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Experimental Analysis of Condensation in Helical Coil Tube

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ABSTRACT

A helically coiled tube enhances heat transfer rate due to development of secondary flows. Use of helical tube as heat exchanger will enhance heat transfer coefficient. Correlations available in the literature for calculating condensation heat transfer coefficient for straight tube are used to evaluate the performance of helically coiled tube-in-shell heat exchanger. Experiments were performed on helically coiled tube of 175 mm coil diameter. Measurements were taken in 10 steps at inlet rate of mass flow of steam. Mean value of the coefficient of heat transfer at inside surface of the tube for condensation was evaluated by experimental methods and results were compared with three correlations available in literature and the deviations are reported. A new empirical correlation is proposed which is based on the experimental investigations.

Keywords: Condensation, heat transfer coefficient, helical coil

INTRODUCTION

Helical coils are coiled tubes used in many industries for enhancing the heat transfer. It provides many advantages over the straight tube heat exchanger (Prabhajan et al., 2004). Helical coils are also used for condensation and boiling. Condensation phenomenon inside tubes is essentially needed for condensers (Colorado et al., 2011). Condensers are employed in most of the chemical, petroleum, processing and power industries, for distillation, refrigeration & air-conditioning industries, most importantly for power generation. Generally, in chemical process industries, water-cooled shell and tube heat exchangers or condensers are employed. Condensation may occur drop-wise or film wise. While drop-wise condensation is most desirable, it is difficult to maintain. On the other hand, film-wise condensation offers resistance to heat transfer (Kern, 1965). In case of single phase fluid flow when fluid flows through helically coiled tube, the flow

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pattern is different in comparison to flow pattern through a straight tube (Bae et al., 1969). In helical tubes, fluid is under influence of centrifugal mass forces producing secondary flow of fluid which is responsible for the enhancement of heat transfer coefficient inside helical tubes (Vashisth et al., 2008). The same phenomenon was reported by Owhadi et al. (1968) when two-phase flow occured in helical tube. The only difference lies in the fact that in case of condensation heat transfer, secondary flow causes increased contact surface area inside the tube between vapour and tube wall which ultimately leads to significant increase in heat transfer coefficient of condensation. Therefore, the purpose of this investigation was to experimentally evaluate heat transfer coefficient in condensation inside vertical helical coil tube by condensing water steam. Experimentally determined values of heat transfer coefficients were compared with predicted values using equations reported in the literature which were experimentally tested and were based on conduction resistance method.

LITERATURE REVIEW

Nusselt theory of film-wise condensation heat transfer for plane surface and horizontal cylindrical surfaces was published in 1916. In the today's world where revolutionary developments are happening in the field of engineering, his theory is still relevant, even after a century. Nusselt's theory explains elementary physics of film condensation (Tanasawa, 1990). He analysed laminar film condensation on vertical flat plate and then extended his work to laminar film condensation inside vertical tube. He assumed the thickness of film was small and it had no effect on condensing process and shear stress on edge of condensate film was proportional to pressure drop. He successfully obtained heat transfer correlation for laminar flow condensate.

Early Research on Condensation in Tubes

Chato (1926) had theoretically and experimentally studied condensation in inclined and horizontal tubes and Nitheanandan et al. (1993) carried out an experimental study for an inclined tube for the study of flow regime transitions for steam condensation. They have concluded that transition between wavy and slug flow regimes of condensate is because of inclination of the tube. It was shown the wavy flow was more dominant on downward inclinations whereas slug flow of condensate was prominent on upward inclinations. Tandon et al. (1995) carried out experiments for forced convection condensation inside the horizontal tube. They had observed that, the effect of various parameters on condensing heat transfer coefficient was the same as reported earlier by other investigators. They found vapour Reynolds number of 3×10^4 at which change over from annular flow/semi-annular flow to wavy flow occurred. Berenson et al. (1968) investigated the condensation of pure R-134a vapour inside a single micro-fin tube subjected to different inclinations. They had used inclination angle from –90 to +90 under refrigerant mass velocity 54 to 107 kg/m^{2}s for each inclination. They had concluded that value of heat transfer coefficient was dependent on the inclination of tube. It decreased as the vapour quality and mass velocity decreased. It was also concluded that clockwise inclination of 3° gave good rise in value of heat transfer coefficient in comparison with 0° inclination.

