Investigation on heat transfer enhancement in a circular pipe with artificial roughness

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Abstract. This paper presents a numerical analysis of convective heat transfer enhancement of transverse ribs in circular tubes. Several CFD simulations are carried out for turbulent airflow to analyze heat transfer and pressure drop provided with transverse rectangular ribs. The rib height and pitch are widely varied along with the flow Reynolds number. The effect of each parameter is examined and discussed. To accurately predict major parameters (Nusselt number, friction factor, and thermal hydraulic performance parameter) a deep neural network is developed, trained, and tested by current CFD data. The result demonstrates that artificial neural network shows better performance compared to other methods of prediction (e.g. power-law approximation) and can offer an economical and powerful approach for modeling optimal heat enhancement parameters.

Introduction

Manufacturers of modern highly efficient tubular heat exchangers are facing continuously increasing industrial demands of unit power and compactness. Both demands can be achieved using heat transfer enhancement methods [1]. Since the growth of heat transfer involves the penalty of friction losses the optimal heat transfer enhancement method needs to be found and investigated for each specific case which may be costly and technically difficult.

One of the most efficient and technologically acceptable heat transfer enhancement methods in tubes is artificial turbulization of flow by roughness elements: annual diaphragms, wire coils, transverse ribs, knurling of the outer tube surface, etc. The periodically located roughness elements turbulize the flow in the wall layer where the highest temperature differences of 85\% to 99\% are focused [3] providing heat transfer enhancement.

Kalinin et al. [2-3] analyzed the mass of experimental data on different heat transfer enhancement methods and flow conditions. As for turbulent airflow in transverse rib roughened tubes, it is shown that the optimal rib pitch-to-diameter ratio is in range 0.25-1.0 and height to-diameter ratio in range e/d=0.025-0.05. Lobanov [4] numerically analyzed enhanced heat transfer in artificially roughened ducts with the help of a compound four-layer model of a turbulent boundary layer. Calculations were performed for a wide Reynolds number range of $10^4$ to $10^9$ and different geometric parameters.
During the last two decades, computational fluid dynamics (CFD) has become a powerful tool for a wide range of research and is often applied to engineering problems. Solving of the RANS equations for turbulent flow simulation is efficient, time, and source saving approach used in numerous studies [5-11]. Vijiaparupu and Cui [5] investigated the effect of the modeling approach and the turbulence model on turbulent flow through rough tubes. The results have been validated by experimental measurements showing the equally good performance of all considered RANS models and the LES model.

Yadav and Bhagoria [6] report CFD investigations on Nusselt number, friction factor, and thermal hydraulic performance of a solar air heater duct provided with circular transverse wire rib roughness on the absorber plate.

Ozceyhan et al. [7] performed a numerical investigation of heat transfer enhancement in a tube with the circular cross-sectional rings separated from the wall. Results are obtained for five different rib pitches and turbulent airflow with Re between 4475 and 43725. The best overall heat transfer enhancement of 18% is reported for the rib pitch-to-diameter ratio p/d=3 at Re=15,600.

Vahidifar and Kahrom [12] experimentally investigated heat transfer characteristics and pressure drop of a horizontal double pipe heat exchanger with wire coil inserts. Tests were performed for wire coils and rings within a geometrical range with a pitch of p/d=1-4 and wire roughness height of e/d=0.1-0.22. Best enhancement performance (128%) is observed for wire coil with e/d=0.22, p/d=1 and Reynolds number of 10,000.

With the interdisciplinary development of modern computational technologies, artificial neural networks (ANNs) have become a powerful approach for modeling highly complicated nonlinear systems. Deep neural networks trained and validated on experimental or CFD modeling data are capable of making accurate predictions without the need for any additional experiments.

Elsayed and Lacor [13] present the performance of a radial basis neural network (RBNN) used for air cyclone optimization. The new cyclone design developed with the help of RBNN showed a 25% less pressure drop than the old design in CFD simulation. Castelani et. al [14] compare different approaches of wind energy forecast in complex cites. The best results were obtained with the full ANN approach.

