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Numerical simulation and sensitivity analysis of heat transfer enhancement in a flat heat exchanger tube with discrete inclined ribs

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In this work, we propose a numerical study of the thermal-hydraulic performance in a novel flat heat exchanger tube with discrete inclined ribs. Analysis of flow structures shows that four longitudinal swirl flows are induced in the flat tube. These swirl flows lead to adequate fluid mixing between the core flow and the near wall regions, and consequently, improve the heat transfer performance significantly. To determine the effects of parameters such as Reynolds number ($300 \leq Re \leq 1500$), the rib pitch ratio ($0.6 \leq P* \leq 1.8$), and the rib height ratio ($0.06 \leq H* \leq 0.18$) on the thermal and flow performance, a sensitivity analysis has been carried out by means of Response Surface Methodology. It is found that a reducing of $P*$ and an increase in $H*$ causes an increment in the Nusselt number and friction factor. The highest values of the Nusselt number and friction factor are achieved at $P* = 0.6$ and $H* = 0.18$ when Re is held at 900. Besides, the Nusselt number is more sensitive to Re and $H*$ while the friction factor is more sensitive to $P*$. The findings from this work may provide useful guidelines for engineers and researchers to design efficient heat exchangers.

1. Introduction

Heat exchangers, which make heat exchange possible between fluids, are widely used in various engineering applications such as air conditioning, refrigeration systems, solar collectors, and automotive radiators. To meet the ever-increasing thermal load and design compact heat exchangers for applications in the fields where space is strictly restricted, many researchers have proposed and investigated different enhanced heat transfer techniques during the past few years. The high surface area to the cross-sectional area ratio of flat tubes makes them superior to circular tubes in attempts to enhance the heat transfer rate and reduce the size of heat exchangers [1]. Hence, replacing circular tubes used in heat exchangers with flat tubes is an impressive technique for efficient heat exchangers.

In the field of using flat tubes, some investigations have been performed to further intensify their thermal performance. Ibrahim [2] experimentally explored the flow and heat transfer behaviors in a flat tube with helical screw-tape. Their results indicated that the flat tubes with helical screw-tapes further intensify the thermal performance of flat tubes. Safikhani and Abbassi [3] examined the combined use of nanofluid and twisted tape to increase the heat transfer rate in flat tubes. They concluded that the twisted tape performed better than nanofluid on heat transfer enhancement. Abdolbaqi et al. [4] experimentally determined the turbulent flow and heat transfer in flat tubes with counter-twisted tape and co-twisted tape. According to their results, both twisted tapes could improve the thermal performance of flat tubes, and the heat transfer performance for co-twisted tape was about 22.5% worse than that of counter-twisted tape. The application of nanofluids for heat transfer enhancement considering their superior thermal physical properties was the subject of investigation in several studies such as Vajjha et al. [5] determined the Al_2O_3 and CuO nanofluid flow and heat transfer in flat tubes of an automotive radiator by numerical simulation. The results showed an increase in particle volume concentration led to an enhancement in heat transfer coefficient and skin friction coefficient. Safikhani and Abbassi [6] presented the influence of tube flattening on the flow structures and thermal performance of nanofluids by numerical simulations. They found that both wall shear stress and heat transfer rate increased with the increment of tube flattening. Delavari et al. [7] numerically explored the nanofluid flow and heat transfer in flat tubes of a car radiator. Zhao et al. [8] evaluated the thermal performance of Al_2O_3–water nanofluids in a flat tube using entropy generation analysis. They found that tube flattening presented a more profound influence on the thermal performance than nanofluids. Multi-objective optimization of effective parameters

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Nomenclature

a	width of a flat tube (mm)
ANOVA	analysis of variance
ANN	artificial neural network
b	height of a flat tube (mm)
b_0	the intercept
CFD	computational fluid dynamics
C_p	specific heat (J kg^{-1} K^{-1})
E	rib length (mm)
D_h	hydraulic diameter of a flat tube (mm)
f	friction factor
GA	genetic algorithm
H	rib height (mm)
h	heat transfer coefficient (W m^{-2} K^{-1})
$H*$	non-dimensional height ratio ($H* = H/D_h$)
k	thermal conductivity (W m^{-1} K^{-1})
L	length of a flat tube (mm)
Nu	Nusselt number
P	rib pitch (mm)
$P*$	non-dimensional pitch ratio ($P* = P/D_h$)
p	pressure (Pa)
q	heat flux (W m^{-2})
RSM	response surface methodology
R^2	coefficient of multiple determination
Re	Reynolds number
T	temperature (K)
U	velocity (m s^{-1})
W	rib width (mm)

Greek symbols

α	rib inclination angle (°)
ε	error
ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})

Subscripts

m	mean
w	wall

on nanofluids flow in flat tubes was carried out by Safikhani et al. [9] by computational fluid dynamics (CFD), artificial neural network (ANN), and genetic algorithm (GA).