They also proposed correlation for evaluating heat transfer coefficient. Wang and Du (2000) conducted condensation heat transfer study for laminar film on tube-in-tube condensers having counter flow arrangement on four small diameter (less than 5 mm) tube with water steam as the working medium for low range of mass flux that is in the range of 10 to 100 kg/s/m^2. It was tested for various inclination angles for assessing the performance of the condenser under the effect of gravity. They had developed an analytical model for predicting the condensation heat transfer characteristics. They had concluded that the effect of gravity in case of small diameter tube decreased. They also found that proposed analytical model gave the good predictions. Akhavan-Behabadi et al. (2007) had conducted an experimental study on R134a for observing condensation inside a micro finned, 8.92 mm in inner diameter tube. They had observed the high value of heat transfer coefficient at 30° inclination. Wang et al. (1991) had proposed semi-empirical correlation for the purpose of designing heat pipe heat exchangers. Further, they observed that inclination of thermosyphon had a strong effect on the value of heat transfer coefficient due to condensation. Saffari et al (2010) theoretically and numerically studied stratified condensation heat transfer mechanism in an inclined tube and reported high value heat transfer coefficient for 30° incline in comparison to 60° and 90° incline tube.

Recent Literature on Condensation in Helical Coil

Han et al. (2005) investigated the condensation heat transfer coefficient of R-134a at various vapor saturation temperatures. He had used annular helical pipe tube-in-shell heat exchanger. He observed that condensation heat transfer coefficient increased with the mass flux in the annular helical pipe. Wongwises et al. (2006) experimentally investigated two-phase pressure drop and condensation of HFC 134a inside tube-in-tube helical coil heat exchanger. They had reported 33-53% increase in the value of heat transfer coefficient in helical coil condenser as compared to straight tube condenser. Shao et al. (2007) examined condensation of R-134a in helical tube-in-tube and horizontal straight tube condenser. Refrigerant R-134a at various saturation temperature and vapor quality were used in experimentation. They reported 4-13.8% higher heat transfer coefficients in helical coil compared with straight tube condenser. Mosaad et al. (2009) reported condensation and pressure drop at 815 kPa pressure in coiled double tube heat exchanger. They concluded that heat transfer coefficient in condensation increased with mass flux and decreases with rising saturation temperature difference. Gupta et al. (2014) investigated condensation and pressure drop characteristics of R-134a helical tube in shell heat exchanger in a horizontal orientation. They studied the flow regimes during condensation on Taitel and Dukler flow maps, and proposed new correlation and enhancement factor for helical coil condenser.

Mozafari et al (2015) studied condensation and pressure drop behaviour of R600a in the helical tube in tube exchanger at different inclination angles. They had reported the highest value of heat transfer coefficient at 30ºC inclination compared with horizontal and vertical position. Salimpour et al (2017) studied heat transfer coefficient for condensation of R-404A vapor. They reported high heat transfer coefficient for small curvature coils compared to large coils. They had proposed new correlation for calculating heat transfer coefficient in condensation for the helical coil.

Yu et al. (2018) studied condensation of hydrocarbon refrigerant propane in a helical tube. Experiments were conducted for mass flux from 200 to 400 kg/m^2s and saturated temperature from 40 to 27°C. The effects of flow parameters were analysed. They concluded heat transfer coefficients increased with the increase in vapour quality and mass flux, while the influence of heat flux on heat transfer at the same quality was observed as insignificant.

Gap in Literature and Novelty of Work

- It is evident from literature review that there is no study on condensation of steam in the vertical helical tube-in-shell heat exchanger. Majority of the studies were oriented towards the condensation of refrigerants, particularly for tube-in-tube helical type heat exchangers.
- There is much application in industries where the tube-in-shell type of heat exchangers are used, for example in chemical reactors, steam generators etc.
- In this context, there is no study for condensation of steam considering the effect of gravity on condensation in the vertical helical tube-in-shell heat exchanger.

