Experimental analysis of small scale water cooler equipped with TTHC heat exchanger

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Abstract. In the present work, experiments were conducted to recover waste heat from water cooler condenser. A Tube in Tube Helical Coil (TTHC) heat exchanger was made from cu pipe of 4.47 mm outer diameter of inner tube and 8.30 mm inner diameter of outer tube replaced the water cooler condenser to recover the waste heat. A new empirical correlation was suggested to predict the annulus Nusselt number for laminar flow of water with Reynolds number ranging from 1500 to 3900 and Prandtl number approx 1.6. The results reveal that the annulus Nusselt number varies with volume flow rate through annulus of helical tube significantly in laminar flow region. The small scale water cooler equipped with TTHC heat exchanger recovered maximum 371.5 W heat by cooling water.

Key Words: Equivalent diameter, Reynolds number, TTHC heat exchanger, Water cooler,

1. Introduction

Helical coiled tube heat exchanger is one of the passive methods to enhance the heat transfer which do not require external power for enhancement of heat transfer. A passive method commonly uses geometrical modification to the flow channel for enhancement and compact in size [1-4]. Helical coiled heat exchanger is used to transfer heat between two or more fluid for numerous heating and cooling in industrial and engineering applications, such as cooling in electronic industries, refrigerator & air-conditioning units, thermal power plant, heat recovery system, domestic water heater, space vehicles, automobiles, etc. The current work mainly focus on heat recovery by cooling water from small scale water cooler equipped with TTHC heat exchanger.

Many researchers Prabhanjan et al. [5], Mao et al. [6], Dravid et al. [7] have reported that the secondary flow occurs in helical tube due to centrifugal force which enhances the heat transfer.

Elsayed et al. [8] studied small scale cooling system with helical coil condenser and evaporator. A mathematical model was developed for this system and result found that the COP increases as the coil diameter decreases. Seban and Mclaughlin [9] Studied on heat transfer in helical coiled tube with laminar flow of medium heavy freeze oil and turbulent flow of water experimentally and developed a correlation for two coil diameter to tube diameter ratios are 17 and 104. Similar work was done by Rogers and Mayhew 1964 for three different coil diameters to tube diameter ratio such as 10.8, 13.3 and 20.12 and compared with the result of Kalb and Seader [10]. Xin and Ebadian [11] discussed the effect of Prandtl numbers on convective heat transfer coefficients in helical tubes, for three different fluids air, water and ethylene glycol and developed a empirical expression from experimental data and some data from previous work.
The above literature shows that numerous studies carried out on helical coil coiled tube as well as tube-in-tube helical coil heat exchanger. Although there are number of correlations were developed for inner tube side helical coil tube but very few correlations are available on annulus region of tube-in-tube helical coil heat exchanger. In the present work, Nusselt number was analyzed through annulus of Tube-in-Tube Helical Coil (TTHC) heat exchanger by using experimental data from suggested correlation.

2. Material and methods
The test section used in the present work consists of soft copper tubing as shown in figure 1. Initially the equal lengths (L) of both inner as well as outer straight tube of 9 m were taken. The geometrical parameters of TTHC heat exchanger is given in table 1.

![Figure 1. TTHC heat exchanger](image)

The inner tube of outer diameter 4.47 mm is inserted into outer tube of inner diameter 8.3 mm and fine sand particles filled in inner tube as well as annulus space in order to maintain the smoothness of the inner surface. The TTHC heat exchanger of 282 mm coil diameter is formed with the help of wooden pattern and flushes the sand particles after coiling.

| Dimensions | L (m) | d₁₁ (m) | d₁₀ (m) | d₂₁ (m) | d₂₀ (m) | D (m) | p (m) |
|------------|-------|---------|---------|---------|---------|-------|-------|
| TTHC heat exchanger | 9 | 0.00442 | 0.00447 | 0.0083 | 0.00952 | 0.282 | 0.034 |

