

Experimental Investigation on Heat Transfer Characteristics in a Circular Tube Fitted with Perforated Helical Screw-Tape Inserts

Sudhir S. Urkude¹, H. S. Farkade²

P.G. Student, Department of Mechanical Engineering, Government College of Engineering, Amravati,
Maharashtra, India¹

Assistant Professor, Department of Mechanical Engineering, Government College of Engineering, Amravati
Maharashtra, India²

ABSTRACT: Experimental studies of heat transfer in a plane circular tube fitted with the perforated helical screw-tape inserts have been presented. The different parameters used for the experimentation include, fixed tape thickness (t) i.e. 1mm, pitch ratios ($P/D= 1$) and perforation index ($PA/TA = 0\%, 5\% \& 10\%$). The experiments are conducted in the range of flow varying between 4,000 to 10,500 Reynolds numbers. The experimentation is carried out in the test section of 1.25 m length with a hydraulic diameter (D) of 52 mm. The test section was heated with constant heat flux of 550 watt/m² with the help of a variable voltage transformer. Using experimental data correlations for Nusselt number and friction factor have also been developed for such perforated helical screw-tape inserts, which gives a good agreement between predicted values and experimental values of Nusselt number and friction factor. Performance evaluation analysis has been made and the maximum performance ratio of 1.20 were obtained for 6518.12 Reynolds Number and perforation index ($PA/TA=10\%$).

KEYWORDS: Heat transfer, friction factor, thermal performance factor, perforated helical screw-tape inserts.

I. INTRODUCTION

The helical tape insert and the twisted-tape insert generate the swirling flow in the circular tube and both of them possess the different characteristics of flow. For the helical tape, the swirling flow goes in single way direction (a screw motion), while the twisted-tape shows the swirling flow in two ways direction simultaneously. Because of lower pressure drop, twisted tape insert is, in general, more popular than the helical tape despite higher heat transfer rate. However, at low values of Reynolds number the pressure drops for using both tapes are not much different. This helical tape can help to promote higher heat transfer exchange rate than the use of twisted-tape because of shorter pitch length which leads to stronger swirling flow and long residence time in the tube.

Past literature shows that as the value of perforation index increases there is huge decrease in the amount of friction factor, as the flow blockages decrease. Heat transfer also decreases with increases in the amount of perforation index because of lesser eddy and vortex formation. But the thermal performance factor shows significant increase with increase in the value of perforation index. This improvement in the thermal performance factor is because of fluid stream detachment and reattachment, and less flow blockages because of perforation.

New parameter of perforation has been implemented in this work and effect of perforation index on heat transfer, friction factor and thermal performance factor has been studied. Some assumptions are made in this study in order to avoid minor losses during the experimentation.

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Nomenclature			
Re	Reynolds number	h	Convective heat transfer coefficient (W/m ² K)
Nu	Nusselt number	K	Thermal conductivity of air (W/mK)
Nu _o	Nusselt number for plain tube	T _w	Local wall temperature (K)
Pr	Prandtl number	T _b	Bulk mean temperature (K)
f	Friction factor	T _{wm}	Mean wall temperature (K)
f _o	Friction factor for plain tube	T _i	Fluid inlet temperature (K)
η	Thermal performance factor	T _o	Fluid exit temperature. (K)
m	Mass flow rate of fluid (Kg/s)	ΔP	Pressure drop across test section (Pa)
D	Hydraulic diameter (m)	ΔP _o	Pressure drop across orifice plate (Pa)
W	Width of Helical Tape inserts (m)	PI	Perforation index
A	Surface area of test section (m ²)	L	Length of test section (m)
PA	Perforated area of insert (m ²)		
TA	Total area of insert (m ²)	Greek symbols	
q	Heat flux (W/m ²)	ρ	density of fluid, kg/m ³
C _d	Coefficient of discharge	μ	viscosity of fluid, N s/m ²

II. EXPERIMENT SET-UP

We proposed to carry out on experimental set-up as shown in the figure1. The experiment setup we have fabricated is an experimental facility to test the different inserts in a circular tube. It is an open loop test section consisted of an air blower, and heat transfer analysis testing section. The test tube has a length of L=1.250m, with 0.052 m inner diameter (D), 0.060 m outer diameter (D_o), and 4 mm thickness (t) of 4 mm. Figure 1 shows the diagrammatic representation of experimental set-up. In this the Test Circular tube was heated by 6 heaters of 200 mm length each connected in parallel with combined capacity of 1000 watts to provide a uniform heat flux boundary condition. The electrical output power was controlled by a 4 Amp dimmer-stat to obtain a constant heat flux over the entire length of the test section.