In the present work, condensation of steam is carried out in the helically coiled tube. Steam flows inside a helically coiled tube and the helical coil is placed in the center of the shell surrounded by cool water. Experimental analysis is carried out and development of the dimensionless equation similar in kind to that of Nusselt's equation is presented. The experimentally obtained results are compared with three chosen equations which predict coefficient of heat transfer in condensation.

EXPERIMENTATION

Analysis on the experimental setup by conducting experiments in 10 steps on vertically mounted single helical coil was done. The helical coil was mounted in the shell. The coil dimensions are given in Table 1. The coil was made using the SS304 material on bending machine. The thickness of the tube of the coil was selected keeping in mind that there should not be a change in tube cross-section which was circular here. The vertical helical coil was surrounded by the continuous flow of cold water. Sufficient amount of insulation was provided everywhere to avoid the heat losses. The experimental setup was divided into two loops, one was water steam loop and other was cooling water loop.

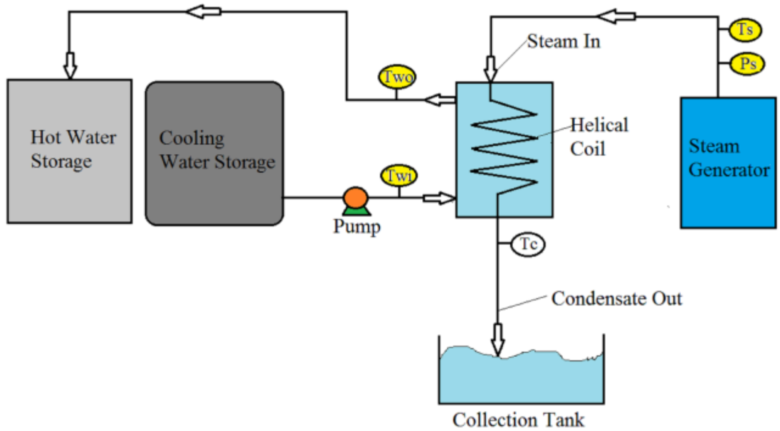

Figure 1. Schematic representation of experimental setup

Figure 2. Actual view of the experimental setup

In the water-steam loop, a steam generator (mini-boiler, Non-IBR, capacity: 27 kW) produced the steam continuously at known temperature T_s (°C) and pressure P_s (bar). The steam entered in the helical coil and condensation took place. Condensate volume flow rate and its temperature were measured at the outlet of the helical coil before the storage or collection tank. Cold water was circulated through shell where the coil is mounted. Volume flow rate and temperature of cold water circulated was monitored at the entrance of shell. The temperature of cold water at the outlet of the shell was measured. The condensate forming in the coil was directly measured by using calibrated measuring flask. The water steam inlet temperature was measured in 10 steps during experimental exercise in the range from T_s = 101.1°C to 109.9°C. Concurrently steam mass flow rate was also changed from $(\dot{m}_s m)$ = 0.00348 kg/s to $(\dot{m}_s)$ = 0.00528 kg/s. The selection of this range was restricted by the availability of the small size mini steam generator. Inlet parameters of steam are maintained constant for a sufficient long span of time in order to ensure thermal steady state as per the monitored parameters. The mass flow rate of cold water which was at 0.0834 ± 0.001 kg/s and inlet temperature 30±1°C was kept constant during experimentation.

Table 1
Physical dimension of the coil under investigation

Do	do	di	p	n	β
mm	mm	mm	mm		Deg
175	13.7	9.22	20	5.5	3

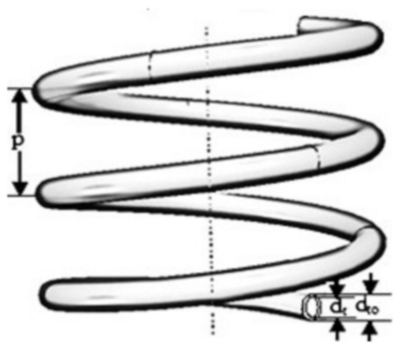

Figure 3. Schematic of helical coil

Uncertainty Analysis

Experimental uncertainty was estimated as described in Holman (2012) using Equation (3.2). In addition to this method, Salimpour (2017) was also referred. All uncertainties are tabulated in Table 2.

