International Journal of Technology and Emerging Sciences (IJTES)

www.mapscipub.com

Volume 01|| Issue 01|| April 2021 || pp. 29-34 E-ISSN: 2583-1925

Thermal performance of concentric tube heat exchanger with modified wire coil inserts

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Abstract - *In this paper, the effect of modified wire coil inserts on heat transfer and friction factor characteristics in a concentric tube heat exchanger have been experimentally investigated for three different configuration of tapered wire coil; Converging, Diverging and Converging-Diverging wire coil. Water has been used as cold fluid (flowing through in-tube side, where wire coil inserts is used) as well as hot fluid (flowing through annulus side). The obtained results show that the Nusselt number increases and the friction factor decreases with increasing Reynolds number for all configurations of tapered wire coil inserts. Diverging wire coil inserts exhibits higher heat transfer performance than others arrangements. The average Nusselt number and friction factor of water flowing in the inner tube with different configurations of tapered wire coils (Diverging, Converging-Diverging and Converging wire coil) respectively, enhances 1.91, 1.73, 1.58 times and 8.60, 7.98 and 7.39 times respectively, that for the plain tube. The value of the ratio h/Δp is greater than unity, it can be concluded that using tapered wire coil in concentric tube heat exchanger is beneficial for practical heat applications. Diverging wire coil inserts shows minimum value of entropy generation among all other arrangements.*

***Key Words*: Concentric tube heat exchanger, Tapered wire coil, Nusselt number, Friction factor, Entropy generation**

1. INTRODUCTION

There are some passive techniques which have been implied and integrated in the heat exchanger including wire coil inserts [1-2] louvered strip inserts [3], conical ring inserts [4-5], delta wing vortex generators [6] and twisted tape inserts with different modification [7-8]. Nowadays, wire coil inserts are one of the significant passive methods that is used for heat transfer augmentation leading to reduce the cost and size of heat transport device. Also, this is one of the best passive technique methods that form a swirl flow inside the pipe and create turbulent near to the wall. Goudarzi and Jamali [9] carried out an experiment to study the hydrothermal performance of a car radiator mounted with helical coil inserts using nanofluid. They reported that the helical coil provides higher heat transfer rate as well as friction factor. Mirzaei and Azimi [10] used helical coil inserts to investigate the thermal-hydraulics characteristics and found 77% enhancement in heat transfer coefficient. Akyurek et al. [2] investigated the heat transfer of nanofluid in a tube with wire coil inserts. They found that heat transfer performance increases with decrease in wire coil pitch. Singh and Sarkar [11] used a novel tapered wire coil inserts in double tube heat exchanger and observed that diverging type tapered coil promotes better heat transfer characteristics.

Many authors have performed experiments on different configurations and geometric parameters of insert to improve the heat transfer characteristics. However, no one have performed the experiments on concentric tube heat exchanger with wire coil inserts by varying both geometric as well as operating parameters. In this paper, an experimental study of water flowing in concentric tube heat exchanger with tapered wire coil inserts has been performed for Reynolds number range of 9000-40000. Also, the impact on the entropy generation are also considered.

Nomenclature

c_p	Specific heat capacity (J/kgK)
d	Small end diameter of wire coil
D	Big end diameter of wire coil
f	Friction factor
G.I	Galvanized iron
k	Thermal conductivity (W/mK)
Nu	Nusselt number
m	Mass flow rate (kg/s)
P	Pitch of the wire coil
Pr	Prandtl number
Q	Heat transfer rate (W)

Re	Reynolds number
S	Entropy (W/k)
T	Temperature (K)
μ	Dynamic viscosity (Pa.s)

2. EXPERIMENTAL SET UP AND PROCEDURE

Figure 1 and 2 shows the schematic diagram of experimental set up. It mainly consisted of concentric tube heat exchanger of length 570 mm, heating tank with temperature controller and cooling tank attached with chiller, two flowmeter, two circulating pump and U-tube manometer. The concentric tube heat exchanger is a double circular G.I. tube (inner and outer tube). The cold fluids (water) flows through the inner tube (where tapered wire coil insert is used) and hot fluid (water) flows through annulus in opposite direction. In this experiment, the hot fluid inlet temperature and mass flow rate are kept constant as 60°C and 15 lpm, respectively; while the mass flow rates of cold fluid are varied from 5-25 lpm at temperature of 30°C respectively. The inner tube has internal and external diameter of 18 and 26 mm while annulus have internal diameter of 42 mm. Four PT-100 thermocouples are provided to measure the temperatures of both fluids. Pressure drop through inner tube and outer tube are measured by U-tube manometer.