The present work submits a numerical study on heat transfer, friction loss characteristics, and the thermohydraulic performance parameter of a tube section with transverse rectangular ribs. Optimal rib and flow parameters are to be found with the help of CFD modeling and ANN predictions. Commercial CFD simulation code FLUENT (version 20.1) is used for the numerical part of the investigation.

1. Numerical modeling

1.1. Solution domain

The numerical simulations are conducted on a two-dimensional axisymmetric domain which represents a tube of 10 mm diameter and 150 mm length. A schematic view of the solution domain is shown in Figure 1 where (1) is velocity inlet; (2) is velocity outlet; (3) is a wall with no-slip and constant temperature conditions; (4) is an axis of the tube with symmetry condition; (5) are the ribs sides with no-slip condition.

![Figure 1. Schematic of two-dimensional solution domain for CFD analysis.](image)

The rib pitch-to-tube diameter ratio (p/d) is in the range 0.1-1.5; the rib height-to-tube diameter ratio (e/d) is in the range 0.01-0.05; the considered Reynolds number (Re) is in the range $10^4$–$10^6$. The overall
number of considered combinations of rib and flow parameters is 651. The working fluid in all cases is air.

1.2. Grid generation

Computational domains consisting of a uniform quadrilateral mesh layout with approximately 230,000 cells are alike in all considered cases. The grid is concentrated near the wall to provide \( y^+ \) value between 30 and 60. Grid independence tests have been conducted for all domains showing less than 5% variation in Nusselt number and friction factor. An example of computational domain for rib parameters \( e/d=0.03 \), \( p/d=1 \) is represented in Figure 2.

![Figure 2. Close up view of the two-dimensional uniform mesh.](image)

1.3. Governing equations

It is assumed that the problem is described by the two-dimensional RANS equations and energy equation with the following assumptions: steady incompressible fluid flow, physical properties of working fluid is temperature independent.

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) + \frac{\mu T}{P_r} \frac{\partial T}{\partial x_j} \right]$$

Energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{P_r} + \frac{\mu T}{P_r T} \right) \frac{\partial T}{\partial x_j} \right]$$

To close equation (2) an additional component \( -\rho u_i u_j \) representing the Reynolds stresses is modeled by the Renormalization-group k-\( \epsilon \) model showing good results in numerous similar studies [5-8].

1.4. Calculation of major parameters

Three parameters of interest of the present study are Nusselt number, friction factor and thermal hydraulic performance parameter developed by Dreitser [1] and representing the ratio of the volumes of a heat exchanger with channels provided with enhancement means compared to a heat exchanger with similar plane channels.

Average Nusselt number is defined as:

$$Nu = \frac{h d}{\lambda}$$
where \( h \) is a convective heat transfer co-efficient and \( \lambda \) is air thermal conductivity.

The friction factor is computed by pressure drop \( \Delta P \) and can be obtained by:

\[
f = \Delta P \cdot \left[ \frac{l}{a} \left( \frac{\rho v^2}{2} \right) \right]^{-1}
\]  
(5)

Thermal hydraulic performance parameter:

\[
\text{Thermal hydraulic performance} = \left(\frac{Nu}{Nu_m}\right)^{1.4} \left(\frac{f}{f_m}\right)^{0.4}
\]  
(6)

Where \( Nu_m \) and \( f_m \) are Nusselt number and friction factor for a smooth tube respectively which has been taken from additional calculations of a smooth tube model.

1.5. Artificial neural network (ANN) approach

Using artificial neural networks for predicting data with a non-linear correlation between inputs and outputs is a powerful approach requiring less time and machine sources than CFD and showing good performance in numerous engineering studies [13-14]. In the present study, a deep feed-forward neural network with two hidden layers of neurons with a hyperbolic tangent activation function is chosen to predict the Nusselt number and friction factor. A schematic diagram of the ANN is shown in Figure 4.

