and 30 revolutions). It was predicted that, high heat transfer rate was obtained for low head geometry and high coil revolutions.

Enough work on study of thermal performance of helical cone coil heat exchanger versus variation of shell side mass flow rate and coil side mass flow rate was not found. Hence it is intended to develop an experimental setup to analyze helical cone coil heat exchanger. Helical cone coil is manufactured using copper tube and have a slant edge angle as 70°. Schematic diagram of helical cone coil heat exchanger is shown in Fig.1.1. Experimentation is carried out to study heat transfer between hot and cold water flowing through helical cone coil and shell respectively.

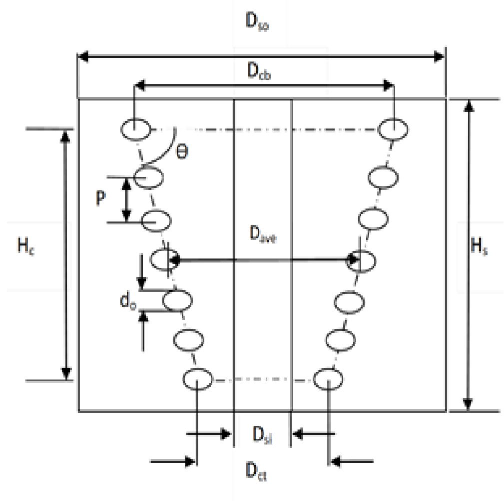


Fig.1.1. Schematic diagram of HCCHE

2. Experimental setup:

To understand heat transfer analysis of helical cone coils, an experimental setup was developed. The schematic diagram and actual experimental set up is shown in Fig.2.1 and Fig.2.2. Major components of the experimental set up were consisted of hot and cold water tanks, heat exchanger unit, and temperature measurement and recording system. Hot water was forced through the coil from top side and cold water was forced in the shell from top side causing parallel flow arrangement. All tests were performed under steady state conditions and observations were recorded when steady state was achieved. In experimentation, coil fluid and shell fluid were hot water and cold water with inlet temperatures of 42 ºC and 28 ºC respectively. Temperatures were measured using RTD type thermocouples [18]. Four thermocouples were located and temperatures were measured as coil inlet temperature (T_1), coil exit temperature (T_2), shell inlet temperature (T_3), and shell exit temperature (T_4).

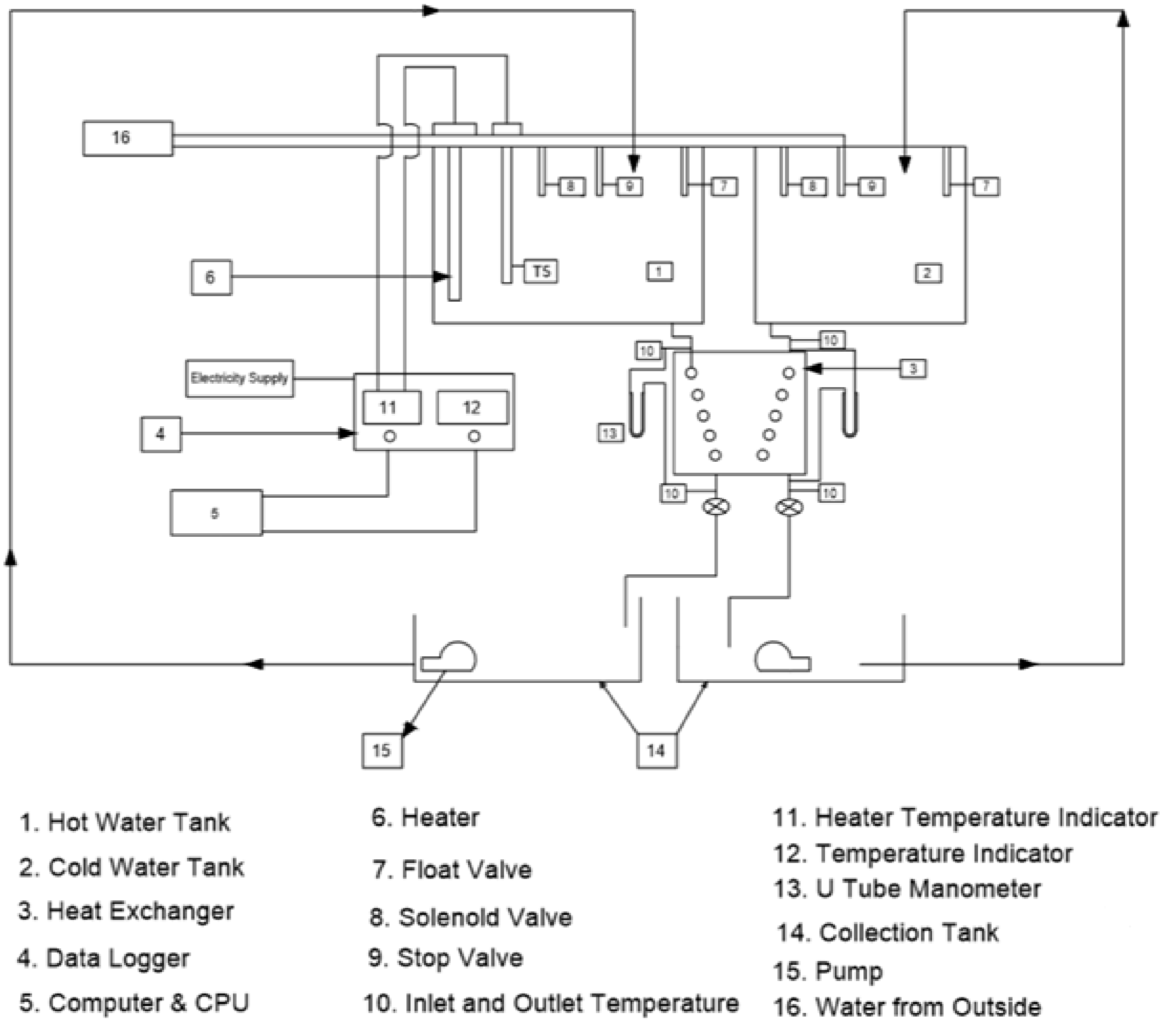


Fig.2.1: Schematic diagram of helical cone coil heat exchanger.

Water was heated using a heater in the hot water tank. The flow rate was measured by using a calibrated measuring cylinder and a stopwatch positioned at the outlet of heat exchanger [17]. Range of mass flow rate of coil fluid and shell fluid were 0.02- 0.1 kg/s respectively.

Fig. 2.2: Photograph of experimental set up of helical cone coil heat exchanger

Copper tube was selected to obtain a helical cone coil which was wrapped around a wooden block of frustum shape. Copper tube was filled with sand and a circular cross section was ensured. Also the shell was manufactured using steel. Dimensions of helical cone coil and shell are given in table No.1.