Table -1: Details of tapered wire coil and operating conditions

Parameter	Value
Wire thickness	2 mm
Pitch of the tapered wire coil, P	10mm
Larger end diameter of tapered wire coil, D	13 mm
Smaller end diameter of tapered wire coil, d	6.5 mm
Cold fluid flow rate	5-25 lpm
Reynolds number	9000-40000
Cold fluid inlet temperature	30°C
Hot fluid inlet temperature	60°C

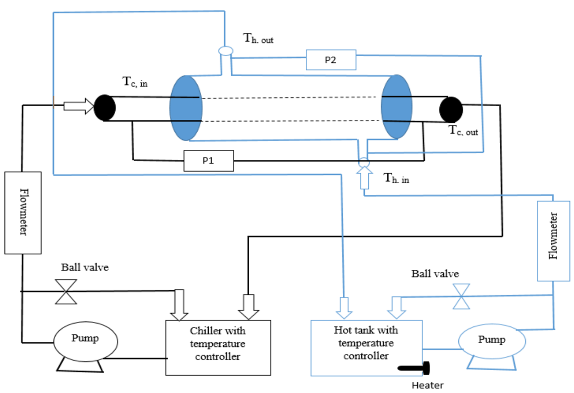

Figure-1: Schematic diagram experimental setup

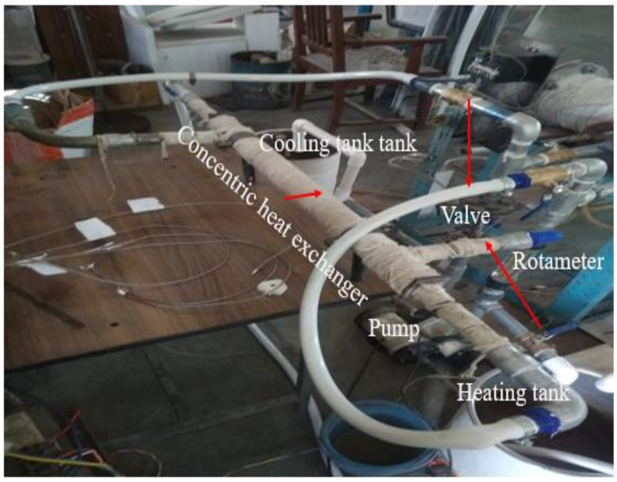

Figure-2: Photograph of the experimental setup

The image of tapered wire coil with different configurations are shown in Figure 3. Tapered wire coil is fabricated from aluminium wire with 13 mm diameter (D) from one side and 6.5 mm diameter (D/2) from other side with a uniform pitch of 10 mm. Three new tapered wire coil inserts, i.e., converging wire coil, diverging wire coil and converging-diverging wire coil are used as an enhancer in this study. Details of tapered wire coil and operating conditions are summarized in **Table 1**.

