CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Abundant works have been done on the flow and heat transfer characteristics in helical coils and heat exchangers in the last several decades. Scientific, industrial and academic people have taken their research interest in this area. This chapter deals with experimental study, numerical study, both experimental and numerical study, effect of the characteristics of non Newtonian fluid on helical coils and heat exchangers and summary. The aim of this literature review is to go through the main topics of interest. This review was mainly focused on geometrical configurations of helical coils. This literature review also provides a comprehensive outline of the attractive research progress made in the area of laminar flow in helical coils. There are a number of papers on fluid flow and heat transfer characteristic through helical coils. Fluid flow and heat transfer through a curved tube was first reviewed by Berger et al. (1983) and subsequently by Shah and Joshi (1987), Naphon and Wongwises (2006), Pawar et al. (2011) etc. In the end of this chapter, a summary from this review is presented.

2.2 Experimental studies on helical coils and heat exchangers

Ito (1969) experimentally determined the friction factors for laminar and turbulent flow in smooth curved pipes with curvature ratios from 0.015 to 0.061. The following correlation was proposed:

For laminar flow and $13.5 < De < 2000$

$$\frac{f_c}{f_s} = 21.5\left[\frac{De}{(1.56 + \log_{10} De)^{5.73}}\right] \tag{2.1}$$

For turbulent flow and $0.034 < \mathrm{Re}\left(\frac{d}{D}\right)^2 < 300$

$$f_c\left[\frac{D}{d}\right]^{1/2} = 0.029 + 0.034\left[\mathrm{Re}\left(\frac{d}{D}\right)^2\right]^{-1/4} \tag{2.2}$$

Mishra and Gupta (1978) experimentally generated pressure drop data in the laminar and turbulent region for Newtonian fluids through 60 helical coils. The inside tube of 0.62, 0.78, 1.165, 1.735 and 1.905 cm was considered. The increase in turbulent drag was dependent on the ratio of the coil tube diameter and its radius of curvature only. Following correlations were proposed for curvature ratio range 0.003 to 0.12 and p/D range 0 to 25.4.

For laminar flow and $1 < De < 3000$

$$f_c / f_S - 1 = 0.033(\log De)^4 \tag{2.3}$$

For turbulent flow and $4500 < \mathrm{Re} < 10^5$

$$f_c - f_S = 0.0075(d/D)^{1/2} \tag{2.4}$$

Austen and Soliman (1988) experimentally investigated effect of pitch on friction factor and the heat transfer characteristic of helical coil. Two coils with curvature ratio of 0.035 and 0.02 in the range of $50 < \mathrm{Re} < 7000$ were considered. Significant effect of pitch on friction factor and Nusselt number was observed at low Reynolds number.

Xin et al. (1996) investigated the pressure drop and void fraction in air-water two phase flows in vertical helical coils. Four different inside diameter of tube (12.7, 19.1, 25.4 and 38.1 mm) and two different outside diameter of concrete cylindrical forms (305 and 609 mm) were used to construct helical coils with different configurations. It was observed that pressure drop in vertical helical coils depends upon both Lockhart Martinelli parameter and flow rates. Geometric parameters had no effects on the void fraction but they had some effect on the frictional pressure drop. The correlation for frictional pressure drop in two phase flow in vertical helical coils was obtained for small diameter of coils.

For $F_d \le 0.1$

$$\phi_L \Big/ \left(1 + \frac{20}{X} + \frac{1}{X^2}\right)^{1/2} = 1 + \frac{X}{65.45 F_d^{0.6}} \tag{2.5}$$

For $F_d \ge 0.1$

$$\phi_L \Big/ \left(1+\frac{20}{X}+\frac{1}{X^2}\right)^{1/2} = 1+\frac{X}{434.8F_d^{1.7}} \tag{2.6}$$

The maximum deviation between the prediction from above equations and the experimental data of the pressure drop multiplier (ϕ_L) was reported about $\pm 35\%$.

Steady state natural convection of air through horizontally helical was experimentally investigated by Ali (1998). The experiments were conducted for different coil geometries in the range of heat flux 500-5000 W/m^2. A decrease of the heat transfer coefficient with Reynolds number was reported in the laminar regime. Furthermore, Ali (2006) also experimentally studied steady state natural convection heat transfer from vertical helical coils in heat transfer oil of a Prandtl number range of 250 to 400. Fifteen coils for different configurations with helix to tube diameter ratio 30, 20.83, 17.5, 13.33 and 10 were used. The heat transfer data were generated and correlated using coil length as a characteristic length. The results showed that the average Nusselt number for oil was higher than that for water at the same Grashof number. Three empirical correlations based on characteristics length were developed.

For $4.37\times10^{10} \le \mathrm{Ra_L} \le 5.5\times10^{14}$

$$\mathrm{Nu_L} = 0.619\mathrm{Ra_L^{0.3}} \tag{2.7}$$

For $1\times10^{8} \le \mathrm{Gr_L} \le 5\times10^{14}$ and $4.4 \le \mathrm{Pr} \le 345$

$$\mathrm{Nu_L} = 0.555\mathrm{Gr_L^{0.301}}\mathrm{Pr^{0.314}} \tag{2.8}$$

For $4.35\times10^{10} \le \mathrm{Ra_L} \le 8\times10^{14}$

$$\mathrm{Nu_L} = 0.714\mathrm{Ra_L^{0.294}} \tag{2.9}$$

Frictional pressure drop of two phase flows in two different helical coils of inner diameter 10 and 11 mm with four different helix inclinations (0^o, 45^o, 90^o and -45^o) were experimentally investigated. Helix axial angles showed little influence on single phase frictional pressure drop. Experimental results indicated that the single phase and boiling two phase frictional pressure drop were higher in small diameter coils than that of larger one. A helical coil positioned at 45^0 upward inclinations had little higher frictional pressure drop; however the difference among four inclined coils was less than 12 %. The boiling two phase flow frictional pressure drop was also higher in small diameter coils and it was affected by system pressure and mass quality. It was also noticed that for single phase flow some previous correlations were quite accurate in predicting frictional pressure drop for lower Reynolds number; Guo et al. (2001).

A comparative study of the heat transfer rates between a straight tube heat exchanger and a helical coil heat exchanger with a curvature ratio of 0.77 was experimentally performed by Prabhanjan et al. (2002). In the transitional regime and turbulent regimes, with Reynolds numbers ranging from 8300 to 41400 and 7700 to 38300 for flow in the coil and the straight pipe respectively. Helical coil heat exchangers had higher heat transfer coefficients compared to that of similar dimension straight tube heat exchanger.