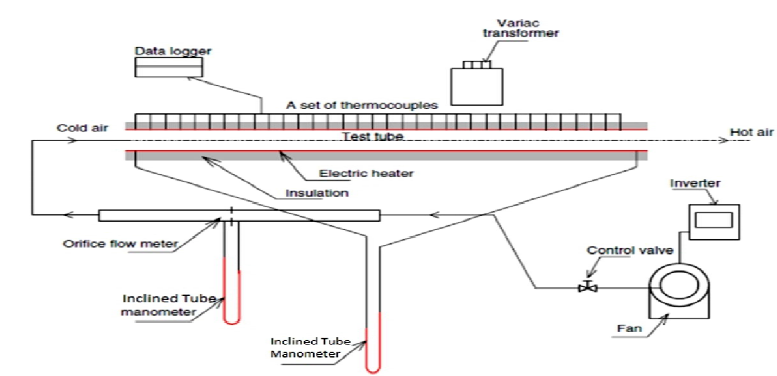


Figure 1: Experimental Setup

The outer surface of the test tube is well insulated by asbestos rope and glass wool to minimize heat loss to surroundings, and necessary precautions are taken to prevent leakages from the system. The inlet and outlet temperatures of the air is measured at certain points with a multichannel temperature measurement unit in conjunction with the K type thermocouples as can be seen in Figure 1. Six thermocouples are installed on the wall of the tube and the thermocouples are placed round the tube to measure the circumferential wall temperature. The mean local wall temperature was determined by means of calculations based on the reading of thermocouples.

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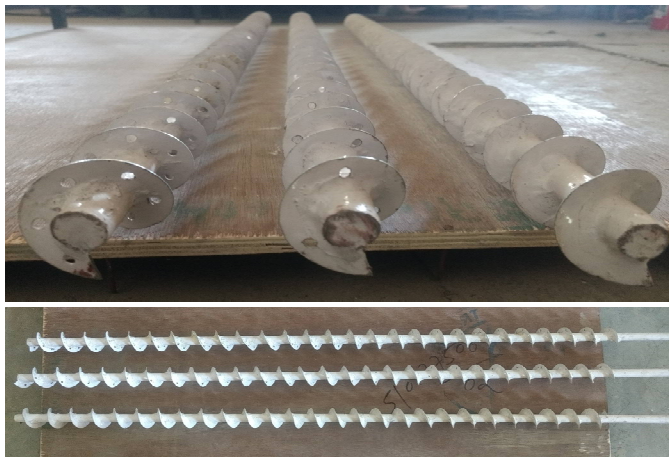
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A. Specifications of Experimental Set-up

Following are the specifications of the various components of the used in the experimental set-up.

- Air blower 0.28 HP
- Orifice meter with inclined tube manometer is used to measure the mass flow rate of air,
- Inclined water tube manometer: range :- 0 to 50 MMW
- The test tube with length of L=1250 mm, with 52 mm inner diameter (d), 60 mm outer diameter (do), and 4 mm thickness (t).
- Pipe heater: 6 heaters of 200 mm length each connected in parallel with combined capacity of 1000 watts.
- 8 Channel temperature recording system unit in conjunction with 6 k-type thermocouples at equal distance on heating section wall and two for measuring inlet and outlet temperature of the air.
- Dimmer stat: 6 ampere Variac.
- Control panel: Ammeter and Voltmeter
-

B. Perforated helical screw-tape insert



Side View

Top View

Figure 2: Photographic view of perforated helical screw-tape inserts

The perforated helical screw-tape inserts are used to increase the turbulence inside the circular tube. The perforated helical screw-tape inserts are made up of mild steel. Helical tape of outer diameter 49 mm, inner diameter 19 mm and pitch ratios (P/D= 1) are manufactured by drilling hole, cutting, forming spiral process respectively on washer. Then these spiral forms of washer are weld on rod of 19 mm diameter. We have used three perforation index (PA/TA = 0%, 5% & 10%).

III. DATA REDUCTION AND VALIDATION

During experimentation, working fluid i.e. air flowed through the test section under the effect of uniform heat flux conditions. At steady state, it is assumed that the heat loss from the test section is equal to the heat transfer rate from the tube wall, which can be expressed as:

$$Q_{air} = Q_{conv} \quad (3.1)$$

Where, $Q_{air} = C_p (T_o - T_i)$ (3.2)

And the convective heat transfer from the heat exchanger wall is given by:

$$Q_{conv} = hA (T_{wm} - T_b) \quad (3.3)$$

Where T_b is bulk mean temperature of fluid and it is calculated by equation

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And,

$$T_b = (T_o + T_i) / 2 \tag{3.4}$$

$$T_{wm} = \Sigma T_w / 6 \tag{3.5}$$

Where, ‘Tw’ is the local wall temperature at which thermocouple was placed. ‘T_{wm}’ is mean wall temperature, which was again the average temperature of the total thermocouple placed on the wall surface.

