ISBN 978-93-84422-63-9
Proceeding of 2016 International Conference on Advances in Software, Control and Mechanical Engineering (ICSCME'16)
Kyoto (Japan) April 12-13, 2016 pp.22-28

New Correlations and Performance Analysis of Single Phase Laminar Flow Heat Transfer Enhancement for (a) Combined Helical Screw Tape Inserts and Wire Coil Inserts and (b) Combined Ribs and Twisted Tapes

Sarbendu Roy, Manvendra Tiwari and Sujoy Kumar Saha[1]

Mechanical Engineering Department, IIEST, Shibpur, Howrah 711103, West Bengal, INDIA

Abstract: *Predictive friction factors and Nusselt numbers along with thermo-hydraulic performances of laminar flow through circular duct for two different cases of compound techniques, namely (i) wire coil combined with helical screw tape having oblique teeth and (ii) rib combined with twisted tape having oblique teeth, have been presented.*

Keywords: *Helical screw tapes, performance evaluation, ribs, wire coil, log-linear analysis.*

1. Introduction

Laminar flow has low heat transfer coefficients and it is often encountered in oil, food, process and chemical industries. Passive techniques of heat transfer enhancement offers low cost solution to improve performance of heat exchangers. In this regard compound enhancement techniques are very promising and this has potential to realise more compact heat exchangers and considerable saving of energy.

2. Experimental Set-up, Operating Procedure and Data Analysis

In this paper, experimental data is generated with servotherm oil (medium type) as a working fluid under constant wall heat flux condition. The schematic of experimental set up is shown in the Fig. 1. At the steady state condition, oil mass flow rate is recorded using rotameters while pressure drop is measured using U-tube manometer. Copper-Constantan type thermocouples in conjunction with selector switch box and digital-multimeter have been used to record oil inlet, exit and tube outer wall temperatures at seven axial stations. Tube inner wall temperatures have been evaluated after finding temperature drop across the tube wall thickness while the oil local temperatures have been obtained through linear interpolation. Local heat transfer coefficients and Nusselt numbers have been obtained. Average Nusselt number based on local Nusselt number is obtained by trapezoidal rule. Uncertainty [1] in friction factor and Nusselt number are + 5.65% and + 2.25% respectively for the case of combined wire coil and helical screw tapes with oblique teeth and + 6.89% and + 8.22% respectively for the case of combine rib and twisted tape with oblique teeth.

http://dx.doi.org/10.17758/UR.U0416010

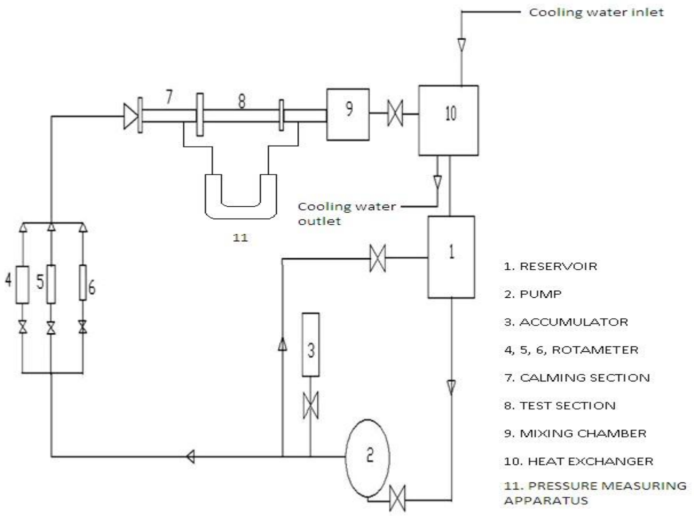

Fig. 1: Schematic diagram of Experimental setup

3. Correlations Development

All correlations have been developed by log-linear regression analysis. Correlation for Nusselt number for combined (Wire Coil & Helical Screw Tape with Oblique Teeth) case:

$$\mathrm{Nu} = 5.172\ \mathrm{Gz}^{c_1}\ (\mathrm{Re})^{c_2}\ \mathrm{Pr}^{c_3}\ \ \mathrm{Gr}^{c_4} \mathrm{p}^{c_5}\ \mathrm{t_{hl}}^{c_6}\ (\sin\theta)^{c_7}\ \ (\sin\alpha)^{c_8}\ \ (\mathrm{d_c})^{c_9} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \tag{1}$$