Table 2
Uncertainty in measurements

Measurements	Uncertainty
Heat Transfer rate	4%
Heat transfer coefficient	10%
Temperature sensor	±0.1

METHODS

Experimental heat transfer coefficient

Average inside coefficient of heat transfer is defined as:

$$h_i = \frac{Q_1}{A_i(T_s - T_{wi})} \quad [1]$$

Where h_i is the average inside coefficient of heat transfer, A_i is inside tube surface area, T_s is saturation temperature of the steam and T_{wi} is temperature at inner side of wall of tube which given by

$$T_{wi}=T_{wo}+\frac{Qdi\ln\left[\frac{d_o}{d_i}\right]}{2A_ik} \quad [2]$$

Where T_{wo} is outside wall temperature which is measured directly using thermocouples.

The heat transfer rate, Q_1 released by the water steam inside the experimental test section (helical coil) can be obtained as per the following relation:

$$Q_1 = \dot{m}_{si}h_{si} - \dot{m}_{co}h_{co} \quad [3]$$

Where $(\dot{m}_{si})$ is rate of flow of steam at inlet, h_{si} is enthalpy of the dry saturated steam at the inlet, $(\dot{m}_{co})$ is mass rate of condensate and hc_o is enthalpy of condensate. The amount of heat transfer rate absorbed by the cold water in the annular drum can be obtained as given below:

$$Q_2=\dot{m}_{cw}C_{pw}\left(T_{cwi}-T_{cwo}\right) \quad [4]$$

Where T_{cwi} and T_{cwo} are temperatures of cold water at entry and exit from shell respectively, $(\dot{m}_{cw})$ is flow rate of water mass through the annular space in the drum and C_{pw} is specific heat of water at prevailing temperature of hot water.

Prediction of the coefficient of condensation heat transfer

It is predicted using various equations available in the literature. The first equation used for comparison is given by Nusselt (1916). His equation is based on the basic approach for finding mean heat transfer coefficient using condensate film thermal resistance.

$$h = 0.943\left(\frac{k_f^3\rho_f^2 g\lambda}{\left(T_s-T_{wi}\right)L\mu_f}\right)^{0.25} \quad [5]$$

Next, chosen equation is proposed by Wang et al (1991) for mean heat transfer coefficient

$$\frac{h}{h_{Nu}}=\left[\frac{2L}{D}\right]^{\frac{\cos\beta}{4}}\left(0.54+5.86\times10^{3}\beta\right) \quad [6]$$

Where h_{Nu} is Nusselt heat transfer coefficient given by the following equation.

$$h_{Nu}=0.943\left[\frac{\rho_f^2\, g\, h_{fg}\, k_f^3 \sin\beta}{L\ \mu_f\ \Delta T}\right]^{0.25} \quad [6a]$$

Next correlation (equation 7) is reported by Tandon et al. (1995) which take into consideration the change in the value of heat transfer coefficient for the change of annular flow or semi-annular flow to wavy flow. Tandon's equation is used here as it satisfies the applicability limits of Reynolds number. In the present work, Reynolds number is greater than 30000, hence, this equation may be used for comparison.

$$Nu = \frac{hd_i}{k_f} = 0.084 Pr_l^{1/3} \left(\frac{\lambda}{Cp_l \Delta T}\right)^{1/6} Re_v^{0.67} \quad [7]$$

For $Re_v > 3\times 10^4$

Tandon's equation is based on liquid Prandtl Number, Reynolds number and Jacob number. Jacob Number is a dimensionless number which is used in phase change heat transfer calculations. Second, this equation is simple to analyse and compare.

RESULTS

The experimentation is performed on the single helical coil (physical dimensions are given in Table 1). The inlet mass flow rate and temperature of the steam is changed in 10 steps. The inside heat transfer coefficient is determined from the experimental observations and compared with three equations which are described above.

Energy Balance

Energy balance study was carried out to ascertain the reliability of experimental observations. It was done on the quantity of condensate collected and rate of flow of cooling water. Cold water heat gain was calculated using equation 4. The heat energy released by water steam was calculated using equation 3. It can be seen from Figure 4 that error of heat balance between cold water sensible heat and latent heat is less than 10%.