Utilizing ribs or fins is another effective technique for heat transfer enhancement [10]. Sayed Ahmed et al. [11] conducted a comprehensive review on the flow and heat transfer characteristics in finned tube heat exchangers. Later, Sayed Ahmed and his co-workers [12,13] numerically examined and analyzed the influence of longitudinal fins on the thermal-hydraulic behavior for wing-shaped-tubes in cross-flow. Ghani et al. [14] applied the rectangular ribs and cavities to enhance the thermal performance in a microchannel heat sink. Staggered 45-deg ribs were proposed by Deng et al. [15] to increase the heat transfer performance in a rotating channel. The results indicated that heat transfer was enhanced by 40–80% with the use of the ribs. Yang et al. [16] experimentally determined the heat transfer and pressure drop behavior in a square channel with high blockage ribs. It was found that the thermal performance in the two-side ribbed channel was much higher than that in the one-side ribbed channel. Xie et al. [17] presented numerical simulations to study the turbulent heat transfer in a square channel with mid-truncated ribs. Their results showed that the 135° mid-truncated ribs provided the best heat transfer enhancement. Arc rib structures were introduced and examined in a channel by Wang et al. [18]. Chai et al. [19] numerically examined the thermal-hydraulic performance of laminar flow in a microchannel with offset ribs. The idea of discrete double-inclined ribs was, firstly, introduced based on heat transfer optimization by Meng [20]. It was found that multiple longitudinal vortexes were induced by the ribs. These unique flow structures were later visualized by Li et al. [21] with the aid of dying injection experiments. Wang et al. [22] analyzed the laminar heat transfer in a mini-channel with discrete double-inclined ribs. According to their results, ribs enhanced the thermal performance effectively. Zheng et al. [23] numerically explored the turbulent heat transfer performance in a tube with discrete inclined ribs and grooves based on the entropy generation analysis.

According to the literature survey, flat tubes and ribs are two effective techniques for heat transfer enhancement. However, the combined use of them has rarely been reported. The lack of information about this investigation has prompted the present work. In this paper, we propose the combined utilization of flat tubes and discrete inclined ribs to enhance the thermal-hydraulic performance. Numerical simulations and sensitivity analysis of parameters such as the Reynolds number, the rib pitch ratio, and the rib height ratio on the heat transfer and flow performance in the proposed flat tube have been performed by Response Surface Methodology (RSM), which has been proven very practical for solving thermal problems [24–35]. The findings from this work may provide convenient guidelines for engineers and researchers to design efficient heat exchangers.

2. Physical model

The physical model considered in this work is presented in Fig. 1. The flat tube is the same as the one in [8], which has a length (L) of 500 mm, a width (a) of 12.28 mm and height (b) of 6 mm. Also, the hydraulic diameter (D_h) of the flat tube is 8.4 mm. Discrete and inclined ribs are mounted on the two flat walls. The main geometric characteristics of these ribs are rib width (W), rib inclination angle (α), rib pitch (P), rib length (E) and rib height (H). In addition, the distance between the rib and the central axis of the flat tube is 1.17 mm, and the distance between the rib and the inlet of the flat tube is 3 mm. The non-dimensional rib pitch ratio ($P* = P/D_h$) and height ratio ($H* = H/D_h$) are fixed as the proportions of the rib pitch and rib height to the hydraulic diameter of the flat tube, respectively. More details about the geometric parameters of the flat tube and ribs are shown in Table 1.

3. Mathematical model

3.1. Governing equations

The commercial CFD software ANSYS Fluent 15.0 [36] has been applied to perform the numerical analysis. The flow and heat transfer phenomenon considered in this paper is assumed steady, laminar, and three-dimensional. During the numerical simulation, the properties of water are held constant, and the effects of gravity, bubbles, and viscous dissipation are not taken into consideration. Based on the above assumptions, the governing equations are given as follows.

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho(\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} \tag{2}$$