Exponents c_1, $c_{2\ldots\ldots}c_9$ are evaluated by the following procedure.

$$\ln Nu = c_1 \ln Gz + c_2 \ln(Re) + c_3 \ln Pr + c_4 \ln Gr + c_5 \ln p + c_6 \ln t_{hl} + c_7 \ln sin\theta + c_8 \ln(sin\alpha) + c_9 ln(d_c)$$

For the ideal case, the square of the differences should be equal to zero.

$$\sum_{i=1}^{N} (c_1 \ln Gz + c_2 \ln(Re) + c_3 \ln Pr + c_4 \ln Gr + c_5 \ln p + c_6 \ln t_{hl} + c_7 \ln sin\theta + c_8 \ln(sin\alpha) + c_9 ln(d_c) - \ln \mathrm{Nu})_i^2 \quad = 0 \tag{2}$$

Now, partially differentiating the above equation with respect to, c_1 to c_9 we get,

$$\sum_{i=1}^{N} (c_1 \ln Gz + c_2 \ln(Re) + c_3 \ln Pr + c_4 \ln Gr + c_5 \ln p + c_6 \ln t_{hl} + c_7 \ln sin\theta + c_8 \ln(sin\alpha) + c_9 ln(d_c) - \ln \mathrm{Nu}) \ln Gz = 0$$

$$\begin{aligned}&\sum_{i=1}^{N} c_1 \ln Gz \ln Gz + \sum_{i=1}^{N} c_2 \ln(Re) \ln Gz + \sum_{i=1}^{N} c_3 \ln Pr \ln Gz + \sum_{i=1}^{N} c_4 \ln Gr \ln Gz + \sum_{i=1}^{N} c_5 \ln p \ln Gz \\ &\quad + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln Gz + \sum_{i=1}^{N} c_7 \ln sin\theta \ln Gz + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln Gz + \sum_{i=1}^{N} c_9\, ln(d_c) \ln Gz \\ &\quad = \sum_{i=1}^{N} \ln Nu \ln Gz\end{aligned} \tag{3}$$

$$\begin{aligned}&\sum_{i=1}^{N}(c_1 \ln Gz + c_2 \ln(Re) + c_3 \ln Pr + c_4 \ln Gr + c_5 \ln p + c_6 \ln t_{hl} + c_7 \ln sin\theta + c_8 \ln(sin\alpha) \\ &\qquad + c_9 ln(d_c) - \ln \mathrm{Nu}) \ln Re \ = 0\end{aligned}$$

$$\begin{aligned}&\sum_{i=1}^{N} c_1 \ln Gz \ln Re \ + \sum_{i=1}^{N} c_2 \ln(Re) \ln Re \ + \sum_{i=1}^{N} c_3 \ln Pr \ln Re \ + \sum_{i=1}^{N} c_4 \ln Gr \ln Re \ + \sum_{i=1}^{N} c_5 \ln p \ln Re \\ &\quad + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln Re \ + \sum_{i=1}^{N} c_7 \ln sin\theta \ln Re \ + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln Re \\ &\quad + \sum_{i=1}^{N} c_9\, ln(d_c) \ln Re \ = \sum_{i=1}^{N} \ln Nu \ln Re\end{aligned} \tag{4}$$

Similarly,

$$\begin{aligned}&\sum_{i=1}^{N} c_1 \ln Gz \ln Pr + \sum_{i=1}^{N} c_2 \ln(Re) \ln Pr + \sum_{i=1}^{N} c_3 \ln Pr \ln Pr + \sum_{i=1}^{N} c_4 \ln Gr \ln Pr + \sum_{i=1}^{N} c_5 \ln p \ln Pr \\ &\quad + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln Pr + \sum_{i=1}^{N} c_7 \ln sin\theta \ln Pr + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln Pr + \sum_{i=1}^{N} c_9\, ln(d_c) \ln Pr \\ &\quad = \sum_{i=1}^{N} \ln Nu \ln Pr\end{aligned} \tag{5}$$