The average heat transfer coefficient, ‘h, and the average Nusselt number, Nu are estimated as follows:

$$Nu = hD/k \tag{3.6}$$

The value of Reynolds number is obtained by standard equations mentioned below:

$$Re = \rho V D / \mu \tag{3.7}$$

And the value of friction factor is obtained by:

$$f = \Delta P / \{ (L/D) (\rho V^2 / 2) \} \tag{3.8}$$

In which V is the mean velocity of the tube. All of thermal properties of the tested fluid are determined at the bulk mean temperature of fluid. Finally the thermal performance factor is calculated by the equation:

$$THP = \frac{\left(\frac{Nu}{Nu_o} \right)}{\left(\frac{f}{f_o} \right)^{1/3}} \tag{3.9}$$

A thorough check of the instruments and the test set-up was followed by experimentation on conventional smooth pipe. The average values of Nusselt number and friction factor were determined. These values are compared with the values obtained from the standard correlation like Blasius equation for friction factor and Dittus-Boelter equation for Nusselt number in case of smooth tube. The standard equations for Friction factor and Nusselt number is given as:

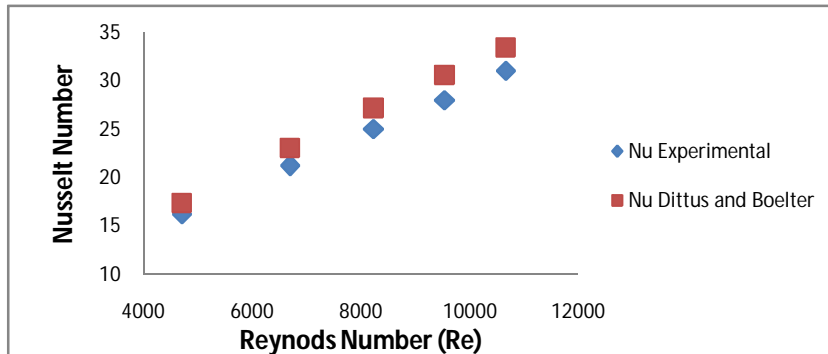


Figure 3: Validation of Nusselt Validation of test setup

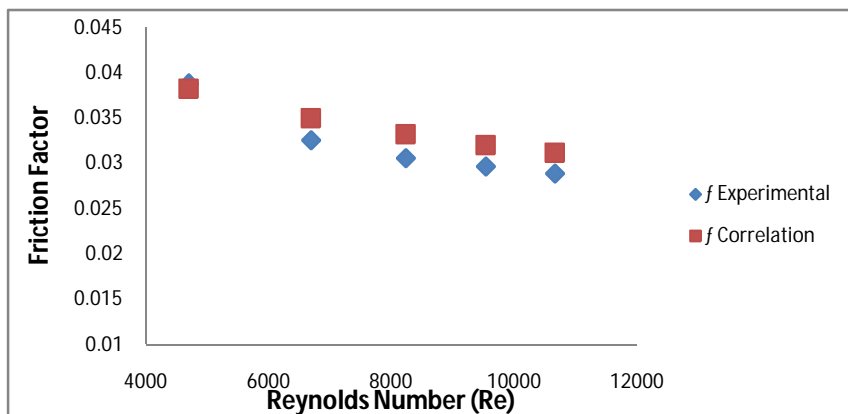


Figure 4: Validation of Friction Factor of test setup

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Blasius equation

$$f_o = 0.316Re^{-0.25} \tag{3.10}$$

Dittus-Boelter equation

$$Nu_o = 0.023Re^{0.8}Pr^{0.4} \tag{3.11}$$

Experimental calculated value, Fig. 3 and Fig. 4 shows the validation of friction factor and Nusselt number over the standard smooth tube equation. Deviation of $\pm 10\%$ is seen in the case of Nusselt number and $\pm 10\%$ in case of friction factor, as compared to smooth tube heat exchanger. This small deviation in experimental result allows proceeding with the experimentation.

IV. RESULTS AND DISCUSSION

The series of experiments were carried out on the experimental test rig. The experiments were first carried out with the circular pipe without any inserts and then the same experiments were repeated by using the perforated helical screw-tape inserts in the plane circular tube. All experiments were performed by providing a different mass flow rate of air by controlling the air flow by using the valve, the different opening of valves gives the different mass flow rate. Following are the results of the experiments.