Yang and Chiang (2002) studied the effects of the Dean number, Prandtl number, Reynolds number and the curvature ratio on the pressure drop and heat transfer for periodically varying curvature curved-pipe inside a larger diameter straight pipe to form a double-pipe heat exchanger. The results showed that the pressure drop and heat transfer rate as compared with a straight pipe increased by 40 and 100 % respectively. All of the experimental data were regressed to obtain the following correlation of the friction factor and Nussult number for curvature ratio 0.05 to 0.096

For laminar flow, $2.5\times10^4 \le De \le 6\times10^5$ and $3.9 < \Pr < 4.5$

$$f_c = 7.39 De^{-0.507} \delta^{0.988} \tag{2.10}$$

$$Nu = 0.185 De^{0.325} \delta^{-0.157} \Pr^{0.234} \tag{2.11}$$

For turbulent flow, $2.1\times10^6 \le De \le 5.5\times10^7$ and $4 < \Pr < 5.2$

$$f_c = 1.69 De^{-0.159} \delta^{0.488} \tag{2.12}$$

$$Nu = 2.87 De^{0.4} \delta^{-0.203} \Pr^{0.386} \tag{2.13}$$

Cioncolini and Santini (2006) investigated experimentally the transition from laminar to turbulent flow in helical coils. Twelve coils were tested, with curvature ratios ranging from 0.0027 to 0.145, d=4-11 mm and D=28-1495 mm, while the coil pitches were small enough to neglect the effect of torsion on the flow. Water was used as working fluid. The interaction between turbulence emergence and coil curvature was analyzed from direct observation of the experimental friction factor profiles. Coil curvature was found effective in smoothing the emergence of turbulence and in increasing the value of the Reynolds number required to attain a fully turbulent flow with respect to straight pipes.

Wongwises and Polsongkram (2006) experimentally investigated two-phase heat transfer coefficient and pressure drop of HFC-134a during evaporation inside a smooth helical coil concentric tube-in-tube heat exchanger consist of the inner tube made from copper 7.2 mm inner diameter with refrigerant flowing in the inner tube and water flowing in the annulus. The test section was a 5.786 m long helical coil with outer diameter of 9.52 mm. The coil diameter was 305 mm. The experiments were conducted at average saturated evaporating temperatures ranging between 10 and 20 ^{0}C. The mass and heat fluxes varied from between 400 to 800 kg/m^{2}s and 5 to 10 kW/m^2 respectively. The inlet quality of the refrigerant in the test section was calculated using the temperature and pressure obtained from the experiment. The pressure drop across the test section was directly measured by a differential pressure transducer. The average heat transfer coefficient of HFC-134a during evaporation tended to increase with increasing average quality, mass flux, and heat flux and saturation temperature. In addition, the pressure drop in the test section increased with increasing average quality, mass flux and heat flux but tended to decrease with increasing saturation temperature. The correlation for predicting the average heat transfer coefficient and pressure drop during evaporation were also developed as

$$Nu_{tp} = 6895.98 De_{eq}^{0.432} \Pr_l^{-5.055} \left(Bo \times 10^4\right)^{0.132} X^{-0.0238} \tag{2.14}$$

$$\phi_l = 1 + \frac{13.37}{X^{1.492}} \tag{2.15}$$

Ghorbani et al. (2010) experimentally studied the mixed convection heat transfer in a coil-in-shell heat exchanger for various Reynolds numbers, various tube-to-coil diameter ratios and different dimensionless coil pitch. The experiments were conducted for both laminar and turbulent flow inside coil with curvature ratio 0.062 and 0.084. Effects of coil pitch and tube diameters on shell-side heat transfer coefficient of the heat exchanger were studied. It was found that the tube diameter had negligible influence on the shell-side heat transfer coefficient. The coil surface area showed a negative effect on heat transfer. On the other hand, the convective heat transfer coefficient of shell-side increased when the coil pitch increased. A desired correlation between the Nusselt number and the Rayleigh and Reynolds numbers based on the equivalent diameter of the shell-side of the heat exchanger was developed.

Correlation was valid for $1.2\times10^{7} < Ra_{Deq} < 3.2\times10^{8}$ and $120 < \mathrm{Re}_{\mathrm{Deq}} < 1200$

$$\mathrm{Nu}_{\mathrm{Deq}} = 0.0041\mathrm{Ra}_{\mathrm{Deq}}^{0.4533}\mathrm{Re}_{\mathrm{Deq}}^{0.2}\mathrm{Pr}_{\mathrm{s}}^{0.3} \tag{2.16}$$

Chen et al. (2011) experimentally studied on critical heat flux (CHF) characteristics of R134a flow boiling in horizontal helical coils. The test sections consist of stainless steel with tube inner diameters of 3.8 to 11 mm, coil diameters of 135 to 370 mm, helical pitches of 40-105 mm and lengths of tube 0.85-7.54 m, were heated uniformly. It was found that both of Bowring (1972) and Shah (1987) correlations were invalid for evaluating CHF in horizontal helical coils. New correlations in terms of Boiling number, Reynolds number, Dean number, liquid gas density ratio and quality for given experimental conditions were developed with errors of ± 20%.

At inlet conditions

$$Bo = 8.071\times10^{-8}\,\mathrm{Re}^{2.12}\,De^{-2.5}N_d^{0.18}x_i^{-0.78} \tag{2.17}$$

At outlet conditions

$$Bo = 3.154\times10^{-7}\,\mathrm{Re}^{2.45}\,De^{-2.1}N_d^{0.46}x_o^{-0.25} \tag{2.18}$$

The above equations were applied in the following range of parameter $0.30 < P < 1.10$ MPa, $3.8 < d < 11$ mm, $850 < L < 7540$ mm, $135 < D < 370$ mm, $40 < p < 105$ mm, $60 < G < 480$ kg/m^{2}s. The CHF values decreased with increasing heated lengths, coil diameters and inner diameters. The coil-to-diameter ratios were more important than length-to-diameter ratios for CHF in helical coils, while the helical pitches had little effect on CHF. It was also noticeable that CHF values greatly increased with increasing mass fluxes; the CHF had declining trend with increasing inlet vapor qualities and became complex at high subcooling conditions.

Gupta et al. (2011) experimentally observed pressure drop measurements for fully developed, incompressible Newtonian fluid flowing through helical coils of constant circular cross section under laminar flow conditions. The five types of coils with 12 different combinations for $d = 4.5 - 12.01$ mm, $D = 114.3 - 655$ mm and

$p = 40 - 300$ mm were considered. The experimental observations indicated that the Germano number successfully signified the combined effect of various coil parameters on the pressure drop. Hence, the data corresponding to low and high Germano numbers ($Gn \le 70$ and $Gn > 70$) had been treated separately, to yield suitable correlations for the laminar flow region. Following correlations were developed based on Germano number within an accuracy of $\pm 15\%$.

Germano number was defined as

$$Gn = \mathrm{Re} \times \delta = \mathrm{Re}\left(\frac{(D/d)}{[\pi(D/d)]^2 + (p/d)^2} \right) \quad (2.19)$$

For $Gn \le 70$

$$f_c = f_s(1 + 0.903 Gn^{0.227}) \quad (2.20)$$

For $Gn > 70$

$$f_c = f_s(1 + 0.525 Gn^{0.516}) \quad (2.21)$$

Mohammed (2011) investigated experimentally steady-state natural convection heat transfer from helical coil tubes in vertical orientation. A straight copper tube of 6 mm inner diameter, 8 mm outer diameter and 3 m length was bend to fabricate the helical coil. Four coils with different curvature ratios and pitches were used in the experiment. Water was used as a bath liquid without any mixing and cold water was used as a coolant fluid. The results showed that the overall heat transfer coefficient and Nusselt number increased with increase of rate of coolant and curvature ratio. The effect of coil pitch was also investigated and the results showed that there was increment in Nusselt number as the coil pitch increased. A correlation was suggested for the outside average Nusselt number of coil.

$$Nu_{do} = 0.2183(Ra)^{4.01}\left(\frac{d}{D}\right)^{2.79}\left(\frac{p}{L}\right)^{7.281} \quad (2.22)$$