$$\begin{aligned}&\sum_{i=1}^{N} c_1 \ln Gz \ln Gr + \sum_{i=1}^{N} c_2 \ln(Re) \ln Gr + \sum_{i=1}^{N} c_3 \ln Pr \ln Gr + \sum_{i=1}^{N} c_4 \ln Gr \ln Gr + \sum_{i=1}^{N} c_5 \ln p \ln Gr \\ &\quad + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln Gr + \sum_{i=1}^{N} c_7 \ln sin\theta \ln Gr + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln Gr + \sum_{i=1}^{N} c_9\, ln(d_c) \ln Gr \\ &\quad = \sum_{i=1}^{N} \ln Nu \ln Gr\end{aligned} \tag{6}$$

$$\sum_{i=1}^{N} c_1 \ln Gz \ln p + \sum_{i=1}^{N} c_2 \ln(Re) \ln p + \sum_{i=1}^{N} c_3 \ln Pr \ln p + \sum_{i=1}^{N} c_4 \ln Gr \ln p + \sum_{i=1}^{N} c_5 \ln p \ln p + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln p + \sum_{i=1}^{N} c_7 \ln sin\theta \ln p + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln p + \sum_{i=1}^{N} c_9\, ln(d_c) \ln p = \sum_{i=1}^{N} \ln Nu \ln p \tag{7}$$

$$\sum_{i=1}^{N} c_1 \ln Gz \ln t_{hl} + \sum_{i=1}^{N} c_2 \ln(Re) \ln t_{hl} + \sum_{i=1}^{N} c_3 \ln Pr \ln t_{hl} + \sum_{i=1}^{N} c_4 \ln Gr \ln t_{hl} + \sum_{i=1}^{N} c_5 \ln p \ln t_{hl} + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln t_{hl} + \sum_{i=1}^{N} c_7 \ln sin\theta \ln t_{hl} + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln t_{hl} + \sum_{i=1}^{N} c_9\, ln(d_c) \ln t_{hl} = \sum_{i=1}^{N} \ln Nu \ln t_{hl} \tag{8}$$

$$\sum_{i=1}^{N} c_1 \ln Gz \ln sin\theta + \sum_{i=1}^{N} c_2 \ln(Re) \ln sin\theta + \sum_{i=1}^{N} c_3 \ln Pr \ln sin\theta + \sum_{i=1}^{N} c_4 \ln Gr \ln sin\theta + \sum_{i=1}^{N} c_5 \ln p \ln sin\theta + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln sin\theta + \sum_{i=1}^{N} c_7 \ln sin\theta \ln sin\theta + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln sin\theta + \sum_{i=1}^{N} c_9\, ln(d_c) \ln sin\theta = \sum_{i=1}^{N} \ln Nu \ln sin\theta \tag{9}$$

$$\sum_{i=1}^{N} c_1 \ln Gz \ln sin\alpha + \sum_{i=1}^{N} c_2 \ln(Re) \ln sin\alpha + \sum_{i=1}^{N} c_3 \ln Pr \ln sin\alpha + \sum_{i=1}^{N} c_4 \ln Gr \ln sin\alpha + \sum_{i=1}^{N} c_5 \ln p \ln sin\alpha + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln sin\alpha + \sum_{i=1}^{N} c_7 \ln sin\theta \ln sin\alpha + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln sin\alpha + \sum_{i=1}^{N} c_9\, ln(d_c) \ln sin\alpha = \sum_{i=1}^{N} \ln Nu \ln sin\alpha \tag{10}$$

$$\sum_{i=1}^{N} c_1 \ln Gz \ln d_c + \sum_{i=1}^{N} c_2 \ln(Re) \ln d_c + \sum_{i=1}^{N} c_3 \ln Pr \ln d_c + \sum_{i=1}^{N} c_4 \ln Gr \ln d_c + \sum_{i=1}^{N} c_5 \ln p \ln d_c + \sum_{i=1}^{N} c_6 \ln t_{hl} \ln d_c + \sum_{i=1}^{N} c_7 \ln sin\theta \ln d_c + \sum_{i=1}^{N} c_8 \ln(sin\alpha) \ln d_c + \sum_{i=1}^{N} c_9\, ln(d_c) \ln d_c = \sum_{i=1}^{N} \ln Nu \ln d_c \tag{11}$$

Where, N is the observed data points in each case.