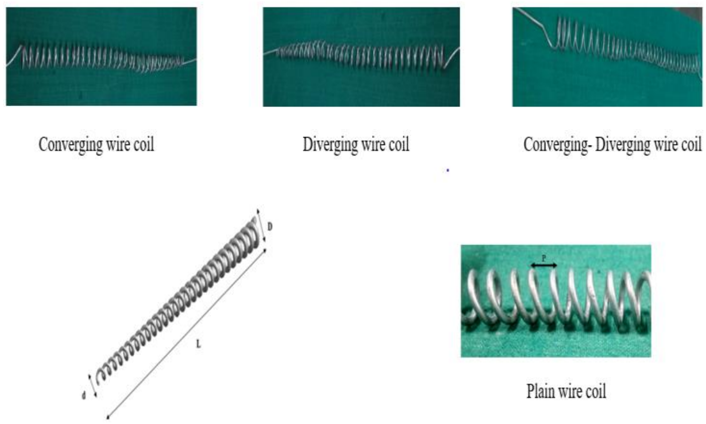

Figure-3: Photo of tapered wire coil insert

Data reduction

Cold fluid heat transfer rate in inner tube is calculated by,

$$Q_c = \dot{V} \rho_c c_{pc} \left(T_{c,out} - T_{c,in} \right) \quad (1)$$

Hot fluid heat transfer rate in outer tube is calculated by,

$$Q_h = \dot{V}_h \rho_h c_{ph} \left(T_{h,in} - T_{h,out} \right) \quad (2)$$

The average heat transfer rate is determined by,

$$Q_{avg} = \left(Q_c + Q_h \right) / 2 \quad (3)$$

Equation (4) is used to estimate the overall heat transfer coefficient for inner tube side,

$$U_{in} = \frac{Q_{avg}}{A_{in} \times \Delta T_{LMTD}} \quad (4)$$

Where,

$$\Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)} \quad (4a)$$

Without considering fouling, heat transfer coefficient can be projected by,

$$\frac{1}{U_{in}A_{in}} = \frac{1}{h_{nf}A_{in}} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi KL} + \frac{1}{h_{out}A_{out}} \quad (5)$$

The calculation of Nusselt number for annulus side is computed by using correlation created by Dirker and Mayer [12],

$$Nu_o = 0.007435\,\mathrm{Re}^{0.91}\,\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad (6)$$

Range: 4000 < Re <30000, 1.72 < $d_{ot,i}/d_{it,o}$ < 3.2

The Reynolds number can be computed as;

$$\mathrm{Re} = \frac{4\dot{m}}{\pi d_i \mu} \quad (6a)$$

From the equation (6) and (7), the heat transfer coefficient of the outer tube can be calculated,

$$h_{out} = \frac{Nu_o \times k_o}{d_{eq}} \quad (7)$$

Where d_{eq} is the equivalent diameter of the outer tube and given by,

$$d_{eq} = \left(d_{ot,i}{}^2 - d_{it,o}{}^2\right)/d_{it,o} \quad (8)$$

The value of h_o from the equation (7) is substituted in the equation (5), to estimate the inner tube side heat transfer coefficient (h_c). The Nusselt number of cold fluids can be measured by the following equation:

$$Nu_c = h_c d_{it,i}/k_c \quad (9)$$

The friction factor is presented as below;

$$f = \frac{\pi^2}{8}\Delta p\left(\frac{\rho_c d_{it,i}{}^2}{\dot{m}_c{}^2 L}\right) \quad (10)$$

The net entropy for heat move can be communicated as follow;

$$S_{gen_{tot}} = m_c cp_c \ln\left(\frac{T_{c,out}}{T_{c,in}}\right) + \frac{m_c \times \Delta P_c}{\rho_c \times T_{avg,c}} + m_h c_{ph} \ln\left(\frac{T_{h,out}}{T_{h,in}}\right) + \frac{m_h \times \Delta P_h}{\rho_h \times T_{avg,h}} \quad (11)$$

Uncertainty analysis

The error analysis of obtained parameters can be estimated by using equations developed by Kline and McClintock [13].

$$\frac{\delta X}{X} = \sqrt{\left(\frac{\delta x_1}{x_1}\right)^2 + \left(\frac{\delta x_2}{x_2}\right)^2 + \text{------} + \left(\frac{\delta x_n}{x_n}\right)^2} \quad (12)$$

Based on the accuracies of mirrored parameter and properties, the uncertainties of several evaluated parameters such as Re, Q, U, h, Nu, f, S_{gen} values are represented in **Table 2**.

Table-2: Uncertainty of parameters

Parameter	**Uncerntainty (%)**
Mass flow rate (kg/s)	± 0.714
Density (kg/m^3)	± 1 %
Viscosity (Pa.s)	± 1 %
Thermal conductivity (W/m.K)	± 1 %
Reynolds number	± 1.23 %
Heat transfer coefficient	± 2.07 %
Nusselt number	± 2.29 %
Entropy generation	± 3.06 %
Friction factor	± 3.70 %
h/Δp	± 3.67 %

3. RESULTS AND DISCUSSION

Validation with plain tube

To ensure the accuracy of experimental data, the experiment was carried out with a plain tube and the results obtained were compared with standard correlation proposed by Sieder and Tate [14] and Nanan et al. [15] for Nusselt number and friction factor as shown in Figures. 4 and 5.