Forced convection from helical coils with different parameters was experimentally studied by Moawed (2011). Ten helical coils with tube outer diameter ranging from 11 to 14, coil diameter ranging from 90 to 205 mm and pitch ranging from 12 to 40 mm were employed. The experiments were conducted in the range of Reynolds number of 660 to 2300. The experiments were performed in an open-circuit airflow wind tunnel system operated in suction mode. The experimental results indicated diameter ratio and pitch ratio had important effects on the average heat transfer coefficient. A considerable agreement between the present experimental data and previously reported results was achieved. The pitch ratio of the coil was affected by average Nusselt number; for lower pitch ratio higher Nusselt number was achieved. A general correlation of the average Nusselt number was obtained to describe the forced convection from the coils as the following:

$$Nu_m = 0.0345 \mathrm{Re}^{0.48} (D/d_o)^{0.914} (p/d_o)^{0.281} \tag{2.23}$$

Suresh et al. (2012) experimentally investigated the heat transfer and friction factor characteristics of CuO-water nanofluid in the fully developed laminar region with constant heat flux in plain and dimpled tube. Helically dimpled tube of 4.85 mm diameter and 800 mm length was used. It was found that the experimental Nusselt number for nanofluids higher than those obtained with distilled water in plain tube. The friction factor of CuO-water nanofluid was increased due to the inclusion of nanoprticle. It was proposed that the mechanism of heat transfer enhancement obtained with nanofluids was due to particle migration from the core of fluid flow to tube wall.

Hashemi and Behabadi (2012) experimentally investigated heat transfer and pressure drop characteristics of CuO base oil nanofluid flow for Reynolds number 10 to 150 in a horizontal helical coil copper tube of curvature ratio 0.044 and coil pitch 55 mm under constant heat flux. The nanofluid was prepared by dispersion of CuO nanoparticle in base oil and stabilized by using an ultrasonic device. Nanofluids with different particle weight concentrations of 0.5%, 1% and 2% were used. The effect of different parameters such as flow Reynolds number, fluid temperature and nanofluid particle concentration on heat transfer coefficient and pressure drop of the flow are examined. Observations showed that by using the helical coil instead of the straight one, the heat transfer performance was improved. The curvature of the tube resulted in the pressure drop enhancement. In addition, the heat transfer coefficient as well as pressure drop was increased by using nanofluid instead of base fluid. A correlation for heat transfer coefficient was developed in hydro-dynamically fully developed laminar flow regime valid for $\mathrm{Re} < 125$ and $700 < \mathrm{Pr} < 2050$ with an error of -15% and +18%.

$$\mathrm{Nu} = 41.730 \mathrm{Re}^{0.346} \mathrm{Pr}^{-0.286} (1+\varphi)^{0.18} \tag{2.24}$$

Effects of tube and coil diameters on flow boiling heat transfer coefficients inside small diameter helical coiled tubes were studied by Elsayed et al. (2012). Four different helical coils with coil diameters ranging from 30 to 60 mm were studied using tube diameters ranging from 1.1 to 2.8 mm. The heat flux and mass velocities varied from 2500 to 12000 W/m^2 and 100 to 450 kg/m^{2}s respectively. The heat flux and mass velocity had significant effects on the boiling heat transfer coefficient of the tested coils, decreasing the tube diameter and the coil diameter the heat transfer coefficient improved with up to 63 and 150% respectively. A new correlation for the boiling heat transfer coefficient inside small tube diameter helical coils was developed based on nucleate boiling suppression and convective boiling enhancement factors with mean absolute relative error of 16%.

For $d > Co$

$$F = MAX\left[1, \left(1 + \left(\frac{1}{X}\right)^{0.99278} (\Pr_l)^{0.8} - 2.9946\left(\frac{1}{X}\right)^{0.822} S^{-0.1755}\right)\right] \tag{2.25}$$

For $d < Co$

$$F = MAX\left[1, \left(1 + \left(\frac{1}{X}\right)^{0.3798} (\Pr_l)^{0.8} - 2.4018\left(\frac{1}{X}\right)^{0.32409} S^{-0.5046151}\right)\right] \tag{2.26}$$

Confinement number (Co) defined as

$$Co = \left(\frac{\sigma}{g(\rho_l - \rho_v)d_i^2}\right)^{0.5} \tag{2.27}$$

Aria et al. (2012) experimentally investigated flow boiling heat transfer and pressure drop of HFC-134a inside a vertical helical coil of 8.9 mm inner diameter heated by water flowing in the annulus of 29 mm inner diameter was performed. The test section was in six turn helical coil with 5.786 m length. The diameter and the pitch of the coil are 305 and 45 mm, respectively. The tests were carried out with three different mass velocities of 112, 132, and 152 kg/m^{2}s and average vapor qualities varied from 0.1 to 0.8. Both the heat transfer coefficient and the pressure drop enhanced when a helical coil was used instead of a straight tube. It was also observed that using helical coils affects the frictional pressure drop more than the heat transfer coefficient. Increment in refrigerant mass velocity and inlet vapor quality results a greater heat transfer coefficient and pressure drop. An empirical correlation with satisfactory deviation of ±15% was proposed.

$$Nu_{tp} = 7850 De^{0.43} \Pr^{-5.055} (Bo \times 10^4)^{0.125} X^{-0.036} \tag{2.28}$$

Kannadasan et al. (2012) experimentally studied the comparison of heat transfer and pressure drop characteristics of CuO-water nanofluids in a helical coil heat exchanger held in horizontal and vertical positions. Heat exchanger had inner tube diameter and coil diameter 9 mm and 93 mm respectively. The coil pitch and numbers of turns were 17 mm and 13 respectively. Experiments were conducted in the turbulent flow regimes using water and CuO-water nanofluids of 0.1 and 0.2% volume concentrations. Irrespective of the positions of the heat exchanger, the enhancement in internal Nusselt numbers was high for higher concentration nanofluids at turbulent flow. Also the experimental friction factors obtained were high for higher concentration nanofluids at low flow rates. The experimental results indicated that there was no much difference between horizontal and vertical arrangements in the enhancement of convective heat transfer coefficient and friction factors of nanofluids compared to water. Following correlations were proposed for Nusselt number and friction factor for both horizontal and vertical positions in the range of Dean number 1600 to 4000.

At the horizontal position

for laminar flow

$$Nu = 1.5 De^{0.827} \delta^{0.0008} \varphi^{1.11694} \tag{2.29}$$

$$f = 0.559 De^{0.0376} \delta^{0.18} \varphi^{1.164} \tag{2.30}$$

For turbulent flow

$$Nu = 1.28 De^{1.1} \delta^{0.9617} \varphi^{1.0985} \tag{2.31}$$

$$f = 0.034 De^{0.412} \delta^{0.085} \varphi^{1.212} \tag{2.32}$$

At the vertical position

for laminar flow

$$Nu = 3.67 De^{0.67} \delta^{0.009} \varphi^{1.004} \tag{2.33}$$

$$f = 0.602 De^{0.0794} \delta^{0.2} \varphi^{1.177} \tag{2.34}$$

For turbulent flow

$$Nu = 0.48 De^{1.23} \delta^{0.99} \varphi^{1.0721} \tag{2.35}$$

$$f = 0.0051 De^{0.902} \delta^{1.001} \varphi^{1.15} \tag{2.36}$$

Heat transfer and thermodynamic analyses of a helical coil heat exchanger using different types of nanofluids were investigated by Khairul et al. (2013). CuO-water, Al_2O_3-water and ZnO-water nanofluids with 1 to 4% particle volume concentration and second law of thermodynamic were considered in the analysis. Heat transfer coefficient and entropy generation rate of helical coil heat exchanger were analytically investigated considering the volume flow rates in the range of 3 to 6 L/min. Helical coil of inner diameter 9 mm, coil diameter 116 mm and coil pitch 18 mm for 10 turn were analyzed. It was observed that increment of particle volume fraction and volume flow rate of nanofluids could enhance heat transfer coefficient and reduce the entropy generation rate. Density and thermal conductivity were the most important parameters for efficiency improvement. In addition CuO-water nanofluids could increase the heat transfer coefficient and decrease the entropy generation about 7.14 and 6.14% respectively.