The determinant (Δ) =

$$\begin{vmatrix}
\sum_{i=1}^{N}(\ln Gz)^2 & \sum_{i=1}^{N}\ln(Re)\ln Gz & \sum_{i=1}^{N}\ln Pr\ln Gz & \sum_{i=1}^{N}\ln Gr\ln Gz & \sum_{i=1}^{N}\ln p\ln Gz & \sum_{i=1}^{N}\ln t_{hl}\ln Gz & \sum_{i=1}^{N}\ln sin\theta\ln Gz & \sum_{i=1}^{N}\ln(sin\alpha)\ln Gz & \sum_{i=1}^{N}ln(d_c)\ln Gz \\
\sum_{i=1}^{N}\ln Gz\ln(Re) & \sum_{i=1}^{N}(\ln Re)^2 & \sum_{i=1}^{N}\ln(Re)\ln Pr & \sum_{i=1}^{N}\ln Gr\ln(Re) & \sum_{i=1}^{N}\ln p\ln(Re) & \sum_{i=1}^{N}\ln t_{hl}\ \ln(Re) & \sum_{i=1}^{N}\ln sin\theta\ln(Re) & \sum_{i=1}^{N}\ln(sin\alpha)\ln(Re) & \sum_{i=1}^{N}ln(d_c)\ln(Re) \\
\sum_{i=1}^{N}\ln Gz\ln Pr & \sum_{i=1}^{N}\ln Pr\ln(Re) & \sum_{i=1}^{N}(\ln Pr)^2 & \sum_{i=1}^{N}\ln Gr\ln Pr & \sum_{i=1}^{N}\ln p\ln Pr & \sum_{i=1}^{N}\ln t_{hl}\ \ln Pr & \sum_{i=1}^{N}\ln sin\theta\ln Pr & \sum_{i=1}^{N}\ln(sin\alpha)\ln Pr & \sum_{i=1}^{N}ln(d_c)\ln Pr \\
\sum_{i=1}^{N}\ln Gr\ln Gz & \sum_{i=1}^{N}\ln Gr\ln(Re) & \sum_{i=1}^{N}\ln Gr\ln Pr & \sum_{i=1}^{N}(\ln Gr)^2 & \sum_{i=1}^{N}\ln Gr\ln p & \sum_{i=1}^{N}\ln t_{hl}\ \ln Gr & \sum_{i=1}^{N}\ln sin\theta\ln Gr & \sum_{i=1}^{N}\ln(sin\alpha)\ln Gr & \sum_{i=1}^{N}ln(d_c)\ln Gr \\
\sum_{i=1}^{N}\ln p\ln Gz & \sum_{i=1}^{N}\ln p\ln(Re) & \sum_{i=1}^{N}\ln p\ln Pr & \sum_{i=1}^{N}\ln Gr\ln p & \sum_{i=1}^{N}(\ln p)^2 & \sum_{i=1}^{N}\ln t_{hl}\ \ln p & \sum_{i=1}^{N}\ln sin\theta\ln p & \sum_{i=1}^{N}\ln(sin\alpha)\ln p & \sum_{i=1}^{N}ln(d_c)\ln p \\
\sum_{i=1}^{N}\ln t_{hl}\ln Gz & \sum_{i=1}^{N}\ln(Re)\ln t_{hl} & \sum_{i=1}^{N}\ln Pr\ln t_{hl} & \sum_{i=1}^{N}\ln Gr\ln t_{hl} & \sum_{i=1}^{N}\ln t_{hl}\ \ln p & \sum_{i=1}^{N}(\ln t_{hl}\ )^2 & \sum_{i=1}^{N}\ln sin\theta\ln t_{hl} & \sum_{i=1}^{N}\ln(sin\alpha)\ln t_{hl} & \sum_{i=1}^{N}ln(d_c)\ln t_{hl} \\
\sum_{i=1}^{N}\ln sin\theta\ln Gz & \sum_{i=1}^{N}\ln(Re)\ln\ sin\theta & \sum_{i=1}^{N}\ln Pr\ln\ sin\theta & \sum_{i=1}^{N}\ln Gr\ln\ sin\theta & \sum_{i=1}^{N}\ln p\ln\ sin\theta & \sum_{i=1}^{N}\ln t_{hl}\ \ln\ sin\theta & \sum_{i=1}^{N}(\ln sin\theta)^2 & \sum_{i=1}^{N}\ln(sin\alpha)\ln\ sin\theta & \sum_{i=1}^{N}ln(d_c)\ln\ sin\theta \\
\sum_{i=1}^{N}\ln(sin\alpha)\ln Gz & \sum_{i=1}^{N}\ln(sin\alpha)\ln(Re) & \sum_{i=1}^{N}\ln Pr\ln\ (sin\alpha) & \sum_{i=1}^{N}\ln Gr\ln\ (sin\alpha) & \sum_{i=1}^{N}\ln p\ln\ (sin\alpha) & \sum_{i=1}^{N}\ln t_{hl}\ \ln\ (sin\alpha) & \sum_{i=1}^{N}\ln sin\theta\ln(sin\alpha) & \sum_{i=1}^{N}(\ln(sin\alpha)\ )^2 & \sum_{i=1}^{N}ln(d_c)\ln(sin\alpha) \\
\sum_{i=1}^{N}ln(d_c)\ln Gz & \sum_{i=1}^{N}ln(d_c)\ln(Re) & \sum_{i=1}^{N}ln(d_c)\ln Pr & \sum_{i=1}^{N}ln(d_c)\ln Gr & \sum_{i=1}^{N}ln(d_c)\ln p & \sum_{i=1}^{N}ln(d_c)\ln t_{hl} & \sum_{i=1}^{N}ln(d_c)\ln\ sin\theta & ln(d_c)\ln(sin\alpha) & \sum_{i=1}^{N}\left(ln(d_c)\right)^2
\end{vmatrix}$$