Train data of 651 CFD simulations are divided into train and validation datasets with 520 and 131 data rows respectively. The inputs (rib pitch-to-diameter ratio, height-to-diameter ratio, and flow Reynolds number) are normalized in the range [0; 1] for better convergence. The number of neurons in hidden layers is varied to find the best solution. Optimal weights and biases in each case are determined using Adam [15] optimization method.

Figure 3. A schematic diagram for the deep feed-forward neural network

2. Results and discussion

Results on Nusselt number and friction factor obtained from 651 CFD simulations are summarized by power-law correlations as follows:

The Nusselt number

\[
\frac{Nu}{Nu_{r.n}} = 4(h/D)^{0.29} (t/D)^{-0.07} Re^{0.003} ,
\]  
(7)

Friction factor

\[
\frac{\xi}{\xi_{r.n}} = 8.2(h/D)^{1.03} (t/D)^{-0.23} Re^{0.227} ,
\]  
(8)
The mean average error of prediction for Equations (7-8) is 12%.

The same data has been normalized and proceeded to deep ANN. The number of neurons in hidden layers are varied to obtain a minimum of mean square error (MSE) calculated as follows:

\[ \text{MSE} = \frac{1}{n} \sum_{i=1}^{n} (y_i - \tilde{y}_i)^2 \]  

(9)

where \( y_i \) is a predicted value, \( \tilde{y}_i \) is a CFD modeled value.

The least MSE of \( 1.8 \times 10^{-4} \) on the validation dataset is obtained after 1459 epochs for ANN with 16 and 8 neurons in the first and the second hidden layers respectively. The training progress of the current ANN is represented in Figure 5.

![Figure 4. Variation of MSE with epoch number for training and validation datasets.](image)

As it is known from [2-3] artificial roughness elements cause turbulization of the flow in the wall layer, boundary layer separation, and vortex formation. The number of vortexes between ribs depends only on the rib relative pitch (p/e). Figure 6 shows streamlines for flow Reynolds number of Re=40,000 and relative roughness pitch ratios p/e=10 (Figure 6a) and p/e=5 (Figure 6b). From Figure 6a two vortexes are seen while from Figure 6b there is only one vortex.

Effect of the rib height-to-diameter ratio (e/d) on relative Nusselt number, friction factor, and thermal hydraulic performance is shown in Figure 7 (a, b and c) along with ANN predictions and power-law Equations (7-8). Figure 7(a, b) shows that the relative Nusselt number and friction factor increase with increasing of rib height. From Figure 7c it can be seen a non-linear correlation between roughness height and thermal hydraulic performance which reaches a maximum at e/d=0.04. The same result is reported by Kalinin et. al [3], but CFD results are under-predicted.

![Figure 5. Streamlines for relative pitch ratio (a) p/e=10 (b) p/e=5.](image)
Figure 6. Variation of enhanced heat transfer characteristics with roughness height-to-diameter ratio:
(a) relative Nusselt number (b) relative friction factor (c) thermal hydraulic performance.

Figure 8 (a, b) shows the variation of relative Nusselt number and friction factor as a function of rib pitch-to-diameter ratio p/d along with ANN predictions (solid lines) and power-law equations (dashed lines) for different rib height. It can be seen that both the Nusselt number and friction factor reach maximum nearby the relative pitch-to-height ratio of p/e=10. These results are in good agreement with experimental results reported by Kalinin et. al [2]. The same is predicted by the ANN while the power-law correlations are showing just a monotonous decrease of both values.

Effect of the flow Reynolds number Re on relative Nusselt number and thermal hydraulic performance is shown in Figure 9 for different height ratios along with ANN predictions. It is observed that the relative Nusselt number mostly decreases with increasing Reynolds number. The best performance is shown for Re<100,000 and optimal Reynolds number is the smaller the greater the rib height. The same result is reported by Lobanov [4].