Pressure drop characteristics of nanofluid flow inside vertical helical coils for isothermal boundary conditions in the laminar flow regime were investigated experimentally by Pakdaman et al. (2013). Experiments were carried out for fluid flow inside helical coil of 15.6 mm internal diameter with coil diameter ranges from 220 to 320 mm and coil pitch ranges from 25 to 95 mm respectively. The temperature of the tube wall was maintained constant at around 95 ^{0}C. Experiments were implemented for fluid flow inside helical coils and a straight one. A wide range of various variables was taken into account. Pitch to tube-diameter ratio ranged between 1.6 and 6.1 and coil-to-tube diameter ratio varied from 14.1 to 20.5. Heat transfer oil was used as the base fluid, and Multi-Walled Carbon NanoTubes (MWCNTs) were utilized as the additive to provide the nanofluids. The working fluids were extremely temperature dependent. Irrespective of the tube geometry in which the fluid flows, nanofluid flows showed higher rate of pressure drop compared to that of the base fluid flow. It was concluded that pressure drop of the flows increased with Reynolds number as well as nanoparticle weight concentration. The dependency of the flow pressure drop on the coil pitch was negligible in the range of parameters considered in this study. Increasing coil to tube diameter ratio pressure drop decreased. Simultaneous utilization of helical coils and nanofluids had a high capability to increase the pressure drop. Based on the experimental data and the least square method, the following correlation was developed to predict the ratio of the friction factor of nanofluids inside helical coils to that of the base fluid flow inside a straight tube.

$$\frac{f_{nf,helical}}{f_{bf,stright}} = \left[1 + (\log De)^4\right] \times (1 + 10\varphi)^{4.9} \tag{2.37}$$

$$De = \mathrm{Re}\left\{\frac{D}{d}\left[1 + \left(\frac{p}{\pi D}\right)^2\right]\right\}^{-0.5} \tag{2.38}$$

Effects of curvature ratio and coil pitch spacing on heat transfer performance of Al_2O_3 water nanofluid laminar flow through helical coils were experimentally investigated by Kahani et al. (2013). Experiments were conducted for coils with curvature ratio of 0.05 to 1 with coil pitch of 24 to 42 mm. Due to presence of nanoprticle in the fluid, nanofluids shows higher pressure drop and heat transfer in comparison with water. In addition, due to curvature of coils, significant enhancement was observed in heat transfer rate as well as pressure drop when helical coils utilize instead of straight one. Increasing pitch of coils and decreasing the curvature ratio heat transfer rate improved. A correlation of the Nusselt number with helical number was developed to describe the forced convective heat transfer of nanofluids.

For $0.0025 < \varphi < 0.01$, $5.89 < \Pr < 8.87$ and $115.3 < He < 1311.4$

$$Nu_C = 0.7068\,\mathrm{He}^{0.514}\,\Pr^{0.563}\,\varphi^{0.112} \tag{2.39}$$

$$\mathrm{He} = De\left[1 + \left(\frac{p}{2\pi D}\right)^2\right]^{1/2} \tag{2.40}$$

Jamshidi et al. (2013) experimentally analyzed heat transfer enhancement in shell and coiled tube heat exchangers having copper tubes of 9 mm inner diameter and 12.7 mm outer diameter with 10 turn, coil diameter 81.3 to116 mm and coil pitch 13 to18 mm. Hot water was flowing in helical tube whereas; cold water was flowing in the shell side. The effect of shell and tube side flow rate, coil diameter and coil pitch on heat transfer rate in coiled tube heat exchangers were studied by the use of Wilson plot and Taguchi method. Experimental apparatus and Taguchi method were used to investigate the effect of fluid flow and geometrical parameters on heat transfer rate. Taguchi method was also used for finding the optimum condition for the desired parameters in the range of coil diameter 0.0813 to 0.116 mm and pitch 13 to 18 mm, tube and shell flow rates from 1 to 4 LPM. The optimum condition according to the overall heat transfer coefficient for the whole heat exchanger was also examined. Results indicated that the higher coil diameter, coil pitch and mass flow rate in shell and tube enhanced the heat transfer rate of heat exchangers. Increase in overall heat transfer coefficient was a function of shell side Reynolds number. In addition, as the coil pitch increased, tube side Nusselt number decreased and shell side Nusselt number increased. Also, as the coil diameter increased, tube side Nusselt number and overall heat transfer coefficient increased and shell side Nusselt number decreased. The optimum condition for increasing overall heat transfer coefficient in coiled tube heat exchanger was obtained by highest level of the coil diameter, coil pitch, hot and coldwater flow rates.

Haruki and Horibe (2013) experimentally studied flow and heat transfer characteristics of ice slurries in a helical pipe of inner diameter 14.4 mm. The helical coil had a pitch of 30.0 mm, and six turns. The flow and heat transfer characteristics of ice slurry in helical pipes of a dynamic ice-thermal storage system were investigated as a function of the ice packing factor (IPF), mean flow velocity, input heat flux, and coil diameter. It was found that the flow resistance of ice slurry in helical pipes was influenced by the interaction between the buoyant force and the centrifugal force, due to secondary flow. Correlations for predicting the flow resistance and heat transfer coefficient of ice slurry were proposed

Flow resistance

$$f_c = 8.1 \times \left(\frac{D}{d}\right)^{-0.47} .(1+IPF)^{-1.0} .De^{-0.50} \left(1 + \frac{m \times L_{ice} \times IPF}{q \times A}\right)^{0.024} \tag{2.41}$$

Heat transfer

$$\frac{Nu_{m-c}}{\Pr^{0.4}} = 0.072 \times \left(\frac{D}{d}\right)^{-0.45} .(1+IPF)^{0.60} .De^{-0.86} \left(1 + \frac{m \times L_{ice} \times IPF}{q \times A}\right)^{-0.036} \tag{2.42}$$

Where L_{ice} and Nu_{m-c} are latent heat of melting and mean Nusselt number of helical coil respectively.

Bozzoli et al. (2013) estimated the local heat transfer coefficient in coiled tubes under inverse heat conduction problem approach. It was characterized by tube internal diameter of 14 mm and eight turns. The helix diameter and pitch were of about 230 and 100 mm respectively, yielding a coiled pipe length L of about 6 m. The investigation was focused on the fully developed region for the laminar flow regime. Temperature distribution maps on the external tube wall were employed as input data for the inverse heat conduction problem under a solution approach based on Tikhonov regularization method. The results showed that the variation of the convective heat transfer coefficient along the boundary of the duct section was very significant. The outer surface of the coil the Nusselt number was four to six times that at the inner surface.