In the determinants below in the right hand side, the Cs refers to the column numbers in the original determinant, Δ.

$$c_1 = \frac{[B \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.27481$$

$$c_2 = \frac{[C_1 \quad B \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.25883$$

$$c_3 = \frac{[C_1 \quad C_2 \quad B \quad C_4 \quad C_5 \quad C_6 \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.29649$$

$$c_4 = \frac{[C_1 \quad C_2 \quad C_3 \quad B \quad C_5 \quad C_6 \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.25381$$

$$c_5 = \frac{[C_1 \quad C_2 \quad C_3 \quad C_4 \quad B \quad C_6 \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.24716$$

$$c_6 = \frac{[C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad B \quad C_7 \quad C_8 \quad C_9]}{\Delta} = 0.29982$$

$$c_7 = \frac{[C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad B \quad C_8 \quad C_9]}{\Delta} = 0.26538$$

$$c_8 = \frac{[C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad C_7 \quad B \quad C_9]}{\Delta} = 0.24715$$

$$c_9 = \frac{[C_1 \quad C_2 \quad C_3 \quad C_4 \quad C_5 \quad C_6 \quad C_7 \quad C_8 \quad B]}{\Delta} = 0.25931$$

Substituting values of exponents in Eq. (1) we get Correlation for Nusselt number for combined Wire Coil & Helical Screw Tape with Oblique Teeth as,

$$Nu_{com} = 5.172 Gz^{0.27481} Re^{0.25883} Pr^{0.29649} Gr^{0.25381} p^{0.24716} t_{hl}^{0.29982} (Sin\theta)^{0.26538} (Sin\alpha)^{0.24715} d_c^{0.25931} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \tag{12}$$

Following similar procedure, other correlations have been derived.

Correlation for predicting friction factor for combined screw-tape with oblique teeth and wire coil roughness is given by,

$$fRe = 17.355 Re^{0.29735} p^{0.38253} t_{hl}^{0.13879} (\sin\theta)^{0.28152} (\sin\alpha)^{0.11836} d_c^{0.20371} \tag{13}$$

While for predicting friction factor and Nusselt number for combined rib and twisted tape having oblique teeth are obtained as

$$fRe = 81.8373 \left(\frac{Re}{\sqrt{y}}\right)^{0.68665} t_{hl}^{0.08254} (sin\,\theta)^{0.025753} \left(\frac{e}{D}\right)^{0.04364} \left(\frac{P}{e}\right)^{-0.6385} \tag{14}$$

$$Nu_{com} = 5.172\, Gz^{0.28823} \left(\frac{Re}{\sqrt{y}}\right)^{0.1469} Pr^{0.2247} Gr^{0.1711}\, t_{hl}^{0.07799} (sin\,\theta)^{0.13324} \left(\frac{e}{D}\right)^{0.08895} \left(\frac{P}{e}\right)^{-0.7438} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \tag{15}$$

4. Performance Evaluation

Bergles *et al.* [2] have suggested several criteria for the performance evaluation of enhancement devices. The performance of the present geometry has been evaluated on the basis of the following two important criteria:

Criterion 1---Basic geometry fixed, pumping power fixed --- increase heat transfer --- performance ratio R_1 given by,

$$R_{11} = \frac{Nu_{com}}{Nu_{OHSOT}} \qquad R_{12} = \frac{Nu_{com}}{Nu_{OWCI}} \tag{16}$$

Nu_{com} at a given Re, Re_{com} is obtained from the correlation for the combined case.