A. Effect on heat transfer

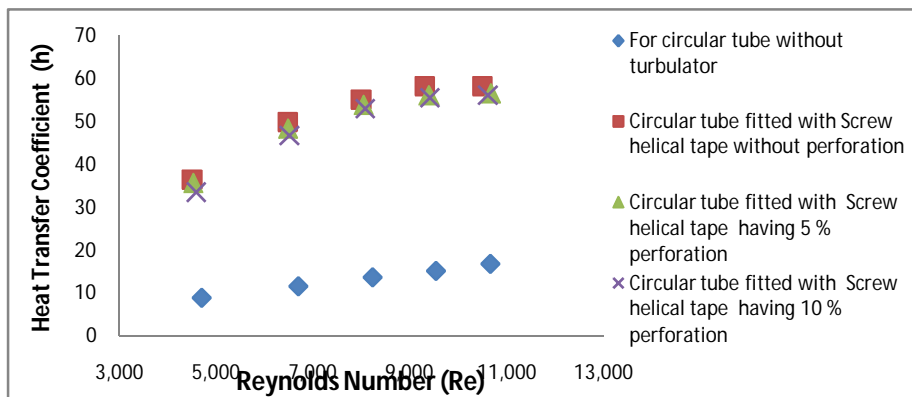


Figure 5: Variation in Heat Transfer Coefficient with Reynolds number

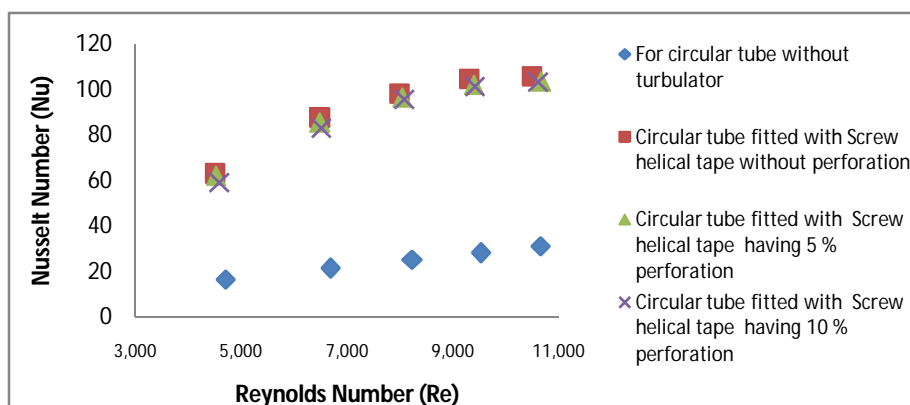


Figure 6: Variation in Nusselt number with Reynolds number

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Significant improvement in heat transfer is found for different set of insert geometries. It is found that with increase in the value of PI heat transfer decreases slightly and maximum heat transfer is found for Circular tube fitted with Screw helical tape without perforation around 4.12 times higher as compared to smooth tube for heat exchangers. The variation can be seen in Figure 5, 6 and 7 mentioned below. It is found that with increase in the value of perforation index (PI), flow blockages decreases significantly, and because of this decreases in flow blockages heat transfer also decreases. Because of presence of perforation frequent detachment and reattachment of fluid streams takes place, due to this proper mixing of fluid takes place that helps in heat transfer enhancement.