3. Conclusions
A 2-dimensional CFD analysis has been carried out to study heat transfer enhancement in a circular tube with artificial roughness. Data on Nusselt number, friction factor, and thermal hydraulic performance is in good agreement with experimental data reported in [2-3] and numerical analysis reported in [4]. The effect of rib height (e/d), pitch (p/d), and relative pitch (p/e) and flow Reynolds number is discussed. The ANN is trained and used along with the power-law correlations for modeling Nusselt number and friction factor. The following conclusions are drawn from the present analysis:

- It is found that the transverse rib roughness parameters e/d=0.05 and p/d=1 provides better thermal hydraulic performance for the studied range of Reynolds number. The highest performance of 156% is obtained for Re=10,000.
It is shown that results on the Nusselt number and friction factor modeled by the artificial neural network are 5 times more accurate than those obtained with the power-law correlations Equation (7-8).

The result demonstrates that ANN can offer a powerful approach with a low computational cost for modeling enhanced heat transfer and flow characteristics based on CFD simulations or experimental data.

Figure 7. Variation of enhanced heat transfer characteristics with pitch-to-diameter ratio for different rib height (a) relative Nusselt number (b) relative friction factor.

Figure 8. Variation of enhanced heat transfer characteristics with flow Reynolds number for different rib height (a) relative Nusselt number (b) thermal hydraulic performance.
The trained ANN of the present study can be used for searching optimal transverse rib roughness parameters for a circular tube based only on the considered range of Reynolds number with no need of repeating any simulations or experiments and hence has a perspective of industrial application.

References

[1] Dreitser G A 2006 Problems in developing highly efficient tubular heat exchangers Therm. Eng. 53 279–87
[2] Kalinin E K, Dreitser G A and Yarkho S A 1990 Intensification of heat transfer in channels (Moscow: Mashinostroenie)
[3] Kalinin E K, Dreitser G A, Kopp I Z and Myakochin A S 1998 Efficient Heat-Transfer Surfaces (Moscow: Energoatomizdat)
[4] Lobanov I E 2020 Modelling Heat Exchange Depending on the Prandtl Number for Various Geometric and Regime Parameters Herald of Dagestan State Technical University Technical Sciences 46 91-101
[5] Vijiapurapu S and Cui J 2010 Performance of turbulence models for flows through rough pipes Appl. Math. Model. 34 1458–66
[6] Yadav A S and Bhagoria J L 2014 Heat transfer and fluid flow analysis of an artificially roughened solar air heater: a CFD based investigation Frontiers in Energy 8 201–11
[7] Ozceyhan V, Gunes S, Buyukalaca O and Altuntop N 2008 Heat transfer enhancement in a tube using circular cross sectional rings separated from wall Appl. Energy 85 988–1001
[8] Selvaraj P, Sarangan J and Suresh S 2013 Computational fluid dynamics analysis on heat transfer and friction factor characteristics of a turbulent flow for internally grooved tubes Thermal Science 17 1125–37
[9] Boulemtafes-Boukadoum A and Benzaoui A 2014 CFD based Analysis of Heat Transfer Enhancement in Solar Air Heater Provided with Transverse Rectangular Ribs Energy Procedia 50 761–72
[10] Desrues T, Marty P and Fourmigué J F 2012 Numerical prediction of heat transfer and pressure drop in three-dimensional channels with alternated opposed ribs Appl. Therm. Eng. 45-46 52–63
[11] Singh A and Singh S 2017 CFD investigation on roughness pitch variation in non-uniform cross-section transverse rib roughness on Nusselt number and friction factor characteristics of solar air heater duct Energy 128 109–27
[12] Vahidifar S and Kahrom M 2015 Experimental Study of Heat Transfer Enhancement in a Heated Tube Caused by Wire-Coil and Rings Journal of Applied Fluid Mechanics 8 885-92
[13] Elsayed K and Lacor C 2011 Modeling, analysis and optimization of aircyclones using artificial neural network, response surface methodology and CFD simulation approaches Power technology 212 115-33
[14] Castellani F, Burlando M, Taghizadeh S, Astolfi D and Piccioni E 2014 Wind energy forecast in complex sites with a hybrid neural network and CFD based method Energy Procedia 45 188–97
[15] Kingma D P and Ba J 2015 Adam: A Method for Stochastic Optimization ICLR 1-15