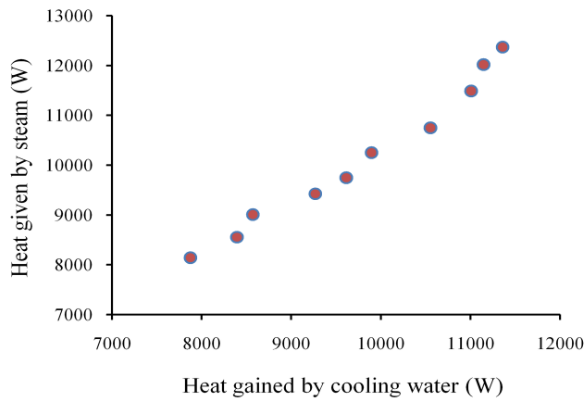

Figure 4. Results of energy balance for experimental observations

Comparison of experimental results with predicted values

The experimentally determined heat transfer coefficient was compared with predicted value using equations 5, 6 and 7. For the purpose of comparing the results, experimental heat transfer coefficient was calculated using equation 1 and it was found to be h_{exp} = 19599±8460 W/m^{2}K with a variation of 43% among the observations for mass flow rate ranging from 0.00348 kg/s to 0.00528 kg/s.

Comparison with Nusselt's Equation. The first equation selected for comparison was one which was theoretically determined by Nusselt (1916). By calculation, it is h = 5377±411 W/m^{2}K with fluctuations of 7.65%. Low value of heat transfer coefficient is inherent as the Nusselt equation is based on the assumption of stationary steam which does not take into consideration the effect of waviness in the condensate liquid film.

Comparison with Wang's Equation. Second equation chosen is equation 6 proposed by Wang et al (1991) which takes care for the inclination of the tube by incorporating angle of inclination 'β'. By calculating, the value of heat transfer coefficient is h = 7087±542 W/m^{2}K with fluctuations of 7.65%. Low value of heat transfer coefficient may be attributed to low inclination angle of helical tube in present case. Wang et al. had reported marginal effect on heat transfer coefficient in condensation at optimum angle of inclination which was 20 to 50 degrees.

Comparison with Tandon's Equation. The third and most important equation considered was proposed by Tandon et al (1995) and it predicted the value of h = 22267±3871 W/m^{2}K with fluctuations of 17.39%.

Influence of mass flow rate

The steam mass flow rate was changed during the experimentation in the range from 0.00348 kg/s to 0.00528 kg/s with an average increase of 5%. The influence of mass flow rate of steam ($\dot{m}_s$) on the heat transfer coefficient calculated using all three equations (Equation 5, 6 and 7) is illustrated in Figure 5. This graph shows that there is significant increase in the heat transfer coefficient with the rise in flow rate. This is observed in case of heat transfer coefficient determined experimentally and predicted by using Tandon's equation 7. On the other hand, equations 5 and 6, under-predicts the values of heat transfer coefficient in case of helical coil whereas the equation proposed by the Tandon et al (1995) predicts the values on average 18% deviations. The large deviation in the predicted values from the experimental heat transfer coefficient is justified by the presence of secondary flow in the coiled tube. In helically coiled tubes, secondary flow is due to curvature of the tube. During condensation of vapour, condensed liquid is pushed to wall of the tube and this increases interfacial shear area between vapour and liquid. This shear causes the waviness on the liquid surface and increases the heat transfer rate. The same phenomenon was reported by Mosaad et al. (2009) and Salimpour et al. (2017).

There is significant improvement in the heat transfer coefficient in helical coiled tube which is one of the biggest advantages of using helical coiled tube as heat exchangers. Here, authors have attempted to correlate the experimental data of the helical coil with the equations available in literature for straight tube.