$Nu_{ohsot,\,owci}$ for the case with 'ohsot' (only helical screw tape with oblique teeth) and 'owci'(only wire coil insert) is taken at the Re, $Re_{ohsot,owci}$ where $Re_{ohsot,owci}$ is calculated from the constant pumping power consideration as given below:

$$Re_{ohsot,owci} = \left[\left(\frac{f_{com}}{f_{ohsot,owci}}\right) Re^3_{ohsot,owci}\right]^{1/3} \tag{17}$$

Criterion 2 --- Basic geometry fixed, heat duty fixed --- reduce pumping power --- performance ratio R_2 is given by,

$$R_{21} = \frac{(fRe^3)_{com}}{(fRe^3)_{ohsot}} \qquad R_{22} = \frac{(fRe^3)_{com}}{(fRe^3)_{owci}} \tag{18}$$

For a given Re, Re_{com}, the Nu_{com} is obtained from the correlation. $Re_{ohsot,owci}$ corresponding to $Nu_{ohsot,owci}$ is obtained from the correlation for the case with ‘ohsot’, ‘owci’.

It has been observed that for combined wire coil roughness and screw-tape with oblique teeth there is 36-133 % increase in heat transfer for constant pumping power and 2-49 % reduction in pumping power for constant heat duty depending upon the values of different parameters while performance analysis (carried out in similar way) for the case of combined rib roughness with twisted tape having oblique teeth, revealed 35- 75% increase in heat transfer for constant pumping power and 26-51% reduction in pumping power for constant heat duty depending upon the rib pitch and rib height. Further details related to this may be obtained from [3, 4].

5. Conclusions

Predictive friction factors and Nusselt numbers along with thermo-hydraulic performances of laminar single phase flow through circular duct for two different cases of compound techniques have been presented. The correlations for combined wire coil roughness and screw-tape with oblique teeth predict the experimental data within ± 10.11 while for the case of combined rib roughness with twisted tape having oblique teeth the proposed correlations predict experimental data within ± 9.71%. Combined wire coil roughness and screw-tape with oblique teeth there is 36-133 % increase in heat transfer for constant pumping power and 2-49 % reduction in pumping power for constant heat duty depending upon the values of different parameters while performance analysis (carried out in similar way) for the case of combined rib roughness with twisted tape having oblique teeth, revealed 35- 75% increase in heat transfer for constant pumping power and 26-51% reduction in pumping power for constant heat duty depending upon the rib pitch and rib height.

6. Acknowledgement

The author gratefully acknowledges the generous financial support of the MHRD, DST, UGC, and CSIR, Government of India, for the current research.

7. References

[1] Kline, S. J. and McClintock, F. A., (), Describing Uncertainties in Single Sample Experiments, Mechanical Engineering, 1953, 75 (1), pp 3-8.

[2] A. E. Bergles, A. R. Blumenkrantz, and Taborek, J., Performance Evaluation Criteria for Enhanced Heat Transfer Surfaces, Paper FC 6.3, *Proc. 1974 5th Int. Heat Transfer Conference*, *Tokyo*, 1974, 2, pp 239-243.

[3] S. Roy and S. K. Saha, Thermal and Friction Characteristics of Laminar Flow Through a Circular Duct Having Helical Screw-Tape with Oblique Teeth Inserts and Wire Coil Inserts, Exp Thermal Fluid Science, vol. 68, 2015, pp 733-743.

http://dx.doi.org/10.1016/j.expthermflusci.2015.07.007

[4] M. Tiwari and S.K. Saha, Laminar Flow Through a Circular Tube Having Transverse Ribs and Twisted Tapes, Journal of Thermal Science and Engineering Applications, 2015, ASME, 7, 041009-1,9.