Sieder and Tate correlation;

$$Nu = 0.027Re^{0.8}Pr^{0.33}\left(\frac{\mu}{\mu_s}\right)^{0.14} \quad (13)$$

Nanan et al. correlation;

$$Nu = 0.0068Re^{0.92}Pr^{0.4} \quad (14)$$

$$f = 1.01Re^{-0.37} \quad (15)$$

From the figures, it is concluded that the experimental data are in acceptable range with the Sieder-Tate and Nanan et al. correlations for Nusselt number with mean deviation of ±12.9% and ±9.5%, respectively while the friction factor is agreed well with the Nanan et al. correlation with an average deviation of ±6.4%.

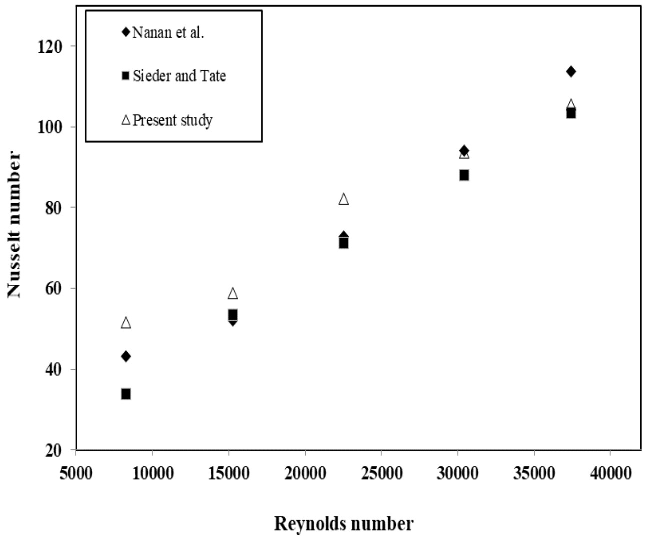

Figure-4: Validation of Nusselt number for water in a plain tube

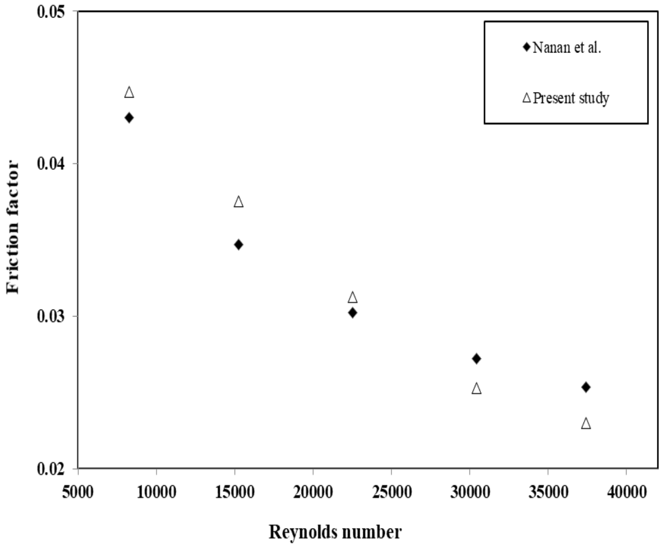

Figure-5: Validation of friction factor for water in a plain tube

Nusselt Number and Friction factor

Figures 6 and 7 show that the impact of tightened wire loop embeds on the Nusselt number and rubbing factor with various setups of the wire curl. The outcomes show that Nusselt number increments and the contact factor decline with an increment in Reynolds number. The outcomes uncover that veering wire loop embeds display higher hotness move execution than different plans because of expanding in home season of stream and contact surface region, when the liquid lull from wandering wire curl embeds. The grating variable declines with an increment in Reynolds number as displayed in Figure 7. Wandering wire loop embeds show a higher rubbing factor than that of different game plans because of the upsetting of the stream at the entry of veering wire curl embeds and prompts an expansion in the tension drop. The normal Nusselt number and grinding component of water streaming in the inward cylinder with various arrangements of tightened wire loops (Diverging, Converging-Diverging, and Converging wire curl) individually, improves 1.91, 1.73, 1.58 occasions and 8.60, 7.98 and 7.39 occasions individually, that for the plain cylinder.