In one of recent studies, Reddy and Rao (2014) experimentally demonstrated the heat transfer coefficient and friction factor of TiO_2 nanofluid flowing in a double pipe heat exchanger with and without helical coil inserts in the range of Re 4000 to 15000 with volume concentration range from 0.0004 to 0.02%. The heat exchanger consist of outer tube made of PVC with an inner diameter of 27.8 mm and an outer diameter of 33.9 mm, while the inner tube was made of copper material with an inner diameter of 8.13 mm and an outer diameter of 9.53 mm. Heat transfer coefficient and friction factor were enhanced by 13.8 and 10.69% respectively for 0.02% nanofluid when compared to base fluid flowing in a tube with helical coil insert of helical pitch to inner tube diameter ratio $(\mathrm{p/d} = 2)$. A regression equation was developed for Nusselt number and friction factor.

$$Nu_{\mathrm{Reg}} = 0.007523\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.5}\,(1+\varphi)^{7.6}\left(1+\frac{p}{d}\right)^{0.037} \tag{2.43}$$

$$f_{\mathrm{Reg}} = 0.3250\,\mathrm{Re}^{-0.237}\,(1+\varphi)^{2.723}\left(1+\frac{p}{d}\right)^{0.041} \tag{2.44}$$

Recently, Hwang et al. (2014) experimentally studied flow boiling heat transfer and dryout characteristics at low mass flux in helical coils of inner diameter 12 mm for different coiled diameter (ranging from 577 to 1290 mm). Heat transfer coefficients in the coiled tubes were accurately predicted by Steiner and Taborek (1992) correlation for straight vertical tubes with standard deviation 29%. Flow boiling heat transfer in the coiled tubes was significantly affected by nucleate boiling and convective boiling and not by secondary flow due to the helical coiling. Coiled tubes significantly influenced the dry out qualities. The effects of helical diameter, mass flux, and pressure were greatly affected by secondary flow caused by the coiled tubes. It was observed that heat transfer coefficients in the coiled tubes could be predicted by correlations for a straight vertical tube but the dry out qualities could be predicted by only correlations for the coiled tube.

Kim et al. (2014) work reports on both an analytic model and experimental results with regards to the pressure drop and heat transfer characteristics of compact straight, C-curved, and U-curved tubes. The inner diameter of the tube for selected heat exchanger type was 12.6 mm with a thickness of 0.12 mm. and a total length of 2000 mm. Good agreement was found between the modified friction factor and existing correlations.

2.3 Numerical studies on helical coils and heat exchangers

White (1929) studied pressure drop and heat transfer to aqueous solution of glycerol flowing in different types of coil for laminar flow in the range of Re 80 to 6000. An empirical correlation with 10% deviation for friction factor was proposed as

$$\frac{f_c}{f_s} = \left[\left\{ 1 - \left(1 - \frac{11.6}{De} \right)^{0.45} \right\}^{2.2} \right]^{-1} \tag{2.45}$$

The above correlation was valid for $f_s = 16/\mathrm{Re}$, $11.6 < De < 2000$

Mori and Nakayama (1965, 1967) numerically studied friction factor and forced convective heat transfer in curved pipes. Studies were experimentally verified. Both laminar and turbulent flows were considered in the analysis. Following correlations were suggested for friction factor and Nusselt number valid for $13.5 < De < 2000$.

$$\frac{f_c}{f_s} = \frac{0.1080\sqrt{De}}{1-(3.253/\sqrt{De}} \tag{2.46}$$

$$Nu = Nu_s (0.1979) De^{0.5} \tag{2.47}$$

Srinivasan et al. (1968) studied pressure drop and heat transfer in coils and developed following correlations empirically for friction factor in different range of Dean number valid for curvature ratio $0.0097 < d/D < 0.135$.

For $30 < De < 300$

$$f_c = \frac{32}{\mathrm{Re}} \tag{2.48}$$

For $30 < De < 300$

$$f_c = 5.22\left(\mathrm{Re}\sqrt{\frac{D}{d}}\right)^{-0.6} \tag{2.49}$$

For $30 < De < \mathrm{Re}_{crit}(d/D)^{1/2}$

$$f_c = 1.8\left(\mathrm{Re}\sqrt{\frac{D}{d}}\right)^{-0.5} \tag{2.50}$$

For $\mathrm{Re} < \mathrm{Re}_{crit}$

$$f_c = 1.084\left(\mathrm{Re}\sqrt{\frac{D}{d}}\right)^{-0.2} \tag{2.51}$$

Kalb and Seader (1974) numerically studied heat transfer characteristics in helical coils for constant wall temperature. The Dean numbers were up to 1200. It was observed that the fully developed temperature field changed with increasing Prandtl number. A helical coil heat transfer correlation was proposed for $0.01 < d/D < 0.1$, $80 < De < 1200$ and $0.7 < \mathrm{Pr} < 5$.

$$Nu = 0.836 De^{0.5}\,\mathrm{Pr}^{0.1} \tag{2.52}$$

Patankar et al. (1978) numerically studied effect of the Dean number on friction factor and heat transfer in helical pipes for laminar flow. The three-dimensional parabolic flows were applied to predict the velocity and temperature fields in helical pipes. Good agreements of results were obtained in comparison with the experimental data.

The heat transfer coefficients for laminar and transition flows for forced convective heat transfer in coiled annular tubes was analyzed by Garimella et al. (1988). Analysis indicated that the coiled ducts had a higher heat transfer coefficients than that of straight tubes.

Yang et al. (1995) numerically studied the fully developed laminar convective heat transfer in a helical pipe with a finite pitch. It was observed that convective heat transfer was influenced by the Dean number, the torsion ratio (τ) and the Prandtl number. Nusselt number increased, as the Dean number and the Prandtl number increased, and the torsion decreased.

Xin and Ebadian (1997) studied the influence of the geometric parameters and the Prandtl number on the local and average convective heat transfer characteristics in helical ducts for curvature ratio 0.0267 to 0.0884. A significant change in the Nusselt number was observed with the increase of the Prandtl and the Dean numbers for the laminar flow. Some correlations for Nusselt number in the range of $0.0267 < \delta < 0.0884$ were suggested:

For $20 < De < 2000$ and $0.7 < \Pr < 175$

$$Nu = (2.153 + 0.318 De^{0.643}) \Pr^{0.177} \tag{2.53}$$

For $5 \times 10^{3} < \mathrm{Re} < 10^{5}$ and $0.7 < \Pr < 5$

$$Nu = 0.0619 \mathrm{Re}^{0.92} \Pr^{0.4} (1 + 3.455\delta) \tag{2.54}$$

The influence of the wall temperature on the development of heat transfer and secondary flow in a coiled tube heat exchanger with a curvature ratio of 0.074 was numerically studied by Rindt et al. (1999). The finite difference discretization scheme was used. The influence of buoyancy forces was analyzed on heat transfer and secondary flow. It was observed that if the heat transfer increases buoyancy effects increases. It was also observed that for all Grashof number, heat transfer was quantified by Nusselt number and secondary flow was quantified by relative kinetic energy, both exhibited a wavy behaviour in axial direction.

Zheng et al. (2000) numerically studied convection and radiation heat transfer in helical pipe with a curvature ratio of 0.05. The three-dimensional governing equations for laminar flow and heat transfer were solved with a control volume finite difference method (CVFDM) with second-order accuracy, and the O-type structure grid was considered in the analysis. The effects of thermal radiation on the convective flow and heat transfer were measured by comparing the numerical results with and without thermal radiation. The friction factor was not sensitive to thermal radiation, especially in the fully developed region. Increasing pitch, the developing region also increased. It was observed that the temperature ratio had significant influence on the total heat transfer when thermal radiation was active and had little influence on pure convective heat transfer. In addition, total heat transfer in helical pipe could be substantially enhanced when thermal radiation was in consideration. In fully developed region, flow fields were insensitive to thermal radiation.