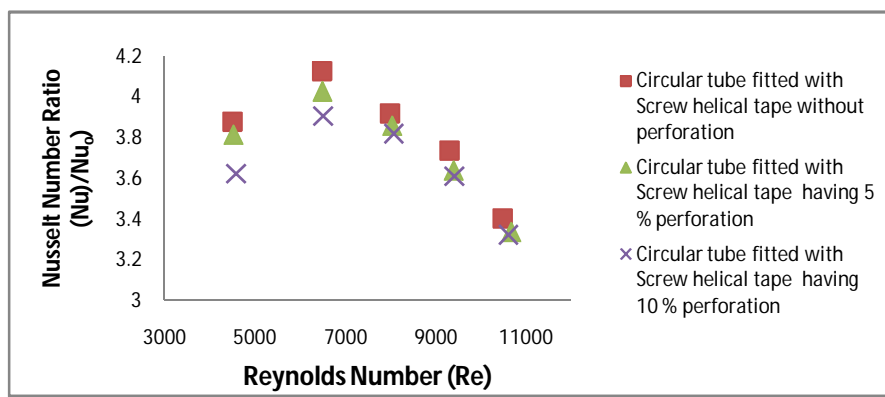


Figure 7: Variation in Nu/Nu₀ with Reynolds numbers

B. Effect on friction factor

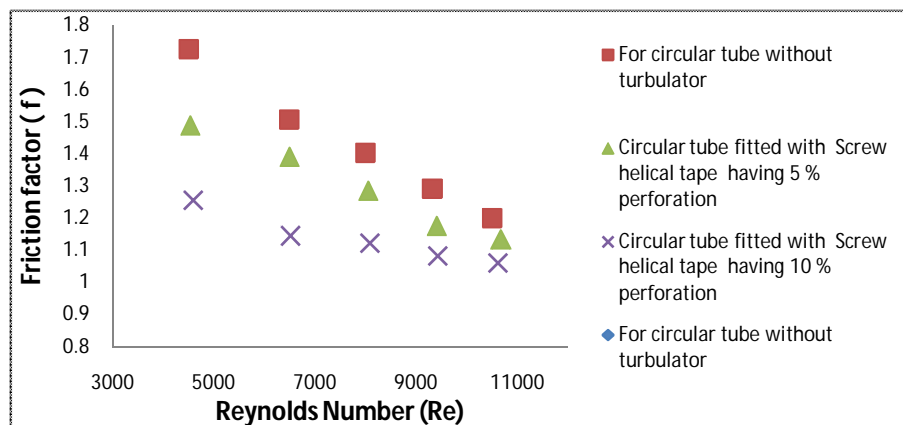


Figure 8: Variation in friction factor with Reynolds number

The friction factor is most important factor for performance analysis of various heat transfer augmentation techniques. It is always observed that while using any inserts in the circular pipe it results in pressure drop because the increased friction in pipes. Lesser the value of friction factors higher the thermal performance factor of heat exchangers. In the present work perforation index played the major role in controlling the value of friction factor. Because of perforation in the helical tape, flow blockages decreases to greater amount, this finally leads to lesser pressure drop, and this lead to lower value of friction factor. So in the present work it is seen that because of increase in the value of perforation index there is significant decrease in the value of friction factor which finally reduces the pumping cost and enhances the working of heat exchangers. It is seen that minimum friction factor is found for the PI=10%, which is about 37.1 times higher as compared to smooth tube heat exchangers. The variation of friction factor with respect to different geometrical and flow parameters can be seen in Figure 8 and 9.

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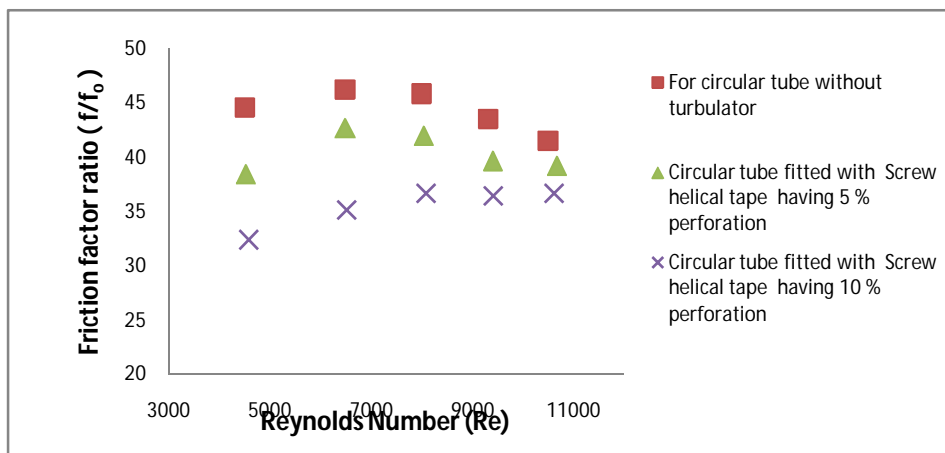


Figure 9: Variation in f/f_0 with Reynolds number

C. Effect on thermal performance factor

The ultimate aim of this experimental study is to improve the thermal performance factor of heat exchanger tube as compared to smooth tube heat exchangers in accordance with higher value of heat transfer. Fig. 10 shows effect of different geometrical and flow parameters on the value of thermal performance factor. Similarly as the amount of perforation index increases, the value of thermal performance factor also increases significantly because of the minimum flow blockages in the higher range of perforation index, also phenomenon like fluid stream detachment and reattachment causes proper mixing of fluid stream which improves heat transfer rate that finally adds to improvement of thermal performance factor. It is found that there is 1.2 times improvement in thermal performance factor as compared to smooth tube heat exchangers, for PI=10%. And as PI decreases, the value of thermal performance factor also decreases because of higher amount of friction factor for the lower values of geometrical parameters