Table No. 1

Dimensions of helical coil

Parameter	**Dimension**
Cone slant edge angle, θ	70 °
Tube inner diameter, d_i	0.01 m
Coil top diameter, D_{ct}	0.07 m
Coil average diameter, D_{ave}	0.12 m

Coil bottom diameter, D_{cb}	0.17 m
Pitch, P	0.018 m
Number of coil turns, N	8 turns
Tube length, L_c	3.3 m
Inner shell diameter, D_{si}	0.02 m
Outer shell diameter, D_{so}	0.30 m
Height of shell, H_s	0.20 m

3. Heat transfer calculations:

In convection heat transfer takes place due to temperature difference between solid surface and fluid in contact with solid surface. Newton's law of cooling provides a simple equation as

$$Q = A * h (T_s - T_f) \qquad 1$$

Where T_s = Temperature of solid surface & T_f =temperature of fluid

Heat transfer for coil fluid, Q_c is given as

$$Q_c = m_c C_{p,c} (T_{c,i} - T_{c,o}) \qquad 2$$

Heat transfer for shell fluid, Q_s is given as

$$Q_s = m_s C_{p,s} (T_{s,o} - T_{s,i}) \qquad 3$$

Average heat transfer, Q_{ave} [7]

$$Q_{ave} = (Q_c + Q_s) / 2 \qquad 4$$

Average inside tube heat transfer coefficient, h_i is obtained from the following equation.

$$h_i = Q_{ave} / A_i(T_{c,i} - T_{c,o}) \qquad 5$$

Logarithmic temperature difference for parallel flow and counter flow is given as:

$$(\Delta T_{LMTD})_{PF} = [(T_{c,i}-T_{s,i})-(T_{c,o}-T_{s,o})]/ \log[(T_{c,i}-T_{s,i})/(T_{c,o}-T_{s,o})] \qquad 6$$

$$(\Delta T_{LMTD})_{CF} = [(T_{c,i}-T_{s,o})-(T_{c,o}-T_{s,i})]/ \log[(T_{c,i}-T_{s,o})/(T_{c,o}-T_{s,i})] \qquad 7$$

Overall heat transfer coefficients, U_i & U_o and outside shell side heat transfer coefficient, h_o is obtained as:

$$U_i = Q_{ave} / A_i (\Delta T_{LMTD}) \quad 8$$

$$U_o = Q_{ave} / A_o (\Delta T_{LMTD}) \quad 9$$

$$h_o = 1/\{ [A_o/U_iA_i]-[A_o(\log (d_o/d_i))/ 2 \Pi L k_t]-[A_o/h_i A_i]\} \quad 10$$

Tube side and shell side Nusselts Numbers are obtained from following equations.

$$(Nu)_i = h_i d_i / k_c \quad 11$$

Effectiveness of heat exchanger, ϵ [11]

$$\epsilon = Qave / \{(mCp)_{min} (T_{c,i} - T_{s,i})\} \quad 12$$

Modified Effectiveness of heat exchanger, ϵ`[17]

$$\epsilon ` = (T_{c,i} - T_{s,o})/ (T_{c,i} - T_{s,i}) \quad 13$$

Further cold water temperature difference, logarithmic mean temperature difference, average rate of heat transfer, effectiveness and modified effectiveness are compared with findings of researchers.

4. Results and discussion

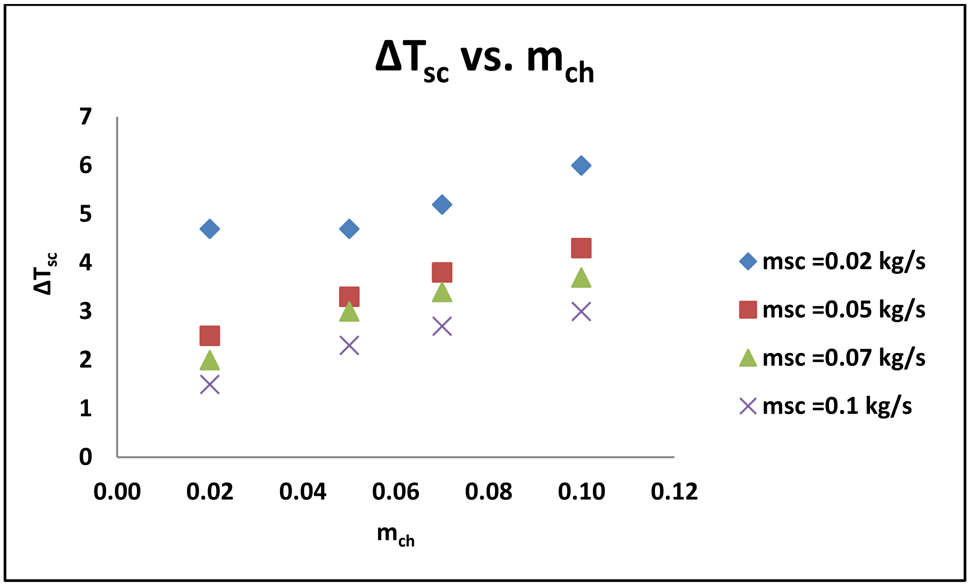
For variation of coil fluid mass flow rate, results were obtained and discussed in section 4.1. Similarly for variation of shell fluid mass flow rate, results are discussed in section 4.2.

4.1 Results for variation of mass flow rate of coil fluid m_c:

Mass flow rate of coil fluid was varied from 0.02 - 0.1 kg/s and ΔT_{sc}, Q_{ave}, h_i, ϵ, ϵ` and ΔT_{LMTD} were obtained for variation of mass flow rate of shell fluid as m_s=0.02, 0.05, 0.07 and 0.1 kg/s.

4.1.1 Shell fluid temperature difference ΔT_{sc} vs. m_{ch}:

Fig. 4.1 (a) shows that, temperature difference of cold water is increasing with increase in hot water mass flow rate and is higher for higher mass flow rate of cold water. Thus the exit temperature of cold water is increasing as the mass flow rate of cold water is increasing (range 0.02 - 0.10 kg/s). These results of the current study are showing agreements with results of P. Naphon [11] shown in Fig.4.1 (b).