Performance analysis of helical coil heat exchangers with circular minichannels of 1mm inner diameter was studied by Kim et al. (2006).The working fluid was R-22, and the properties of R-22 were estimated using REFPROP program. Numerical simulation was performed calculating heat transfer rate and pressure drop for performance analysis of helical coil heat exchangers. It showed the good performance when the flow rate of each channel was suitable to heat load of air side. An optimum helical coil minichannels evaporator was designed. The heat transfer rate and pressure drop in low mass velocity from simulation showed good agreement with experimental results with accuracy of $\pm 15\%$.

Laminar forced convection and entropy generation in a helical coil with curvature ratio of 0.1104 in the range of Re 1000 to7500 for constant wall heat flux numerically investigated by Ko (2006). Both the entrance and fully developed regions were considered. Water (Pr = 5.98) was selected as working fluid in the study. The wall heat fluxes varied from 160 to 640W/m^2. The development of flow fields, including secondary flow motion, distributions of temperature, Nusselt number, and friction factor, were examined. An optimal Reynolds number was suggested for the least irreversibility and best energy utilization. It was also found that the relationship between entropy generation and heat flux was not monotonic and was dependent on Reynolds number.

Shokouhmand and Salimpour (2007) analytically investigated the optimal Reynolds number of laminar forced convection based on minimal entropy generation principle in a helical tube of curvature ratio $\delta = 0.01 - 0.3$ subjected to uniform wall temperature. In the study $\mathrm{Re}_{opt} = 2000 - 14000$ for air and $\mathrm{Re}_{opt} = 5000 - 15000$ for water were considered. The influence of coil curvature ratio and fluid properties, β_1 and β_2 (dimensionless parameter) on the optimum Reynolds number had been investigated for air and water. It was revealed that optimum Reynolds numbers decrease as curvature ratio increases except in the low ranges of curvature ratio where transition to turbulent flow occurs. Following correlation was developed based on dimensionless parameter:

For air with an error of 2.15 %

$$\mathrm{Re}_{opt} = 2100\beta_1^{-0.45}\left(\frac{\beta_2}{10^{-10}}\right)^{-0.53}\delta^{-0.19} \tag{2.55}$$

For water with error of 0.69%

$$\mathrm{Re}_{opt} = 1790\beta_1^{-0.05}\left(\frac{\beta_2}{10^{-10}}\right)^{-0.53}\delta^{-0.02} \tag{2.56}$$

Where β_1 and β_2 defined as

$$\beta_1 = \frac{4k}{\mu Cp} \tag{2.57}$$

$$\beta_2 = \frac{\mu^3}{32\rho^2 a^2 k T_w} \tag{2.58}$$

Kharat et al. (2009) numerically developed heat transfer coefficient correlation for concentric helical coil heat exchanger using CFD methods. Experimental data and CFD simulations using Fluent 6.3.26 were used to develop improved heat transfer coefficient correlation for the flue gas side of heat exchanger. Mathematical model was developed to analyze the data obtained from CFD and experimental results to account for the effects of different functional dependent variables such as gap between the concentric coil, tube diameter and coil diameter which affects the heat transfer. Optimization was done using Numerical Technique. It was found that the new correlation for heat transfer coefficient developed in this investigation provides an accurate fit to the experimental results within an error band of 3 to 4%.

$$Nu = 0.02652604\,\mathrm{Re}^{0.834693285}\,\mathrm{Pr}^{0.3}\,(Gap\ ratio)^{-0.096856199} \tag{2.59}$$

Where gap ratio defined as

Gap ratio = $(D_o\text{-}D_i)/d$ (2.60)

Purandare et al. (2012) studied parametric analysis of helical coil heat exchanger of internal tube diameter of 8, 10 and 12 mm for a constant coil diameter of 200 mm in the range of Re 100 to 6000. The analysis indicated that, for constant coil diameter as the tube diameter increased, the intensity of developed secondary fluid flow increased hence increment in Nusselt no. Exchanger was efficient in low Reynolds number.

Heat transfer and flow characteristics in helical coils with various curvature ratios (0.125, 0.0862 and 0.05) and different coils pitch was predicted by Beigzadeh and Rahimi (2012) using artificial neural networks (ANNs). Three-layer feed forward ANNs were developed to predict Nusselt number and friction factor in the studied coiled tubes. Optimal neural network configurations were evaluated by trial-and-error method. An ANN with 9 hidden neurons was selected for predicting of Nusselt number and a network with 12 hidden neurons was employed to predict friction factor in the tubes. The predicted Nusselt number from ANNs was compared with experimental results as well as those obtained from correlation developed by Xin and Ebadian (1997). The ANN predicted friction factor was compared with measured values and those obtained from empirical correlation proposed by Ito (1969). In both cases, the superior performance of developed neural network was proved.

Ferng et al. (2012) studied the thermal and hydraulic characteristics in a helical coil heat exchanger of curvature ratio 0.08 using CFD methods. The governing equations were discretized into the finite-differencing forms. Equations of continuity and momentum were treated by SIMPLEC scheme. CFD methodology was validated by the previous experimental works. It was observed that Nusselt number increases as the pitch size increases.

A computational fluid dynamics (CFD) methodology was proposed to investigate thermal and hydraulic characteristics of nanofluid flow in laminar region in a helical coil heat exchanger by Mohammed and Narrein (2012). A CuO nanoparticle with a diameter of 25 nm dispersed in water with a particle concentration of 4% was used as the working fluid. The effect of flow configuration (parallel and counter) was also examined in this study. The performance of the exchanger was evaluated in terms of Nusselt number, heat transfer rate, pressure drop, performance index, and effectiveness. The three dimensional governing equations (continuity, momentum and energy) along with the boundary conditions are solved using the finite volume method (FVM). The second-order upwind differencing schemes for the convective terms and SIMPLEC algorithm for solving flow field were used. The heat transfer could be enhanced by reducing the helix diameter, increasing the inner tube diameter and decreasing the annulus diameter under laminar flow conditions. However the pressure drop increases as the helix diameter and inner tube diameter decreases. It was also found that counter-flow configuration produced better results as compared to parallel-flow configuration.

Recently Seara et al. (2014) developed a numerical model in order to predict the heat transfer process and pressure drop in a vertical helical coil heat exchanger located inside a fluid storage tank in which water was used as inner and outer fluid, and validated with experimental data obtained from an own facility with two exchangers tested under several operating conditions. Natural convection was considered as boundary condition for the heat exchanger outer surface. The model developed was used to evaluate the main exchanger representative geometrical parameter influence on the overall heat transfer coefficient and pressure drop. Following correlation was suggested.

For $4.67\times10^{6} \leq Ra \leq 3.54\times10^{7}$

$$Nu_{do} = 0.4998 Ra^{0.2633} \tag{2.61}$$

above correlation showed good agreement with experimental results. Furthermore the Nusselt number increased with increasing the tube diameter.