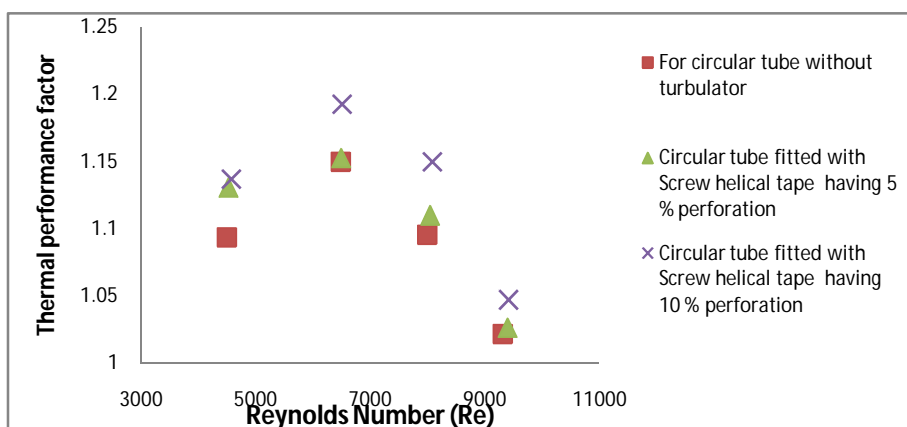


Figure 10: Variation in thermal performance factor with Reynolds number

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V. CORRELATION FOR PREDICTING THE VALUE OF NUSSLETT NUMBER, FRICTION FACTOR AND THERMAL PERFORMANCE FACTOR

In order to make useful such study by designer and researcher it becomes necessary to develop the correlations for heat transfer coefficient and friction factor having various parameters investigated. Accordingly, using experimental data correlations for Nusselt number and friction factor have been developed and discussed as follows.

A. Correlation for Nusselt number

Based on the experimental study, the effects of various parameters on Nusselt number have been discussed earlier and are reproduced as follows:

- i. Nusselt number increases monotonically with increasing Reynolds number (Re).
- ii. Nusselt number decrease with increase Perforation Index (PI).

The Nusselt number is strongly dependent on Perforation Index (PI) and the operating parameter Reynolds number (Re). Thus the equation for Nusselt number can be written as

$$Nu = f(Re, PI)$$

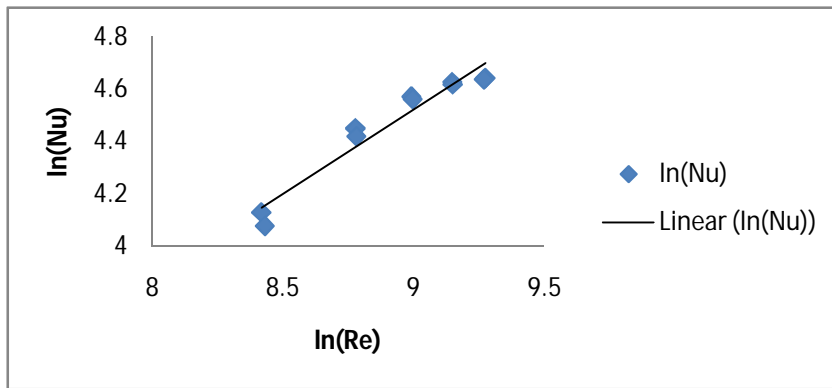


Figure 11: Plot of ln (Nu) Vs ln (Re)

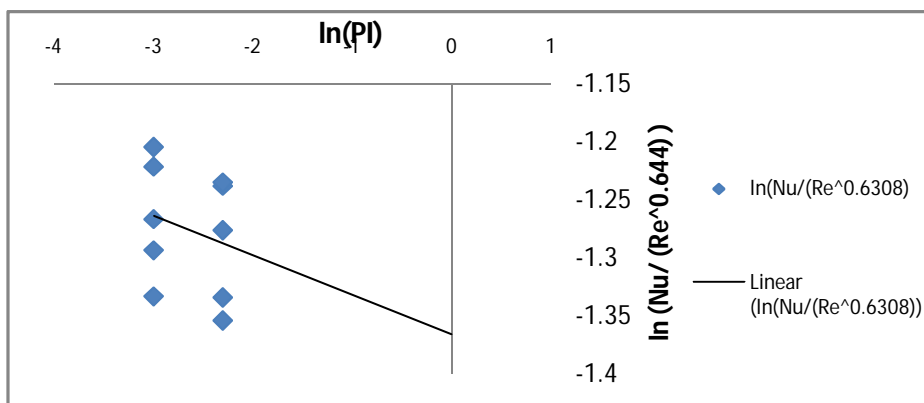


Figure 12: Plot of Nu/ (Re^0.6308) vs. ln (PI)

