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Performance predictions of laminar heat transfer and pressure drop in an in-line flat tube bundle using an adaptive neuro-fuzzy inference system (ANFIS) model☆

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A R T I C L E   I N F O

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A B S T R A C T

This paper shows how to predict the heat transfer and pressure drop for in-line flat tube configuration in a crossflow, using an adaptive neuro-fuzzy inference system (ANFIS). A numerical study of a 2D steady state and incompressible laminar flow for in-line flat tube configuration in a crossflow is also considered in this study. A finite volume technique and body-fitted coordinate system is used to solve the Navier–Stokes and energy equations. The Reynolds number varies from 10 to 320. Heat transfer and pressure drop results are presented for a tube configuration at transverse pitch and longitudinal pitch. The variation in velocity profile, isotherm contours and streamlines were compared for various configurations. The predicted results for average Nusselt number and dimensionless pressure show a good agreement with available previous work. The accuracy between numerical values and ANFIS model results were obtained with a mean relative error for average Nusselt number, pressure drop less than 1.9% and 2.97% respectively. Therefore, the ANFIS model is capable of predicting the performance of thermal systems in engineering applications, including the model of the tube bundle for heat transfer analysis and pressure drop.

1. Introduction

The fluid flow and heat transfer in tube banks represent an application of many industrial significant processes [1]. Tube bundles are employed widely in cross-flow heat exchangers, and their design is still based on empirical correlations of heat transfer and pressure drop. Heat exchangers with tube banks in cross-flow are of great practical interest for many thermal and chemical engineering processes. The effects of tube shape and geometric configuration on the heat transfer and flow-field performance of these devices have been studied using various analytical numerical and experimental techniques [2–4]. Flat tube designs have been newly introduced for use in modern heat exchanger applications, such as automotive radiators. Flat tubes seem to have appropriate pressure drop characteristics compared to circular tubes. In addition, owing to the smaller wake size compared with circular tubes, flat tubes have good noise and vibration characteristics [5]. In the numerical analysis of 2D steady laminar forced convection in circular cylinder banks of tube using the square and non-square in-line arrangements, the study presents the maximum heat transfer rate at first tube compared with the other tubes. Also, the pressure drop increases significantly as the transverse pitch-to-diameter ratio is reduced [6]. The flow over elliptic cylinders bank of tubes is presented in Yianneskis et al. [7], both numerically and experimentally. Jang et al. [8] studied 3D numerical study heat transfer and fluid flow, over a plat-finned tube heat exchanger, at laminar flow. The effect of geometrical parameters including the tube row numbers, tube arrangement and fin pitch studied for the Reynolds number range from 60 to 900. The study shows that the average heat transfer coefficient increase of 15%–27% and the pressure drop increase of 20%–25% at the staggered arrangement are compared with in-line arrangement, respectively. The forced convection heat transfer over a bundle of circular cylinder was investigated numerically, and solved the governing equation by a finite difference method. Furthermore, the thermal boundary condition, a constant heat flux on the surface of the tube, or a constant surface temperature, and the Reynolds number varied in the range of 1–500. The results of the Nusselt number on the surface of the tube were presented [9]. Tahseen et al. [10–12] did numerical studies on a steady state incompressible flow, using the body fitted coordinate (BFC). The studies include heat transfer over staggered circular tube banks, the second study heat transfer over a two-flat tube for staggered configurations and the heat transfer over a series of flat tubes between two parallel plates. The two studies show the effect of the Reynolds number on the Nusselt number. The Nusselt number increases along with increases in the Reynolds number. Wung and Chen [13] developed a numerical analysis both of in-line and staggered tube arrangements, with the

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Nomenclature

C_p	specific heat capacity at constant pressure, kJ/kg K
d	small diameter of tube, m
D	longitudinal tube diameter, m
D_h	hydraulic diameter of tube, m
G_1, G_2	contravariant velocity components
J	Jacobian of the transformation
$\bar{h}$	average heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
Nu	average Nusselt number
P	pressure, Pa
Pr	Prandtl number
Re	Reynolds number
S	source term
S_1	longitudinal pitch, m
S_2	transverse pitch, m
S_1^*	longitudinal pitch-to-small diameter of tube
S_2^*	transverse pitch-to-small diameter of tube
T	temperature, °C
u, v	velocity components, m/s
U, V	dimensionless velocity
x, y	Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates

Greek symbols

α, β, γ	the coefficients of transformation
μ	dynamic viscosity, kg/m s
υ	kinematic viscosity, m^2/s
θ	dimensionless temperature
ρ	density, kg/m
ζ, η	curvilinear coordinates
ϕ	general dependent variable
ΔP^*	dimensionless pressure drop in cross flow

Subscripts

out	out
∞	free stream

transverse and longitudinal pitches fixed at 2. Using the finite analytic method to solve the governing equations, the solutions at the Reynolds numbers ranged from 40 to 800. The main results show that the zone of separation for both configurations increased with the increase in the Reynolds number. The experimental study of the heat transfer and pressure drop was done on the staggered flat tube banks. The Reynolds number varied from 373 to 623 and the heat flux supplied changes from 967.92 to 3629.7. The pressure drop increases and the dimensionless pressure drop decreases with an increase in the Reynolds number. The result of the study shows that the average Nusselt number increased by 11.46%–46.42% [14].