In one of the recent studies by Pan et al. (2014)**,** numerically investigated heat transfer and pressure drop for oscillating flow in helical coil heat exchanger based on the Navier Stokes equations using the commercial CFD code Fluent. The exchanger had a tube diameter and coil diameter of 3 and 103 mm. It was investigated for single turn having pitch of 22 mm. The two factors, frequency and velocity, influenced the flow in oscillating helical coil heat exchanger. The field synergy principle was also used to explain the heat transfer enhancement in oscillating flow in helical coil heat-exchanger. The volume average field synergy angle could reflect the level of heat transfer in oscillatory flow. The better heat transfer would be at smaller angle.

Recently Raj et al. (2014) numerically analyzed helical coil heat exchanger using CFD technique. The coil had an inner diameter of 10 mm and coiled diameter of 300 mm with pitch of 30 and 60 mm. The three dimensional flow through the helical coil was considered which would overcome the anisotropic flow properties that would arise due to complex turbulence phenomenon and flow deviations. Analysis of heat exchanger was done using conjugate heat transfer. The flow field through the helical coil was simulated by solving the appropriate governing equations: conservation of mass, momentum and energy. The turbulence was taken care by Shear Stress

Transport (SST) k-ε model of closure. The heat transfer characteristics of a 60 mm coil pitch were better as compared to 30 mm coil pitch at higher Dean Number with limitation in space and more loss in pressure drop. There was good agreement between the experimental and numerically predicted data.

2.4 Experimental and numerical studies on helical coils and heat exchangers

Dravid et al. (1971) conducted a numerical and experimental study on heat transfer through coils with a curvature ratio of 0.0536 for laminar regime. Water was used as the working fluid. The numerical results were matched with experimental results. Based on the asymptotic Nusselt numbers, following correlation was developed for $50 < De < 2000$ and $5 < \Pr < 175$ with standard deviation of 6%.

$$Nu = \left[0.76 + 0.65\sqrt{De}\right]\Pr^{0.175} \tag{2.62}$$

Janssen and Hoogendoorn (1978) investigated experimentally and numerically convective heat transfer in helical coils with curvature ratio 0.01 to 0.082 for laminar flow. Prandtl no. varied from 20-450 and uniform wall heat flux was considered. Correlations of Nusselt number for different range of Dean number were proposed.

For $De < 20$ and $(De.^2 \Pr)^{1/2} < 100$

$$Nu = 1.7(De^2.\Pr)^{1/6} \tag{2.63}$$

For $20 < De < 100$

$$Nu = 0.9(De^2.\Pr)^{1/6} \tag{2.64}$$

For $100 < De < 830$

$$Nu = 0.7De^{0.43}\Pr^{1/6}\delta^{0.07} \tag{2.65}$$

Kumar et al. (2006) numerically and experimentally investigated the hydrodynamics and heat transfer characteristics of tube-in-tube helical heat exchanger at the pilot plant scale. The experiments were carried out in counter current mode operation with hot fluid in the tube side (with outer diameter 25.4 mm) and cold fluid in the annulus area. The outer tube (with 50.8 mm of outer diameter) was fitted with semicircular plates to support the inner tube and also to provide high turbulence in the annulus region. Overall heat transfer coefficients were calculated and Wilson plots were used to determine heat transfer coefficients in the inner and outer tube. A commercial Computational Fluid Dynamics package (FLUENT) was used to predict the flow and thermal development in tube-in-tube helical heat exchanger. The numerical predictions for hydrodynamics and fully developed heat transfer were in good agreement with experimental results. The overall heat transfer coefficient increases with increase in the inner coiled tube Dean number for constant flow in annulus region.

Numerical calculations was carried out to examine different geometrical parameters and the impact of flow and thermal boundary conditions for the heat transfer rate in laminar and transitional flow regimes in helical coil heat exchanger by Zachar (2010). The test section had following configurations for Re = 100-7000, tube inner diameter = 15, 20 and 25 mm, helical pitch = 40 mm, coil diameter = 370 mm, helical pitch of corrugation = 22.5, 44.5, 89 mm and corrugation depth in the range of 0.75 to 2 mm. Predicted results were compared with existing empirical correlations. In order to validate numerical results experimental test was also performed using water and water–ethylene glycol mixture as working fluid. It was concluded that the heat transfer rate was almost independent of the inlet temperature and the outer surface temperature. From computer simulation point of view it was important to consider the temperature dependency of the working fluid, in case of the water–ethylene glycol mixture because the change in the physical properties such as specific heat capacity and the dynamic viscosity. Development of the peripherally averaged Nusselt number was found to be more oscillatory than the oscillatory behaviour observed in case of smooth helical coils. When the flow rates increased the oscillation phenomenon was enhanced. An empirical correlation was proposed for the fully developed inner side heat transfer coefficient in case of helical corrugated wall configuration.

For $30 < De < 1400$ and $3 < \Pr < 30$

$$Nu = 0.585 De^{0.6688} \Pr^{0.408} \left(\frac{e}{d}\right)^{0.166} \left(\frac{p}{d}\right)^{-0.192} \tag{2.66}$$

The performance of helical cone coils and ordinary helical coils under laminar flow both investigated experimentally and numerically by Abo et al. (2011). Two coils with different heights of 40 and 50 mm and thicknesses 0.6 and 0.7 mm were used for the investigation. Numerical simulation showed better heat transfer characteristics in the helical cone coil than the ordinary helical coils. Taper angle of the helical cone coil showed a significant effect on its heat transfer characteristics.

Akbaridoust et al. (2013) studied both numerically and experimentally steady state laminar flow in helical coils at a constant wall temperature. Four helical coils with different curvature (0.089, 0.199, and 0.133) and torsion (0.010, 0.012, 0.026, and 0.024) ratios were used. Pressure drop measurement and average convective heat transfer coefficient calculations were carried out. In the numerical investigation, the three dimensional governing equations were solved by finite difference method with projection algorithm using FORTRAN programming language. Homogeneous model with constant effective properties was used. To observe difference between numerical and experimental results modified dispersion model was employed. Dispersion model reduced the difference between the numerical and the experimental results. For the greater curvature ratio there was more enhanced heat transfer. Utilization of base fluid in helical tube with greater curvature compared to the use of nanofluid in straight tubes enhanced heat transfer more effectively. The coils with equal curvature ratio and different torsion ratio predicted same results, due to the low coils pitch.

Amicis et al. (2014) studied both experimentally and numerically of the laminar flow in helical pipes of 12.53 mm inner diameter. A new experimental campaign was performed to collect pressure drop experimental data in a helical pipe of the steam generator. Pressure losses were measured in all regimes. The hydraulic problem of laminar flow in helical ducts was solved by use of commercial software. The numerical simulation was used to describe the effect of geometry on the flow through the onset of a secondary motion and the deformation of the axial velocity profile, which affects in turn the friction factor. Three numerical codes were tested, the ANSYS FLUENT and Open- FOAM FVM codes and the COMSOL Multiphysics FEM package. It was found that results were in agreement with previous analyses conducted by other authors in the past and between the different adopted tools. Maximum deviations result of the order of few percent.

2.5 Summary

Huge volume of published work on the flow and heat transfer characteristics in helical coils and heat exchangers has been reported in the last several decades. The key conclusions as discussed by various researchers are Nusselt number increases as the pitch size and tube diameter increases, where as pressure drop decreases as tube diameter increases. However pressure drop increases as helix diameter and coil to diameter ratio decreases. Increment of nanoprticle concentration in base fluid and volume flow rate of nanofluids could enhance the heat transfer characteristics. At constant velocity due to influence of secondary flow there would be higher heat transfer coefficient and lower pressure drop. Most of the developed correlations are suitable for either limited range of parameters or fitted with single value of parameters. Further investigation is required for considerable range of parameters like, curvature ratio, Reynolds number and Prandtl number etc. Summary of results reported by authors based on conventional and mini size tubes are shown in Table 2.1 and 2.2 respectively. From the literature review it has been seen that most of the published work is done on large and medium diameter tubes. Limited researches are available on mini and micro sizes helical coil. Very limited studies have been reported in the literature for helical coils of micro-diameter tubes.