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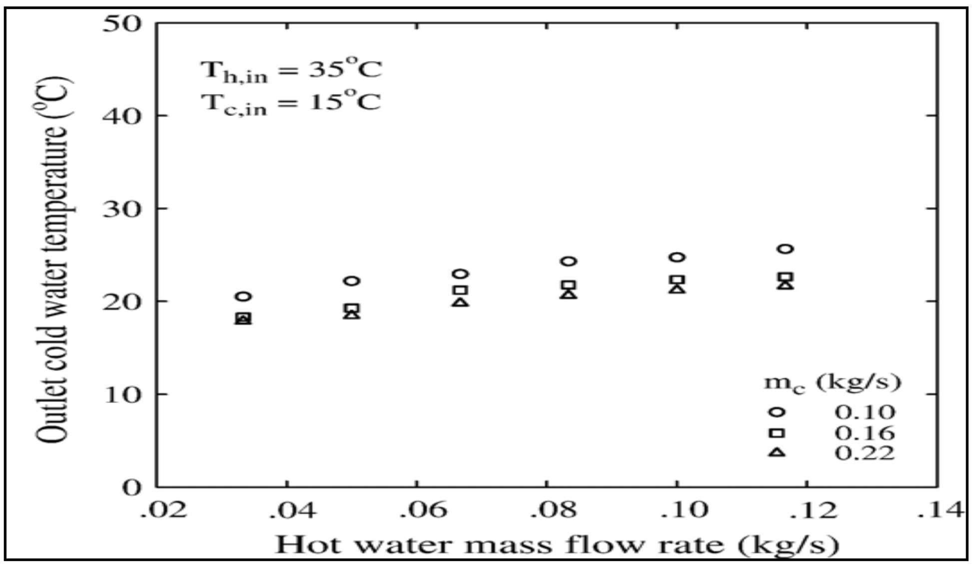
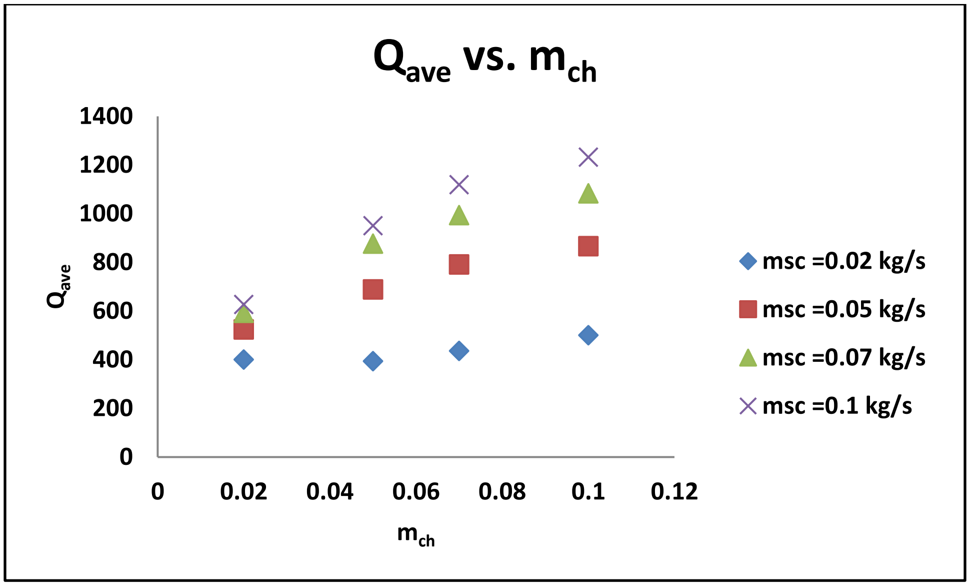


b)

Fig.4.1: $\Delta T_{s,o}$ vs. m_{ch} a) Current Study b) P. Naphon [11]

4.1.2 Q_{ave} vs. m_{ch}:

Fig.4.2 shows the variation of the average heat transfer rate with hot water mass flow rate. At the same hot water mass flow rate, the heat transfer rates at lower cold water mass flow rate are lower than those at higher ones across the range of hot water mass flow rate. However, this effect becomes relatively larger as hot water mass flow rate increases as shown in Fig. 4.2 (a). These results of the current study are showing agreements with results of P. Naphon [11], shown in fig. 4.2 (b)



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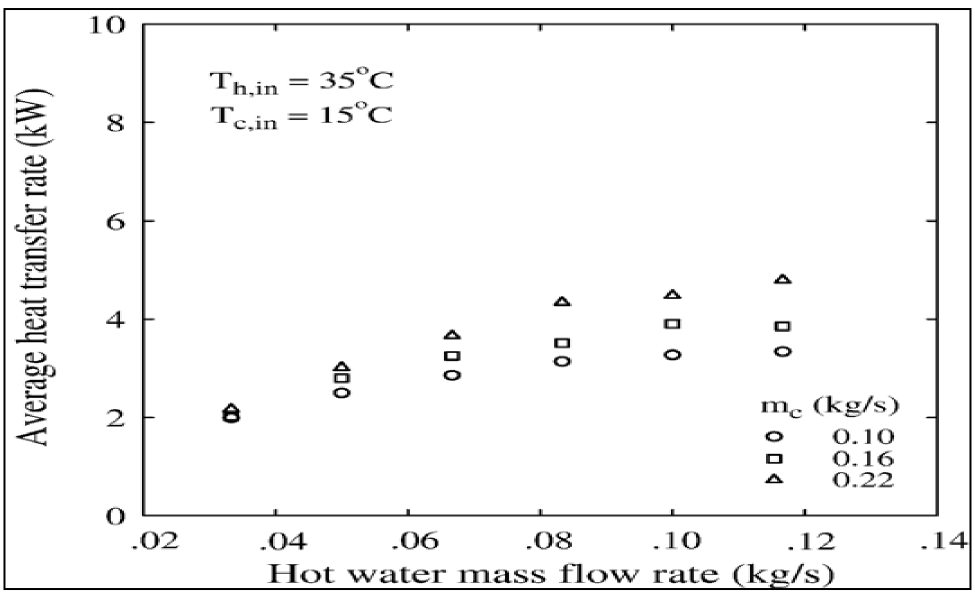
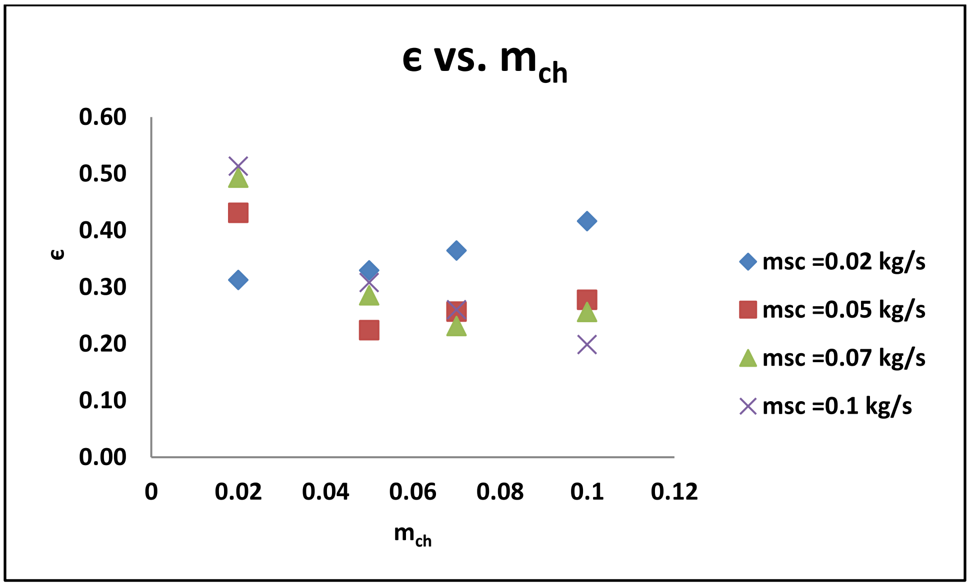


b)

Fig.4.2: Q_{ave} vs. m_{ch} a) Current Study b) P. Naphon [11]

4.1.3 Effectiveness ϵ vs. m_{ch}:

Fig. 4.3 (a) shows that, for the higher range of cold water mass flow rate (0.05-0.1 kg/s) effectiveness is higher for lower mass flow rate of hot water and as mass flow rate of hot water starts increasing, it starts dropping. This is in agreement with P. Naphon [11].