3. Experimental setup and test section
The flow diagram of the experimental setup is shown in figure 2. The test facility was made-up of a primary open loop and a secondary closed loop. The primary open loop consists of cooling water tank, pipe fittings, measuring instruments, 12 volt DC brushless water pump, flow control valve, rotameter.
with accuracy within 1.5% of full scale and an outer helical tube. The secondary closed loop consists of a complete set of water cooler but the present work considering only condenser part that is TTHC heat exchanger. The test section is a TTHC heat exchanger consisting of an inner helical tube in which refrigerant flow at a constant rate for maintaining its outer surface at 42±0.2°C and an outer helical tube (annulus passage) through cooling water as working fluid flow at different rate. The outer surface of TTHC heat exchanger is insulated to minimize the heat loss to the surrounding. In this experiment, there is five k type thermocouples were used out of these; one is fixed in cooling water tank and remaining four were inserted into drilled hole at each inlet and outlet of inner and outer helical test section. The epoxy is used at the drilled hole to prevent the leakage of fluid. Two four channel temperature indicator were used to measure the temperature at each point.

![Flow diagram of experimental set-up](image)

The experiments were performed under steady state condition. Switch on the compressor of water cooler, refrigerant flow through inner tube of TTHC heat exchanger. Tap water is pumped from water bucket at 26±1°C to the annulus passage of helical tube in counter clockwise direction of refrigerant at six different flow rates 15 l/h, 20 l/h, 25 l/h, 30 l/h, 35 l/h and 40 l/h by flow regulating valve. The temperatures are recorded after steady state achieved by 4 channel temperature indicator with 0.1°C precision.

4. Analysis of experiment

In the present work, thermo-physical properties of water are obtained as a function of mean film temperature Kays et al. [12].

Heat recovered by cooling water from refrigerant R-134a

\[
Q_c = \rho_w V c_p (T_{w,i} - T_{w,o})
\]  

(1)

Reynolds number of water flow in annulus of helical tube based on equivalent diameter is calculated from Eq. (2)

\[
Re = \frac{\rho w V D_{eq}}{\mu_w A}
\]

(2)
Cross sectional area of annulus helical tube and annulus equivalent diameter as given by Kumar et al. [13].

\[
A = \frac{\pi}{4}(d_{2,i}^2 - d_{1,o}^2)
\]  

(3)

\[
D_{eq} = \frac{4 \times A}{wetted\ perimeter} = \frac{4\pi(d_{2,i}^2 - d_{1,o}^2)}{4\pi d_{1,o}} = \left(\frac{d_{2,i}^2 - d_{1,o}^2}{d_{1,o}}\right)
\]  

(4)

where \(d_{1,i}, d_{1,o}, d_{2,i}, d_{2,o}\) are the inner diameter of inner tube, outer diameter of inner tube, inner diameter of outer tube, outer diameter of outer tube of TTHC heat exchanger respectively.

Dean number of water flow in annulus of helical tube based on equivalent diameter is defined by Eq. (5)

\[
De = Re\left(\frac{D_{eq}}{D}\right)^{1/2}
\]  

(5)

5. Results and discussion

Figure 3. illustrates the variation of Nusselt number with Reynold number in annulus of TTHC heat exchanger. It can be clear that annulus Nusselt number increases with an increase in Reynold number. Figure 4 also shows the comparison of present calculated annulus Nusselt number with the data of Seban & McLaughlin, Xin & Ebadian and Garimella et al. The calculated Nusselt number in the present work is higher as compared to Seban & McLaughlin and Garimella et al. but lower than that of Xin & Ebadian. This may be due to curvature ratio of the helical tube.
Figure 4: Variation of annulus Nusselt number versus volume flow rate of cooling water

Figure 4 shows the variation of annulus Nusselt number at different volume flow rate of cooling water. It can be seen that annulus Nusselt number increased with the volume flow rate of cooling water. The present results compared with the previous works and found appropriate results.