Artificial neural networks (ANNs) have been used in many engineering applications because they provide better and more reasonable solutions [15,16]. The study carried out using a feed-forward back-propagation ANN by Ermis et al. [17] to analyze the heat transfer of phase change process around a finned tube. The experimental mean relative error of 5.58% while the numerical model ends up at 14.99% in the ANN model.

Fadare and Fatona [18] studied ANN in the modeling of a staggered multi-row, multi column, cross-flow, tube-to-tube heat exchanger, as well as the experimental data for air flow over a bundle of tubes. The results show that the mean absolute relative error is less than 4%, and 1% for the test and training data sets, respectively. In addition, the study suggests that the ANNs model can, therefore, be used as a modeling tool for the primary design of heat exchangers. Islamoglu and Kurt [19] used the ANNs model for heat transfer in a corrugated channel. The experimental data set is used in the ANN model. The error between the experimental results and the ANN approach is the approximation of the mean absolute relative error less than 4%. Rezaei et al. [20] showed the effects of partition angle and Rayleigh number on the heat transfer in the partition cavity, using the adaptive neuro-fuzzy inference system (ANFIS) of natural convection. The training data for optimizing the ANFIS structure is obtained experimentally. The results show that the mean relative errors were estimated at 0.005% and 1.735% for the test and train data, respectively. The ANN was also used by Sözbir [21] for the prediction of experimental unsteady heat transfer at a rectangular duct. The ranges of Reynolds number are from 1120 to 2200, and the heat input frequency is between 0.02 and 0.24 Hz. The accuracy between experimental and ANNs is in good agreement with the mean absolute relative error that is less than 39%. Tahavvor and Yaghoubi [22] were studied using ANN technique to determine free convection fluid flow and heat transfer around a cooled horizontal circular cylinder. The Rayleigh number ranges between 106 and 108. The code of ANN is compared with the CFD code for a study of general induced convection from cold cylinders, which is higher than 9%–25% for hot cylinders with the same Rayleigh numbers. At high Rayleigh numbers, buoyancy is a dominant effect that overcomes gravitational acceleration. The heat transfer analysis of shell and tube heat exchanger for ANN is explained by Xie et al. [23]. The forced convection from the v-shaped plate under the influence of an air slot trauma jet directed at the inner surface used the adaptive neuro-fuzzy model [24]. The ANN and ANFIS models were used by Varol et al. [25] to predict the free convection and fluid flow in a triangular space, with the bottom side heated and the sloping side always cooling, whereas the vertical side remained adiabatic. The Rayleigh number varied from 104 to 106 with the triangle ratio 0.5 and 1. Predictions obtained from the ANFIS appear more credible than ANN when compared with the true values of the numerical simulation, particularly at bigger Rayleigh numbers. Therefore, the present article aims to study the role of varied transverse and longitudinal pitch-to-small diameter of flat tube (circular tube) on the rate of heat transfer and pressure drop from the in-line flat tube bank.

This study uses a finite-volume method to solve the continuity, momentum and energy conservation equations for steady, two-dimensional laminar cross-flow. The computational domain is derived by assuming symmetry along lines in the longitudinal directions, through the centers above the flat tubes and the centers below the flat tubes. However, this study also focuses on the applicability of adaptive neuro-fuzzy inference system (ANFIS) model for heat transfer analysis and pressure drop over the in-line flat tube bank, utilizing heat exchangers in the design to promote heat transfer. The results are presented for the friction factor and average Nusselt number, for three different geometric configurations—the longitudinal pitch-to-small diameter ratios 2, 4 and 6, as well as for the four different geometric configuration transverse pitch-to-small diameter ratios between 1.5 and 4.5. The Prandtl number fixed at 0.71 in Reynolds varied between 10 and 320. In this study, the Reynolds number is based on the hydraulic diameter of flat tube and the uniform velocity at the inlet of the domain.

2. Mathematical formulation

Four isothermal heated horizontal flat tubes in a row are considered in this study. The flat tube has two diameters including the transverse d and longitudinal D, the surface temperature of tube T_s, placed in the velocity U_∞ and the uniform free stream of temperature T_∞ in the in-line arrangements. The longitudinal pitch-to-small diameter ratio is $S_1^* = S_1/d$ and the transverse pitch-to-small diameter ratio is $S_2^* = S_2/d$. The flat tube is long enough so that the end effect of tube can be