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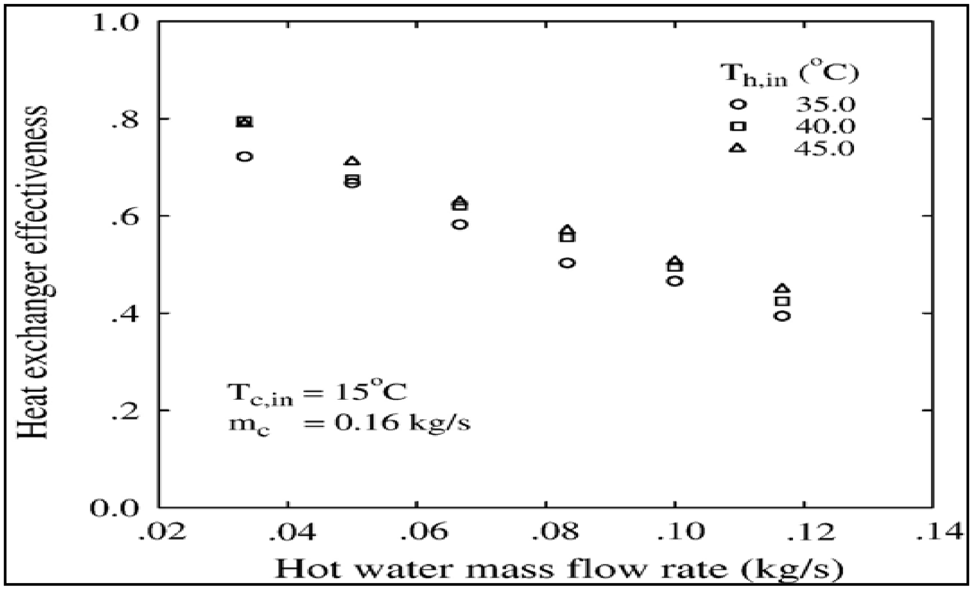
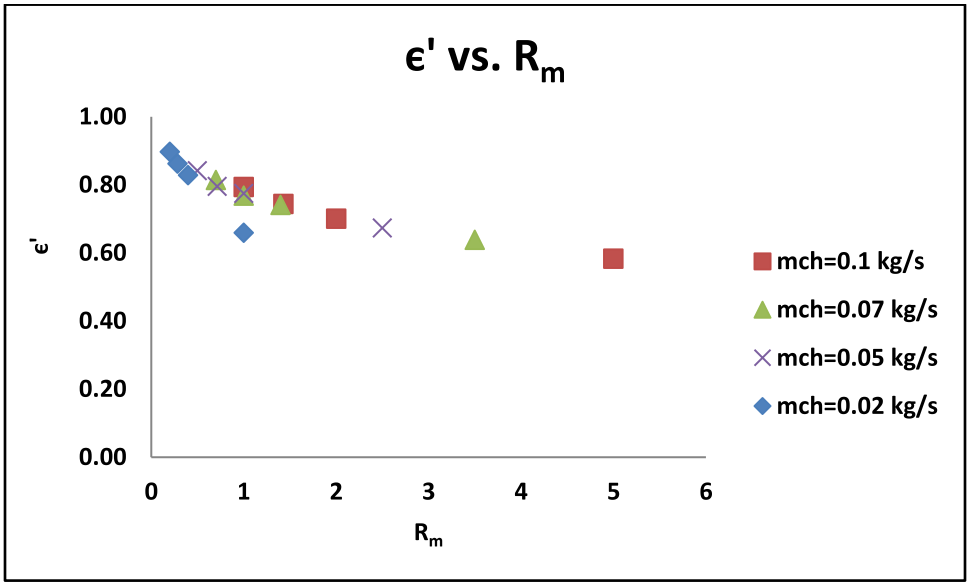


b)

Fig. 4.3: ϵ vs. m_{ch} a) Current Study b) P. Naphon [11]

4.1.4 Modified effectiveness ϵ\` vs. R_m=m_{ch}/m_{sc}:

Fig. 4.4 shows variation of ϵ\` vs. $R_m = m_{ch} / m_{sc}$. The slope of the curve falls rapidly as the value of $R_m = m_{ch} / m_{sc}$ increases. Modified effectiveness $\epsilon$\` shows agreements with result of Ghorbani and Taherian [17], obtained for straight helical coil heat exchanger. It was observed that, for this helical cone coil heat exchanger it is in a better range of 0.9 to 0.6.



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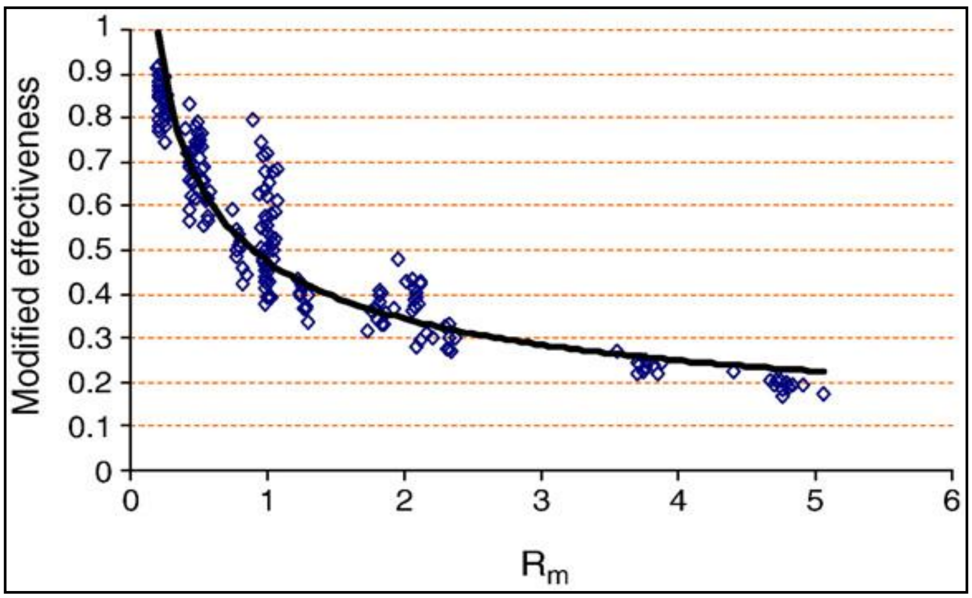