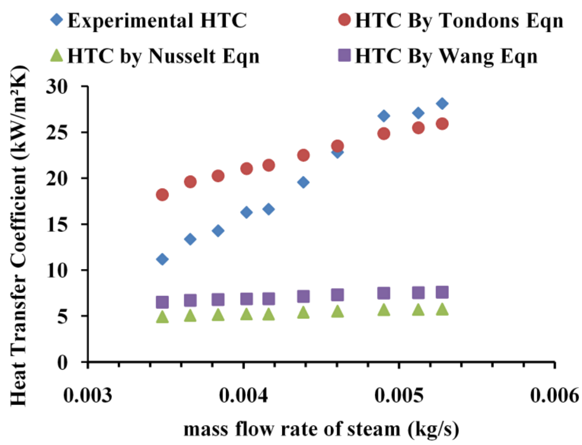

Figure 5. Influence of vapor mass flow rate on heat transfer coefficient

Correlation of the experimental data

The experimental data is correlated as per the coordinates suggested by the Equation 8 and are used to correlate the data obtained experimentally as reported in the McAdams (1958).

$$\mathrm{h}\left(\frac{\mu_f^2}{k_f^3\rho_f^2 g}\right)^{1/3} = a\left(\frac{4\tau}{\mu_f}\right)^b \quad [8]$$

The constants 'a' and 'b' in the above equation are determined by using the least square power-law fitting technique, based on the experimental data collected. A log-log plot of $\left(\frac{4\tau}{\mu_f}\right)$ against $\mathrm{h}\times\left(\frac{\mu_f^2}{k_f^3\rho_f^2 g}\right)^{1/3}$ is illustrated in Figure 6. The trend line on the plot is the curve fitting line through the experimental readings, using the least square power law fitting technique. The Pearson's correlation coefficient is 0.981.

Following correlation is obtained from the graph.

$$\mathrm{h}\left(\frac{\mu_f^2}{k_f^3\rho_f^2 g}\right)^{1/3} = 3\times10^{-7}\left(\frac{4\tau}{\mu_f}\right)^{1.967} \quad [9]$$

the values of constants 'a' and 'b' are 3×10^{-7} and 1.967 respectively.

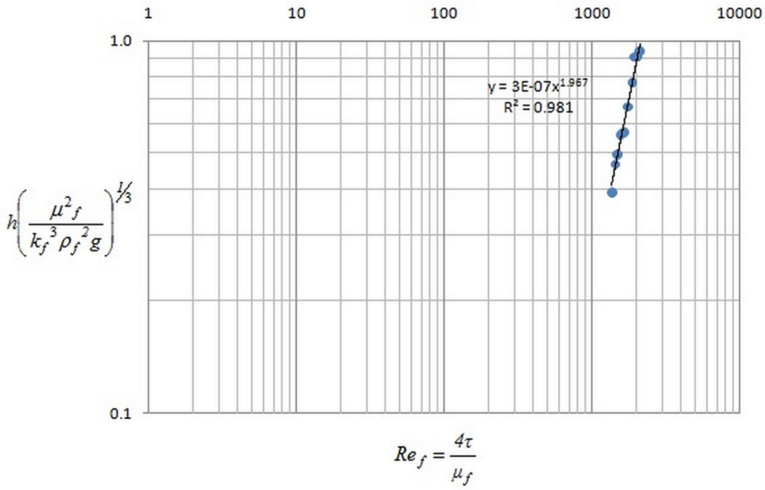

Figure 6. Representation of variation in magnitude of heat transfer coefficient as a function of Reynolds Number

CONCLUSION

An experimental investigation was carried out on the 175 mm coil diameter vertical helical coiled tube under variable mass flux conditions. Mass flux was varied in 10 steps. Experimental heat transfer coefficient was evaluated from observations recorded. The experimental heat transfer coefficient was compared with three equations reported in the literature for prediction of heat transfer coefficient. An attempt had been made to calculate the heat transfer coefficient using Jacob number in the equation of heat transfer coefficient for in-tube condensation in the vertical tube-in-shell heat exchanger. It was observed that basic Nusselt equation under-predicts the condensation heat transfer coefficient. This is quite obvious as the Nusselt equation is based on simplified assumptions of stationary vapour and laminar flow and neglects the shear stress. A similar trend is observed for the Wang equation. Tandon’s equation has less deviation compared with the other two equations. Experimentally determined value of heat transfer coefficient is more on account of the secondary flow pattern in the the helical coil which enhances the condensation heat transfer coefficient significantly. Based on the experimental data new correlation is developed.

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