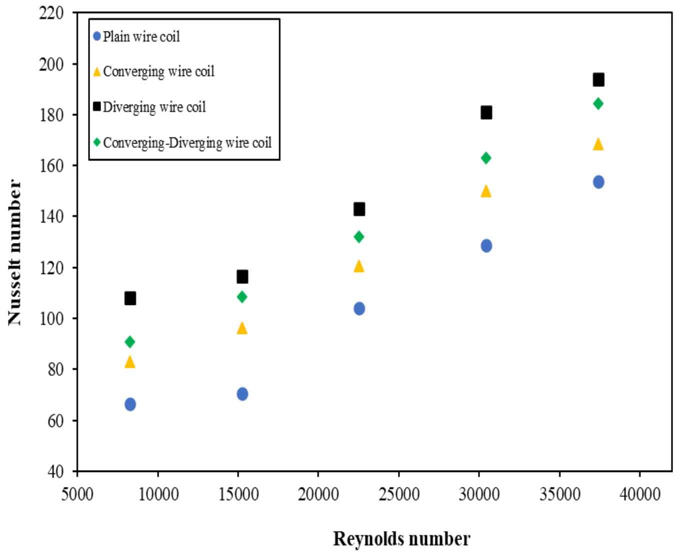

Figure-6: Nusselt number versus Reynolds number

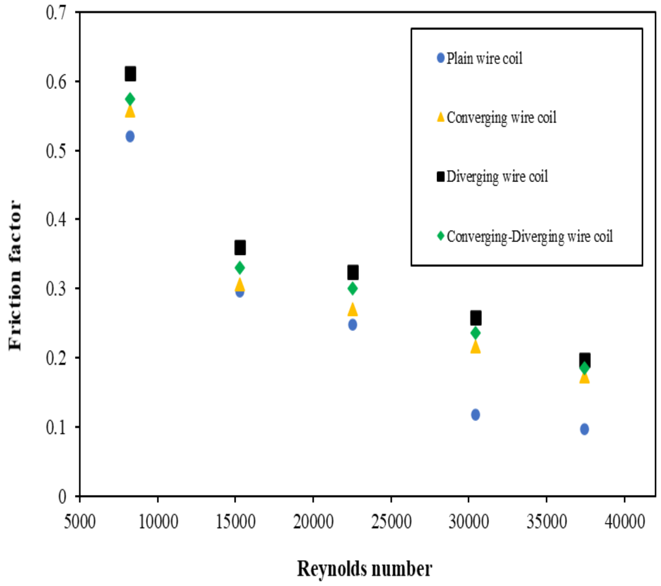

Figure-7: Friction factor versus Reynolds number

The variation of $h/\Delta p$ ratio with Reynolds number for different configurations of tapered wire coil is depicted in Figs. As seen in Figure 8, it is clear that with the increase in Reynolds number, the ratio $h/\Delta p$ decreases and diminishes up to the Reynolds number of 30,000 and then increases for all configurations of wire coil inserts. In fact, while increasing the Reynolds number, the pressure drop increases much more than the heat transfer rate and this leads to reducing $h/\Delta p$ ratio. The ratio $h/\Delta p$ yields maximum value at a low flow rate as heat transfer coefficient dominances over the pressure drop at a low flow rate. Since the value of the ratio $h/\Delta p$ is greater than unity, it can be concluded that using tapered wire coil in concentric tube heat exchanger are beneficial for practical heat applications.

Entropy generation

The total entropy generation ($S_{gen,tot}$) determined by equations (11) and depicted in Figure 9 with respect to the Reynolds number for different configurations of tapered wire coil inserts. The total entropy generation increases with an increase in the Reynolds number. Also, the result shows that $S_{gen,tot}$ reduces by the use of tapered wire coil inserts in the tube as it creates strong mixing of fluids which in results improve heat transfer. Diverging wire coil inserts shows minimum value of entropy generation among all other configurations. Using diverging wire coil inserts, the average entropy generation reduces by around 12.95 % less than that for the plain tube, 6.70 % less than that for converging wire coil and 5.44 % lower than that for converging-diverging wire coil inserts, respectively.