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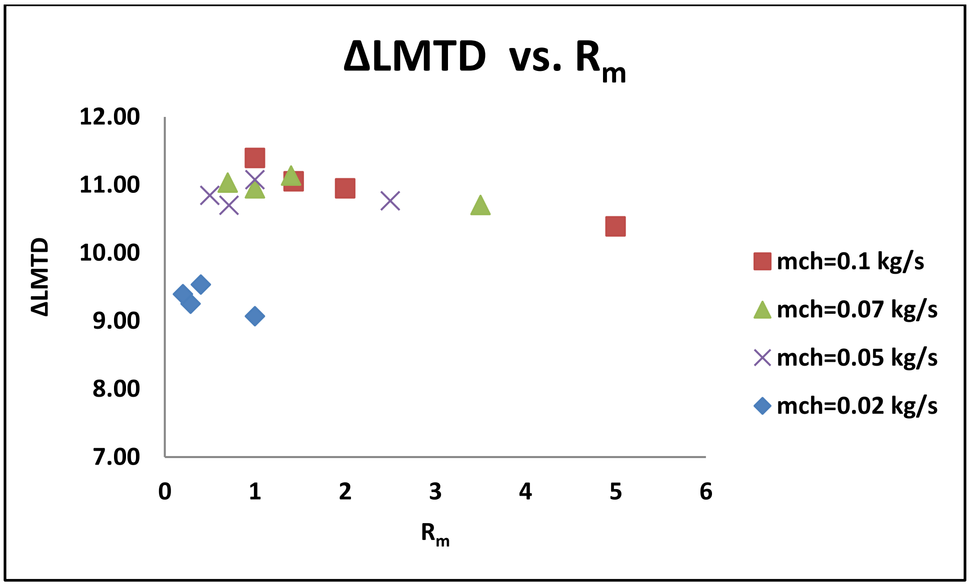
Fig. 4.4: Modified effectiveness, ϵ` vs. $R_m = m_{ch} / m_{sc}$, a) Current Study

b) Ghorbani and Taherian [17]

4.1.5 ΔT_{LMTD} vs. $R_m = m_{ch}/m_{sc}$:

Fig. 4.5 (a) shows that the tendency of ΔT_{LMTD} is such that at lower values of R_m it is increasing and as the value of R_m is reaching towards maximum i.e. 5 it starts decreasing. In Fig. 4.5 (b) Ghorbani and Taherian [17] showed that ΔT_{LMTD} decreased for increase in R_m.



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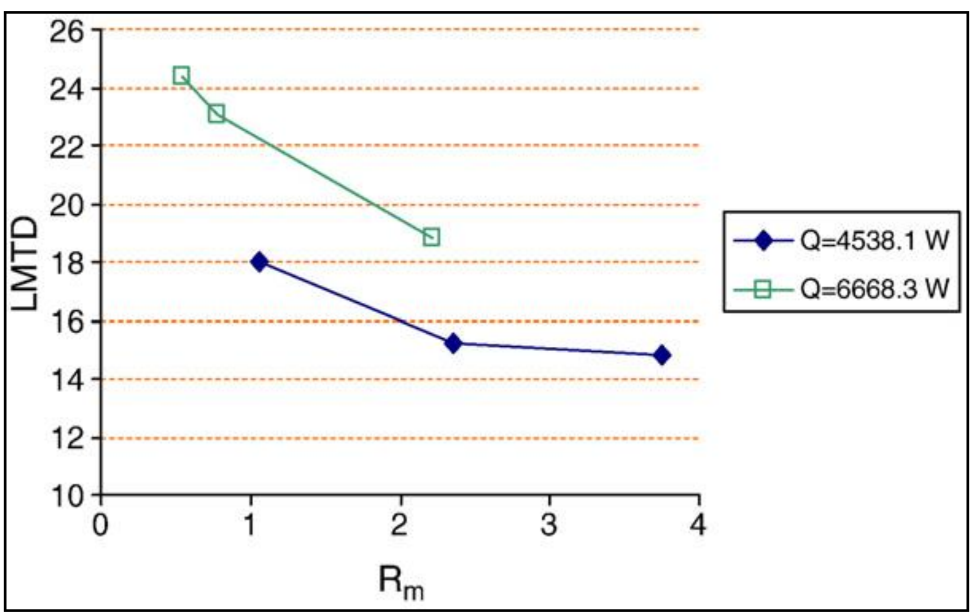


b)

Fig.4.5: ΔT_{LMTD} vs. R_m, a) Current Study b) Ghorbani and Taherian [17]

4.1.6 h_i vs. m_{ch}:

Fig. 4.6 shows that average inside heat transfer coefficient (hi ave) increases with increase in hot water mass flow rate.

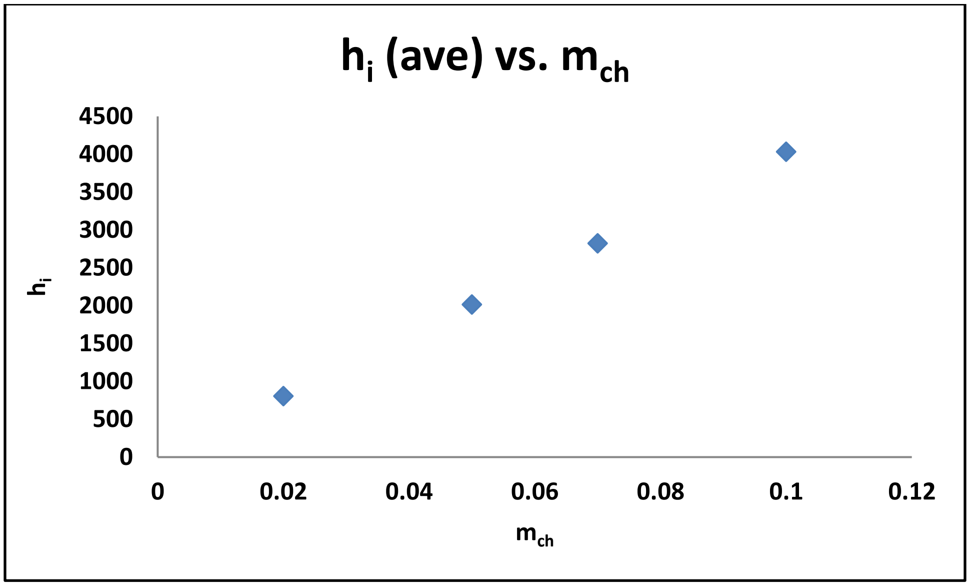
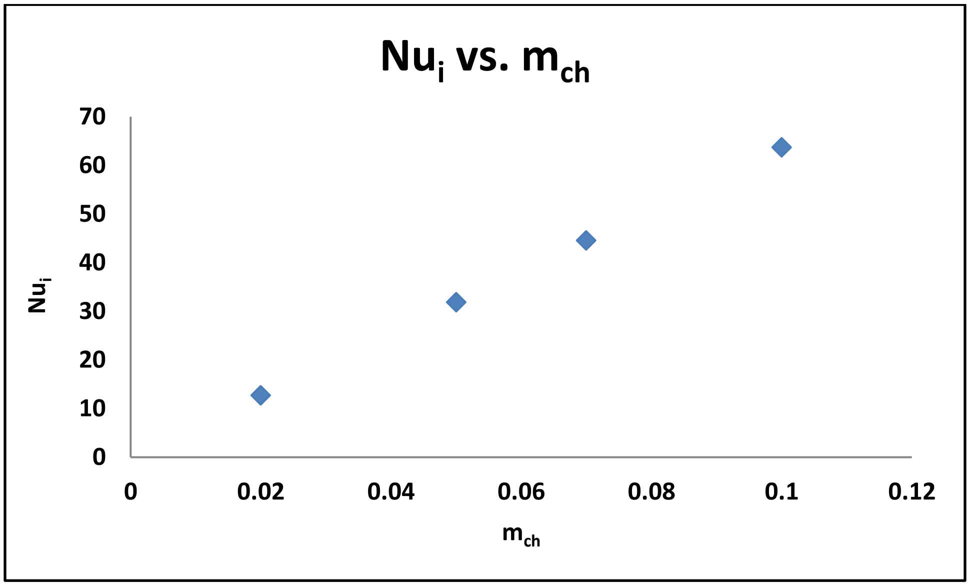


Fig.4.6: h_i vs. m_{ch}

4.1.7 Nu versus Re:

Fig. 4.7 shows the variation of tube side Nusselt numbers with Reynolds numbers. From Fig. 4.7 (a) it is seen that Nu_i increases with Reynolds number and it is in agreement with results of Shokouhmand and Salimpur [14] shown in Fig. 4.7 (b).