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The data collected from the experimental study for temperature of air and wall, manometer reading across the orifice for calculating air mass flow rate to calculate the heat transfer coefficient. The Nusselt numbers calculated by using the heat transfer coefficient were plotted against Reynolds number and are shown in Figure 11. The regression analysis has been carried out to fit a straight line through the data point, the regression resulted the following:

$$\ln(\text{Nu}) = 0.6308 \ln(\text{Re}) - \ln(C_0)$$

$$\text{Nu} = C_0 \text{Re}^{0.6308}$$

The constant C_0 is dependent of the parameters Perforation Index (PI). The Perforation Index (PI) is incorporated to show the effect of Perforation on Nusselt number. The values of $\text{Nu}/\text{Re}^{0.6308}$ are plotted against relative Perforation Index (PI) as shown in Figure 12. The best fit regression yields the following correlation for Nusselt number:

$$\ln(\text{Nu}/(\text{Re}^{0.6308})) = -0.034 \ln(\text{PI}) - 1.3655$$

$$\text{Nu} = 0.2552 \text{Re}^{0.6308} \text{PI}^{-0.034}$$

The calculated values of Nusselt number from developed correlation have been compared with the experimental values as shown in Figure 13. It has been found that these values are reasonably good as maximum deviation found within $\pm 7\%$.

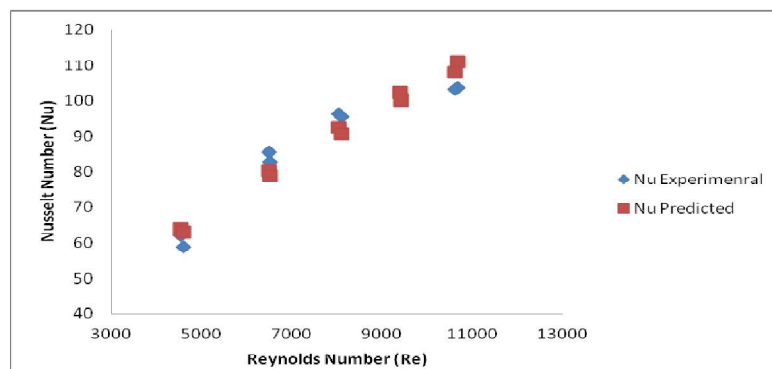


Figure 13: Comparison of predicted and experimental values of Nusselt number

B. Correlation for friction factor

As discussed earlier under results and discussions the effect of various parameters on friction factor are reproduce as

- i. Friction factor decreases with increasing Reynolds number (Re).
- ii. Friction factor decreases with decreases in Perforation Index (PI).

The friction factor dependents strongly on Perforation Index (PI) and the operating parameter, Re. Thus the equation for friction factor can be written as

$$f = f(\text{Re}, \text{PI})$$

By following similar procedure of correlation for Nusselt number the regression analysis has been carried out to fit a straight line through the data point for friction factor shown in Fig. 14. The relationship is as follows

$$\ln(f) = -0.2659 \ln(\text{Re}) + \ln(C_1)$$

$$f = C_1 (\text{Re})^{-0.2659}$$

The constant C_1 is dependent of the parameters Perforation Index (PI). The Perforation Index (PI) introduced to incorporate the effect of Perforation on friction factor. The values of $f/\text{Re}^{-0.2659}$ are plotted against Perforation Index (PI) as shown in Figure 15. The best fit regression yields the following correlation for Friction Factor.

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$$\ln(f/(\text{Re}^{-0.2659})) = -0.1869 \ln(\text{PI}) + 2.0649$$

$$f = 7.8845 \text{Re}^{-0.2659} \text{PI}^{-0.1869}$$

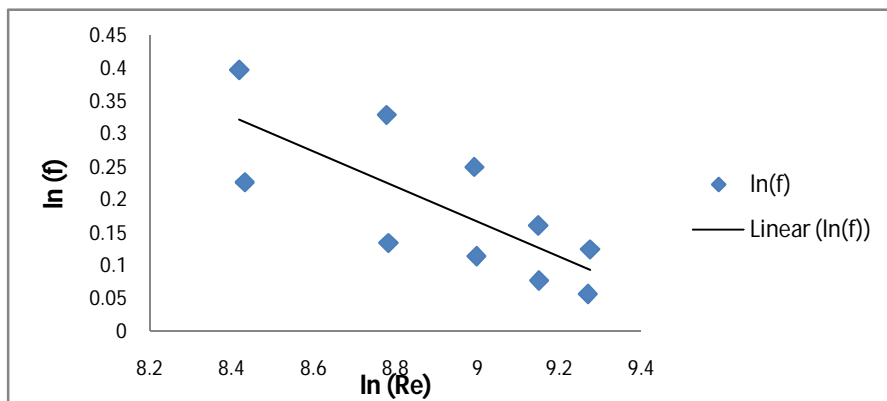


Figure 14: ln (f) Vs ln (Re)