Table 2.1 Summary of results reported by authors based on conventional size tubes

Authors	Parametric conditions	Analysis	Remarks
Mishra and Gupta (1978)	d=6.2-19 mm, $\delta = 0.003$ - 0.12, p/D = 0 -25.4, 60 helical coil	Experimental	Correlation developed for laminar flow, $f_c / f_s - 1 = 0.033(\log De)^4$ for turbulent flow, $f_c - f_S = 0.0075(d/D)^{1/2}$
Xin et al. (1996)	d=12.7-38.1 mm, four vertical helical coil, two phase flow	Experimental	Geometrical parameters had some effect on pressure drop.
Guo et al. (2001)	d=10 and11 mm, helix angle 0-90^0 two helical coil, two phase flow	Experimental	For lower Reynolds no. friction factor was in good agreement with previous correlations.
Wongwises	d=9.52 mm,	Experimental	Correlations were developed

and Polsongkram (2006)	D=305 mm, L=5.786 m, two phase flow		$Nu_{tp} = 68.98 De_{Eq}^{0.432} \Pr_l^{-5.055} \left(Bo \times 10^4\right)^{0.132} X^{-0.0238}$ $\phi_l = 1 + \frac{13.37}{X^{1.492}}$
Kumar et al. (2006)	Inner tube d_o=25.4 mm outer tube do=50.8 mm tube-in-tube helical heat exchanger	Experimental and Numerical	The numerical predictions for hydrodynamics and fully developed heat transfer were in good agreement with experimental results.
Cioncolini and Santini (2006)	d=4-11mm, D=28-1495 mm, 0.0027<δ<0.145 12 coils	Experimental	Coil curvature was found very effective.
Rennie and Raghavan (2007)	Outer tube d_i=100 mm inner tube d_i= 28 mm p=115 mm, double pipe heat exchanger CFD methods	Numerical	Thermally dependent viscosities had very less effect on the Nusselt number and significant effects on the pressure drop for Newtonian fluids.
Zachar (2010)	d= 15-25 mm, D=370 mm, p=22.5-88.9 mm, CFD method was applied in laminar and transitional region	Numerical	An empirical formula was proposed. $Nu = 0.585 De^{0.6688} \Pr^{0.408} \left(\frac{e}{d}\right)^{0.166} \left(\frac{p}{d}\right)^{-0.192}$ for $30 < De < 1400$ and $3 < \Pr < 30$
Chen et al. (2011)	d= 3.8-11 mm, D=135-370 mm, p=40-105 mm, L= 0.85-7.54 m horizontal	Experimental	Correlation developed At inlet conditions $Bo = 8.071 \times 10^{-8} \mathrm{Re}^{2.12} De^{-2.5} N_d^{0.18} x_i^{-0.78}$ At outlet conditions

	helical coil, flow boiling and constant heat flux		$Bo = 3.154\times10^{-7}\,\mathrm{Re}^{2.45}\,De^{-2.1} N_d^{0.46} x_o^{-0.25}$
Gupta et al. (2011)	d=4.5-12 mm, D=114-655 mm, p=40-300 mm, five helical coil with 12 different combination	Experimental	Correlation developed based on Germano number. for $Gn \le 70$ $f_c = f_s(1+0.903Gn^{0.227})$ for $Gn > 70$ $f_c = f_s(1+0.525Gn^{0.516})$
Mohammed (2011)	d_i= 6 mm, d_o=8 mm, L=3 m, four helical coils with different combinations	Experimental	A correlation was suggested for the outside average Nusselt number of coil. $Nu_{do} = 0.218(Ra)^{4.01}\left(\frac{d}{D}\right)^{2.79}\left(\frac{p}{L}\right)^{7.281}$
Suresh et al. (2012)	d=4.85 mm, L=800 mm, CuO-water nanofluid, laminar flow, constant heat flux	Experimental	Mechanism of heat transfer enhancement was due to particle migration.
Pakdaman et al. (2013)	d=15.6 mm, D= 220-320 mm, p=25-95 mm, vertical helical, constant wall temperature	Experimental	Following correlation was developed $\frac{f_{nf,helical}}{f_{bf,stright}} = \left[1+(\log De)^4\right]\times(1+10\varphi)^{4.9}$
Jamshidi et al. (2013)	d=9 mm, D=81.3-116 mm, p=13-18 mm	Experimental	Increase in overall heat transfer coefficient was a function of shell side Reynolds number.

	and N=10, shell and coiled tube heat exchangers		
Beigzadeh and Rahimi (2012)	d=5-7.5 mm, D=60-110 mm, p=15-75 mm, L=1.4-1.8 m artificial neural networks	Numerical	Superior performance of developed neural network was found.
Purandare et al. (2012)	d=8, 10 and 12 mm, for constant D=200 mm, Re =100-6000	Theoretical	For constant coil diameter as the tube diameter increased, there was increment in Nusselt number exchanger was efficient in low Reynolds number.
Kahani et al. (2013)	d=7 mm, D=70-140 mm, p=24-42 mm, N=3-6	Experimental	Correlation for Nusselt number was developed. $Nu = 0.7068\, \mathrm{He}^{0.514}\, \mathrm{Pr}^{0.563}\, \varphi^{0.112}$
Hwang et al. (2014)	d=12 mm, D=577-1290 mm, flow boiling	Experimental	Flow boiling heat transfer in the coiled tubes was significantly affected by nucleate boiling and convective boiling.
Raj et al. (2014)	d=10 mm, D=300 mm, p=30 and 60 mm, CFD methods	Numerical	Good existence between the experimental and numerically predicted data.
Amicis et al. (2014)	d=12.53 mm, three codes tested, ANSYS, FOAM	Experimental and Numerical	Results were in agreement with previous analyses conducted by other authors.

	FVM and COMSOL		

Table 2.2 Summary of results reported by authors based on mini size tubes

Authors	Parametric conditions	Analysis	Remarks
Kim et al. (2006)	d=1 mm, R- 22 working fluid	Numerical	The heat transfer rate and pressure drop in low mass velocity from simulation showed good agreement with experimental results with accuracy of ±15%.
Elsayed et al. (2012)	d=1.1-2.8 mm, D= 30-60 mm, N=3 four different helical coils, constant heat, flux flow boiling	Experimental	A new correlation for the boiling heat transfer coefficient was suggested. For $d > Co$ $F = MAX\left[1, \left(1+\left(\frac{1}{X}\right)^{0.99278}(\Pr_l)^{0.8} - 2.996\left(\frac{1}{X}\right)^{0.822} S^{-0.1755}\right)\right]$ For $d < Co$ $F = MAX\left[1, \left(1+\left(\frac{1}{X}\right)^{0.3798}(\Pr_l)^{0.8} - 2.418\left(\frac{1}{X}\right)^{0.32409} S^{-0.5046151}\right)\right]$
Pan et al. (2014)	d=3 mm, D=103 mm, p=22 mm, N=1, oscillating flow, field synergy principle, CFD methods	Numerical	The better heat transfer enhancement at smaller angle.