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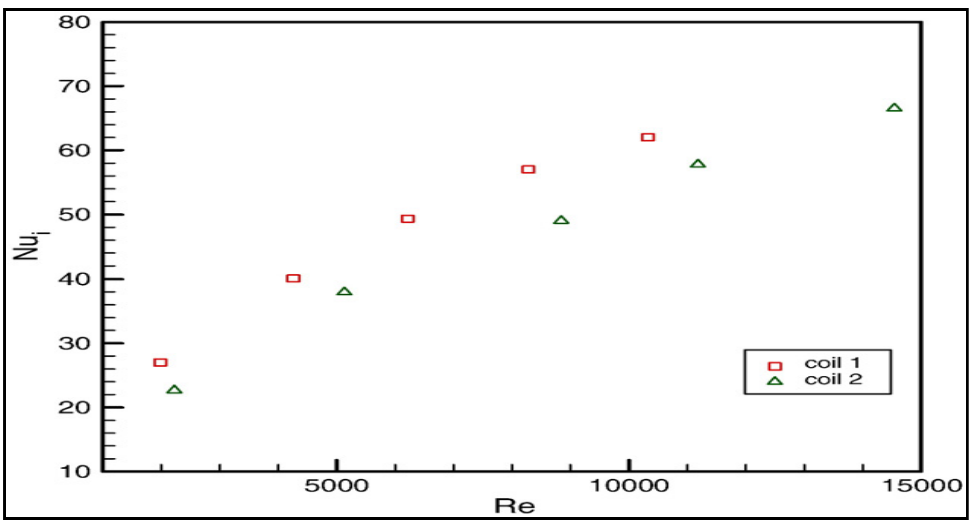

b)

Fig.4.7: Nu_i vs. Re_i a) Current Study b) Shokouhmand and Salimpur [14]

4.2 Results for variation of mass flow rate of shell fluid m_{sc}:

Mass flow rate of shell fluid is varied from 0.02 - 0.10 kg/s and Q_{ave}, h_i, ϵ, and ΔT_{LMTD} were obtained for mass flow rate of coil fluid, m_{ch}=0.01 kg/s, 0.05 kg/s, 0.07 kg/s and 0.09 kg/s and subsequent plots are given in Fig. 4.8 to 4.11.

4.2.1 Q_{ave} vs. m_{sc}:

Fig.4.8 shows the variation of the average heat transfer rate with shell side (cold water) mass flow rate. At a specific temperature of cold and hot water entering the test section, at the same cold water mass flow rate, the heat transfer rates at higher hot water mass flow rate are higher than those at lower ones across the range of cold water mass flow rate.

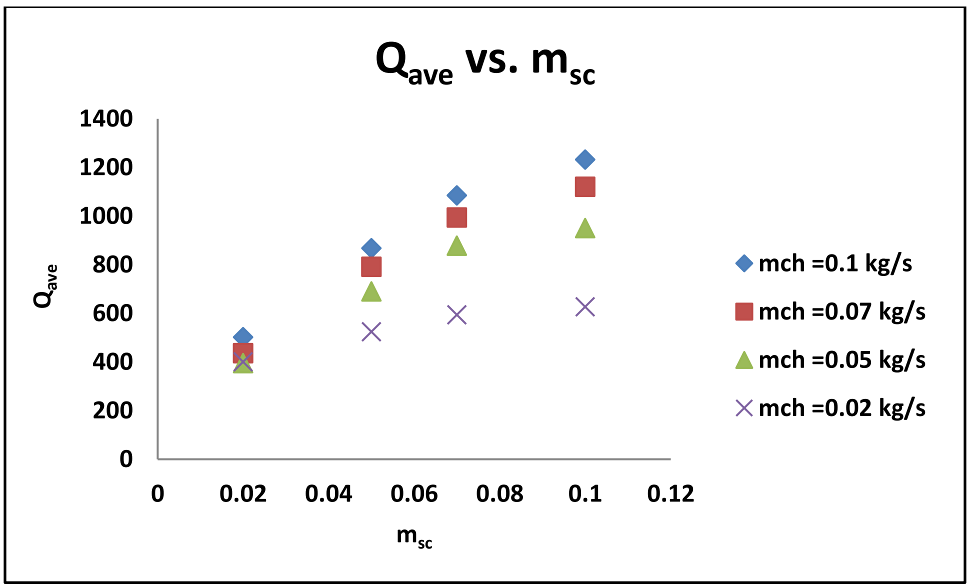

Fig.4.8: Q_{ave} vs.m_{sc}

4.2.2 ϵ vs. m_{sc}:

Fig. 4.9 shows the variation of the heat exchanger effectiveness with shell (cold water) mass flow rate. For the range of hot water mass flow rate, 0.05 - 0.1 kg/s effectiveness tends to decrease with increasing cold water mass flow rate.

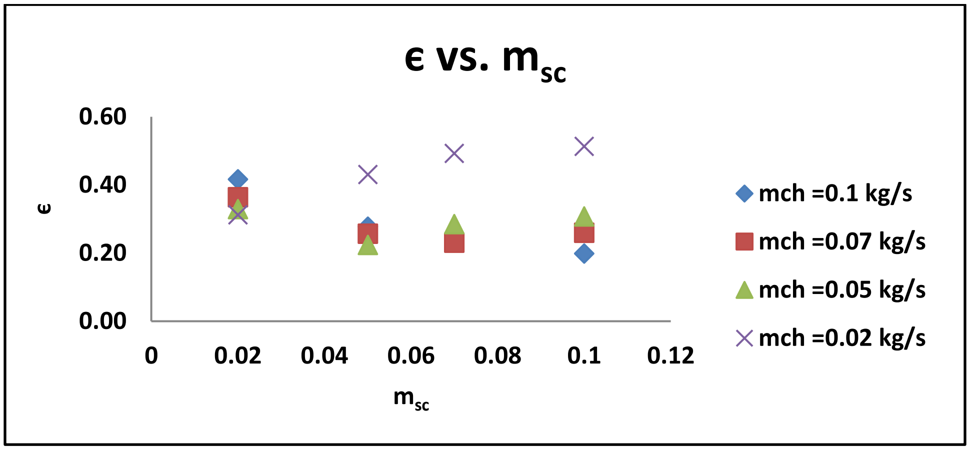

Fig.4.9: ϵ vs. m_{sc}

4.2.3 ΔT_{LMTD} vs. m_{sc}:

Fig.4.10 shows the variation of ΔT_{LMTD} with shell side (cold water) mass flow rate. For the range of hot water mass flow rate, 0.05-0.1 kg/s tendency ΔT_{LMTD} is decreasing as an increase in cold water mass flow rate.