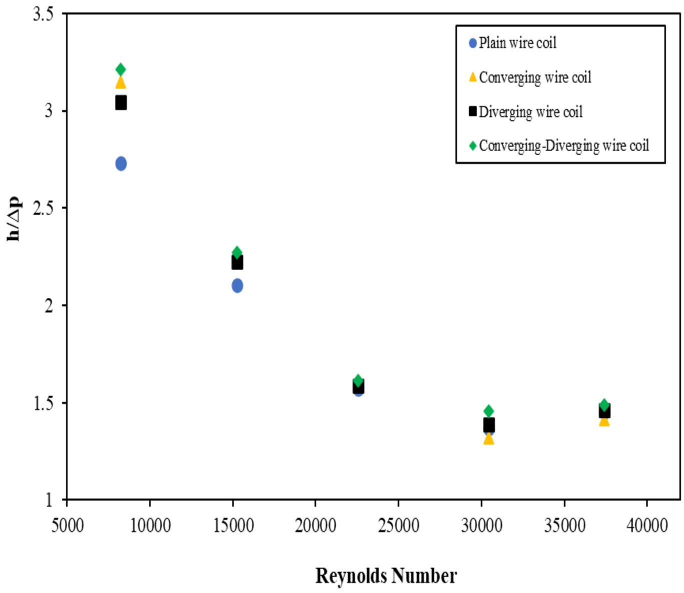

Figure-8: Ratio $h/\Delta p$ versus Reynolds number

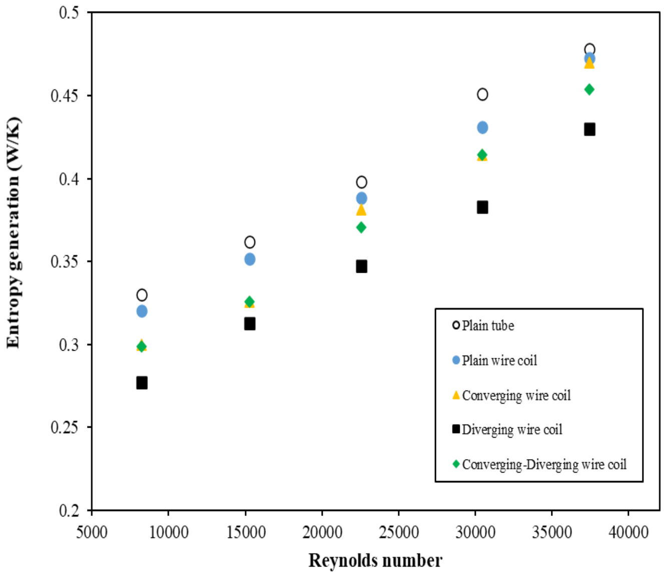

Figure-9:Variation of entropy generation with Reynolds number

3. CONCLUSIONS

An experimental analysis for hydrothermal performance in concentric tube heat exchanger with novel tapered wire coil inserts was conducted under turbulent flow condition. The main results of this study are summed up below:

- The significant increase in Nu with increase in Reynolds number obtained by inserting tapered wire coil. The friction factor decreases with increase in Reynolds number.
- Among all coil arrangements, diverging wire coil inserts exhibits higher heat transfer performance than others arrangements.
- The average Nusselt number and friction factor of water flowing in the inner tube with different configurations of tapered wire coils (Diverging, Converging-Diverging and Converging wire coil) respectively, enhances 1.91, 1.73, 1.58 times and 8.60, 7.98 and 7.39 times respectively, that for the plain tube.
- The value of the ratio $h/\Delta p$ is greater than unity, it can be concluded that using tapered wire coil in concentric tube heat exchanger are beneficial for practical heat applications.
- Diverging wire coil inserts shows minimum value of entropy generation among all other configurations.

- Using diverging wire coil inserts, the average entropy generation reduces by around 12.95 % less than that for the plain tube, 6.70 % less than that for converging wire coil and 5.44 % lower than that for converging-diverging wire coil inserts, respectively.

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