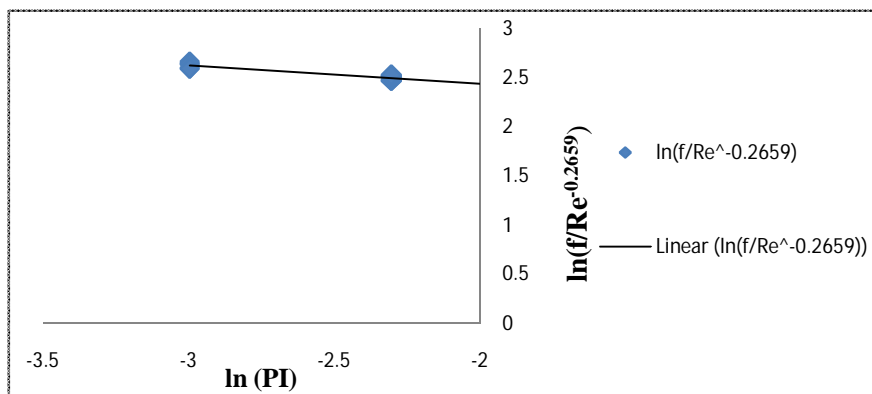


Figure 15: Plot of $\ln(f/(\text{Re}^{-0.2659}))$ Vs ln (PI)

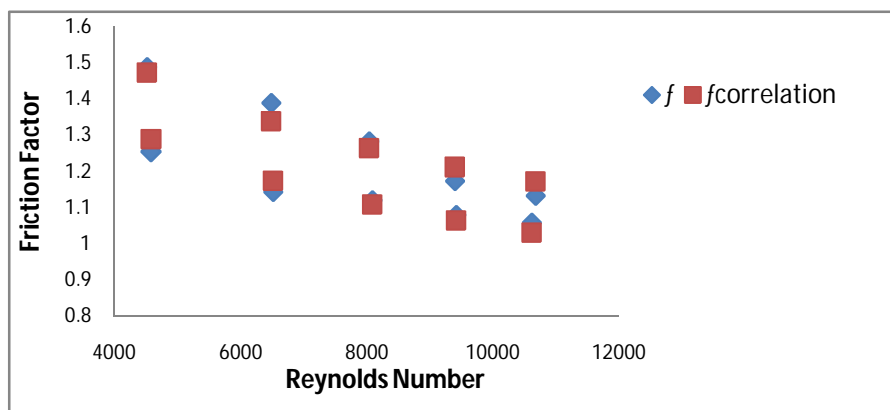


Figure 16: Comparison between experimental and correlational value of f

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The values of friction factor calculated by using the correlation are compared with the experimental values as shown in Figure 16. It is seen from the Figure 16 that the developed correlation for friction factor, can predict the values of friction factor reasonably correct in the range of parameters studied. The maximum deviation for these cases has been found to be $\pm 5\%$.

VI. CONCLUSIONS

Experimental investigations have been carried out to study the effects of perforated helical screw-tape inserts on heat transfer, friction and enhancement efficiency, in a circular tube. We used the perforated helical screw-tape inserts of perforation index (PA/TA = 0%, 5% & 10%). Following conclusions can be made:

- For PI, as the value of perforation index increases there is huge decrease in the amount of friction factor, as the flow blockages decreases. Heat transfer also decreases with increases in the amount of perforation index because of lesser eddy and vortex formation. But the thermal performance factor shows significant increase with increase in the value of perforation index. This improvement in the thermal performance factor is because of fluid stream detachment and reattachment, and less flow blockages because of perforation.
- For flow parameters, in the lower range of Reynolds number, high thermal performance is found, and as the value of Reynolds number increases thermal performance factor decreases. Heat transfer is maximum for the higher range of Reynolds number and friction factor is minimum.
- As compared to smooth tube heat exchangers, there is 4.12 times improvement in the value of heat transfer for Screw helical Tape without perforation, and thermal performance factor is found 1.20 times higher as compared to smooth tube heat exchangers for PI=10%.
- Based on the experimental values, correlations for Nusselt number and friction factor have been developed and found to fit the experimental data within $\pm 7\%$ and $\pm 5\%$ for Nusselt number and friction factor, respectively.

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