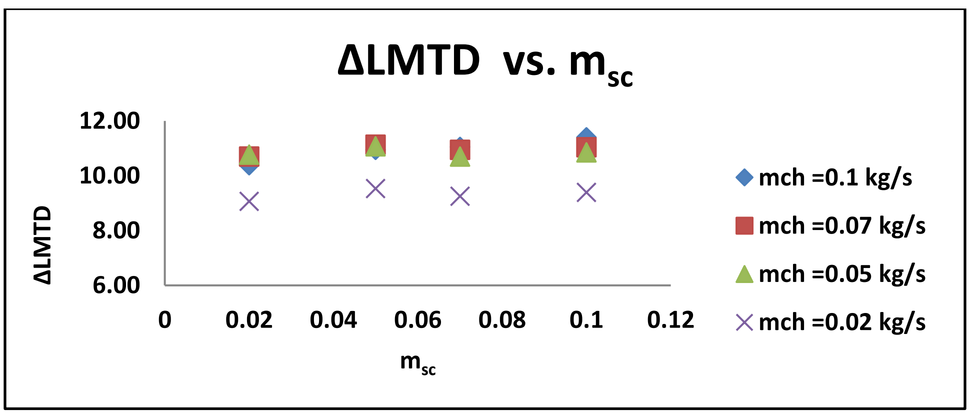

Fig. 4.10: ΔT_{LMTD} vs. m_{sc}

5. CONCLUSION:

Experimental setup was developed to check thermal performance of helical cone coil heat exchanger having slant edge angle (cone angle, θ) as 70°. Mass flow rate of hot water in the coil was kept constant (in the range 0.02-

0.10 kg/s) and mass flow rate of cold water in the shell was varied in steps (range 0.02-0.10 kg/s). Inlet and exit temperatures of hot and cold water were measured.

- Temperature difference of cold water is increasing with increase in hot water mass flow rate and is higher for higher mass flow rate of cold water. Also the exit temperature of cold water is increasing as the mass flow rate of cold water is increasing.
- At the same hot water mass flow rate, the heat transfer rates at lower cold water mass flow rate are lower than those at higher ones across the range of hot water mass flow rate. However, this effect becomes relatively larger as hot water mass flow rate increases.
- For the higher range of cold water mass flow rate (0.05-0.1 kg/s) effectiveness is higher for lower mass flow rate of hot water and as mass flow rate of hot water start increasing, it starts dropping.
- Tendency of logarithmic mean temperature difference (ΔT_{LMTD}) is such that at lower values of ratio of mass flow rates of both fluids (R_m) it is increasing and as value of R_m is reaching towards maximum i.e. 5 it starts decreasing. ΔT_{LMTD} at lower hot water mass flow rate are higher than those at higher ones across the range of cold water mass flow rate.
- Tube side Nusselt number is found to increase as tube side Reynolds number increases.
- At a specific temperature of cold and hot water entering the test section, at the same cold water mass flow rate, the heat transfer rates at higher hot water mass flow rate are higher than those at lower ones across the range of cold water mass flow rate.
- For the range of hot water mass flow rate, 0.05 - 0.1 kg/s effectiveness tends to decrease with increasing cold water mass flow rate.
- Modified effectiveness (ϵ`) shows agreements with result of researchers. For the helical cone coil heat exchanger studied here modified effectiveness is in the better range of 0.9 to 0.6. In this connection it is necessary to vary the cone angle of the helical coil and study its effect on the thermal performance.

NOMENCLATURE:

Lowercase letters

Cp	:	Specific Heat, J/kg°K
d	:	Diameter of tube, m
De	:	Dean Number

h	:	Hot
h	:	Heat transfer coefficients, $W/m^2 K$
k		Thermal Conductivity, W/m K
m	:	Mass flow rate, kg/s
$(mC_p)_{min}$	:	Minimum Value of Product of m and C_p
Nu	:	Nusselt No.
Pr	:	Prandtl No.
Re	:	Reynolds No.
Re_{crit}	:	Critical Reynolds No.
t	:	Tube, Top
v	:	Velocity, m/s

Uppercase letters

A	:	Area, m^2
D	:	Coil Diameter, m
H	:	Height, m
L	:	Coil Length, m
LMTD	:	Log Mean Temperature Difference
N	:	Number of Turns
P	:	Pitch, m
Q	:	Rate of Heat Transfer, W
T	:	Temperature °C
U	:	Overall Heat Transfer Coefficients
V	:	Volume, m^3

Greek letters

ρ	:	Mass Density, kg/m^3

μ	:	Dynamic Viscosity, m/kg s
ϵ	:	Effectiveness
ϵ'	:	Modified Effectiveness
ϴ	:	Angle, °
ΔT	:	Temperature Difference , ° C

Subscripts

ave	:	Average
c	:	Cold Water, Coil
bot	:	Bottom
top	:	Top
h	:	Hot Water
i	:	Inner, Tube side, Inlet
min	:	Minimum
o	:	Outer, Outside, Exit
ov	:	Overall
s	:	Shell
si	:	Inner Shell
so	:	Outer Shell
t	:	Tube

Abbreviations

CF	:	Counter Flow
CFD	:	Computational Fluid Dynamics
PF	:	Parallel Flow

REFERENCES:

(1) Patil R, Shende R, Ghosh P. Designing a helical- coil heat exchanger. Chemical Engineering 1982; 85-88.

(2) Ali M. Experimental investigation of natural convection from vertical helical coiled tubes. International Journal of Heat and mass transfer 1994;37(4):665-671.

(3) Prabhanjan D, Raghavan G, Rennie T. Comparison of heat transfer rate between a straight tube heat exchanger and a helically coiled heat exchanger. International Communications in Heat and Mass Transfer 2002; 29(2):185-191.

(4) Aravind G, Arun Y, Sunder R, Subrahmaniyam S. Natural Convective Heat Transfer in Helical Coiled Heat Exchanger. IE (I) Journal 2003; 84: 1-7.

(5) Rose J. Heat-transfer coefficients, Wilson plots and accuracy of thermal measurement. Experimental Thermal and Fluid Science 2004; 28:77-86.

(6) Rennie T, Raghavan V. Numerical studies of a double-pipe helical heat exchanger. Applied Thermal Engineering 2006; 26 (11–12):1266-1273.

(7) Vimal K, Supreet S, Sharma M, Nigam K. Pressure drop and heat transfer study in tube-in-tube helical heat exchanger. Chemical Engineering Science 2006; 61(13) : 4403-4416.

(8) Parker J. Helical coil heat exchanger –Thermal design of heat exchanger. Saint Martin's University,ME 436 2007: 1-32.

(9) Seara J, Uhia F, Sieres J., Campo A. A general review of the Wilson plot method and its modifications to determine convection coefficients in heat exchange devices. Applied Thermal Engineering 2007;27:2745-2757.

(10) Naphon P, Suwagrai J. Effect of curvature ratios on the heat transfer and flow developments in the horizontal spirally coiled tubes. International Journal of Heat and Mass Transfer 2007; 50:444–451.