A new correlation Eq. (7) was recommended for annulus Nusselt number of TTHC heat exchanger by modifying the existing correlation Eq. (6) developed by Kalb and Seader [10].

$$\text{Nu} = 0.913 \text{Re}^{0.476} \text{Pr}^{0.2} \left( \frac{d_i}{D} \right)^{0.238}$$  \hspace{1cm} (6)

Most of the previous works used hydraulic diameter in place of inner tube diameter for annulus Nusselt number; however in the present suggested correlation $d_i$ should be replaced by $D_{eq}$ and Eq. (7) becomes a new set of correlation for annulus Nusselt number calculation.

$$\text{Nu} = 0.913 \text{Re}^{0.476} \text{Pr}^{0.2} \left( \frac{D_{eq}}{D} \right)^{0.238}$$  \hspace{1cm} (7)

for $1500 < \text{Re} < 3900$ and $\text{Pr} = 1.6$

The experiments were carried out to obtain annulus Nusselt number from Eq. (7) using experimental data. The annulus Nusselt number of TTHC heat exchanger were compared with the previous developed correlations by Seban & McLaughlin [9], Xin & Ebadian [11] and Garimella et al. [14] correspondingly.

$$\text{Nu} = 0.023 \text{Re}^{0.35} \text{Pr}^{0.4} \left( \frac{d_i}{D} \right)^{0.1}$$  \hspace{1cm} (8)

for $12 \leq \text{Re} \leq 5600$ laminar flow, $6000 \leq \text{Re} \leq 65000$ turbulent flow and $D/d = 17$ and 104

$$\text{Nu} = (2.153 + 0.318D_{eq}^{0.643})\text{Pr}^{0.177}$$  \hspace{1cm} (9)

for $20 \leq D_{eq} \leq 2000$, $0.7 \leq \text{Pr} \leq 175$ and $0.0267 \leq \delta \leq 0.0884$

$$\text{Nu} = 0.027D_{eq}^{0.94} \text{Pr}^{0.69} \left( \frac{d_{2j} - d_{eq}}{D} \right)^{0.01}$$  \hspace{1cm} (10)

for $300 \leq D_{eq} \leq 4002$
Figure 5. Variation of heat recovery by cooling water from R-134a versus volume flow rate of cooling water

Figure 5 shows the effect volume flow rate in annulus of helical tube on heat recovery from R-134a. Heat recovery from refrigerant increased as the water flow through annulus of helical tube increases.

6. Conclusion
In this study, experiments were conducted on TTHC heat exchanger. The maximum 371.5 W heat recovered by cooling water at 40 l/h from small scale water cooler equipped with TTHC heat exchanger. Based on equivalent diameter, a new set of correlation was suggested for calculating the annulus Nusselt number for laminar flow of cooling water. The present suggested correlation results were found to be better agreement with the previous suggested correlations within $1500 < \text{Re} < 3900$, $\text{Pr} = 1.6$ and $\frac{D_o}{d} = 25.77$.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | Cross sectional area of annulus helical tube, m² |
| D      | Helical coil diameter, m |
| d      | Tube diameter, m |
| De     | Dean number |
| D_eq.  | Annulus equivalent diameter, m |
| k      | Thermal conductivity, W/mK |
| L      | Length of tube, m |
| Nu     | Nusselt number |
| p      | Pitch of helical coil, m |
| Pr     | Prandtl number |
| Q      | Heat transfer rate, W |
| Re     | Reynold number |
| T      | Temperature, °C |
| V      | Volume flow rate of water, m³/sec |

Greek Symbols

| Symbol | Description |
|--------|-------------|
| ρ      | Density, kg/m³ |
| C_p    | Specific heat, J/kgK |
| θ      | Bulk mean temperature, °C |
| µ      | Viscosity, Ns/m² |

Subscripts

| Symbol | Description |
|--------|-------------|
| c      | Cooling |
| i      | Inlet/Inner |
| o      | Outlet/Outside |
| w      | Water |