(11) Naphon P. Thermal performance and pressure drop of the helical-coil heat exchangers with and without helically crimped fins. International Communications in Heat and Mass Transfer 2007;34:321–330.

(12) Jayakumar J, Mahajani S, Mandal J, Vijayan P, Bhoi R. Experimental and CFD estimation of heat transfer in helically coiled heat exchangers. Chemical Engineering Research and Design 2008;86(3):221-232.

(13) Vimal K, Faizee B, Mridha M, Nigam K. Numerical studies of a tube-in-tube helically coiled heat exchanger. Chemical Engineering and Processing: Process Intensification 2008; 47(12):2287-2295.

(14) Shokouhmand H, Salimpour M, Behabadi M. Experimental investigation of shell and coiled tube heat exchangers using wilson plots. International Communications in Heat and Mass Transfer 2008; 35:84–92.

(15) Kharat R, Bhardwaj N, Jha R. Development of heat transfer coefficient correlation for concentric helical coil heat exchanger. International Journal of Thermal Sciences 2009; 48(12): 2300-2308.

(16) Moawed M. Experimental study of forced convection from helical coiled tubes with different parameters. Energy Conversion and Management 2011;52:1150–1156.

(17) Ghorbani N, Taherian H, Gorji M, Mirgolbabaei H. An experimental study of thermal performance of shell-and-coil heat exchangers. International Communications in Heat and Mass Transfer 2010; 37(7):775-781.

(18) Ghorbani N, Taherian H, Gorji M, Mirgolbabaei H. Experimental study of mixed convection heat transfer in vertical helically coiled tube heat exchangers. Experimental Thermal and Fluid Science 2010;34 (7):900-905.

(19) Huminic G, Huminic A. Heat transfer characteristics in double tube helical heat exchangers using nanofluids", International Journal of Heat and Mass Transfer 2011;54(19-20):4280-4287.

(20) Jamshidi N, Farhadi M, Sedighi K, Ganji D. Optimization of design parameters for nanofluids flowing inside helical coils. International Communications in Heat and Mass Transfer 2012; 39: 311-317.

(21) Yang Z, Zhao Z, Liu Y, Chang Y, Cao Z. Convective heat transfer characteristics of high-pressure gas in heat exchanger with membrane helical coils and membrane serpentine tubes. Experimental Thermal and Fluid Science 2011;35(7):1427-1434.

(22) Zhao Z, Wang X, Che D, Cao Z. Numerical studies on flow and heat transfer in membrane helical-coil heat exchanger and membrane serpentine-tube heat exchanger. International Communications in Heat and Mass Transfer 2011; 38(9):1189-1194.

(23) Ferng Y, Lin W, Chieng C. Numerically investigated effects of different Dean number and pitch size on flow and heat transfer characteristics in a helically coil-tube heat exchanger. Applied Thermal Engineering 2011:1-8.

(24) Naphon P. Study on the heat transfer and flow characteristics in a spiral-coil tube. International Communications in Heat and Mass Transfer 2011; 38:69–74.

(25) Yan K, Pei G, Yan-cai S, Hai-tao M. Numerical simulation on heat transfer characteristics of conical spiral tube bundle. Applied thermal Engineering 2011;31: 284-292.

(26) Elazm M, Ragheb A, Elsafty A, Teamah M. Experimental and numerical comparison between the performance of helical cone coil and ordinary helical coils used as dehumidifier for humidification dehumidification in desalination units. International journal of applied engineering research, Dindigul 2011;2(1):104-114.

(27) Geneic S, Jacimovic B, Jaric M. Research on the shell side thermal performance of heat exchangers with helical tube coils. International Journal of Heat and Mass Transfer 2012; 55(15–16):4295-4300.

(28) Pawar S, Shetty P, John A, Pawar S, Jagtap P. Experimental study for comparison of overall heat transfer co-efficient in helical coils of fixed length using water. International Journal of Latest Research in Science and Technology 2015; 4:161-166.

(29) Alimoradi A. Study of thermal effectiveness and its relation with NTU in shell and helically coiled tube heat exchanger. Case Studies in Thermal Engineering 2017; 9:100-107.

(30) Jamshidi N, Mosaffa A. Investigating the effects of geometric parameters on finned conical helical geothermal heat exchanger and its energy extraction capability. Geothermics 2018; 76: 177-189.

(31) Daghigh R, Zandi P. Experimental analysis of heat transfer in spiral coils using nanofluids and coil geometry change in a solar system. Applied Thermal Engineering. 2018: Available from URL: doi: https://doi.org/10.1016/j.applthermaleng 2018.09.053

(32) Palanisamy K., Mukesh K. Experimental investigation on convective heat transfer and pressure drop of cone helically coiled tube heat exchanger using carbon nanotubes/ water nanofluids. Heliyon 2019; 5:1-10.

(33) Heyhat M, Jafarzad A, Changizi P, Asgari H, Valizade M. Experimental research on the performance of nanofluid flow through conically coiled tubes.Powder Technology 2019: Available from URL: https://doi.org/10.1016/j.powtec.2020.05.058.

(34) Ali M, M. Rad M, Nuhait A, Almuzaiqer R, Alimoradi A, Iskander T. New equations for Nusselt number and friction factor of the annulus side of the conically coiled tubes in tube heat exchangers. Applied Thermal Engineering 2019: Available from URL: doi: https: //doi.org/10.1016/ j.applthermaleng. 2019.114545

(35) Sheeba A, Akhil R, Prakash M. Heat Transfer and Flow Characteristics of a Conical Coil HeatExchanger. International Journal of Refrigeration 2019: Available from URL: https://doi.org/10.1016/j.ijrefrig.2019.10.006

(36) Khaled A, Hosseini E, Nohesara A, Mehri M, Ali M, Almuzaiqer R, Alimoradi A, Iskander T. Suggestion of new correlations for the exergy efficiency and coefficient of exergy performance of annulus section of conically coiled tube-in-tube heat exchangers. Chemical Engineering Research and Design 2019: Available from URL: https://doi.org/10.1016 /j.cherd. 2019. 10.002.

(37) Maghrabie H, Attalla M, Mohsen A. Performance of a shell and helically coiled tube heat exchanger with variable inclination angle: Experimental study and sensitivity analysis. International Journal of Thermal Sciences 2021;164:1-12.

(38) Chokphoemphun S, Eiamsa-ard S, Promvonge P, Thongdaeng S, Hongkong S. Heat transfer of a coil-tube heat exchanger in the freeboard zone of a rice husk fluidized-bed combustor. International Communications in Heat and Mass Transfer 2021: 127:1-7.

(39) Omri M, Aich W, Rmili H, Kolsi L. Experimental Analysis of the Thermal Performance Enhancement of a Vertical Helical Coil Heat Exchanger Using Copper Oxide-Graphene (80-20%) Hybrid Nanofluid. Applied Sciences. 2022; 12: 1-13.

(40) Hasan M, Ahmed S, Bhuiyan A. Geometrical and coil revolution effects on the performance enhancement of a helical heat exchanger using nanofluids. Case Studies in Thermal Engineering 2022; 35: 1-13.