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Numerical investigation on heat transfer performance and flow characteristics in enhanced tube with dimples and protrusions

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ABSTRACT

In the present investigation, a new design of enhanced tube aiming to improve heat transfer by employing dimples and protrusions was put forward. The special enhanced tube with dimples and protrusions is obtained by extruded the conventional plain tube. The objective is to present details of flow field characteristics and heat transfer mechanisms for the ETDP, then effects of protrusion depth, pitch and radius on thermal-hydraulic performance also being discussed. The operating Reynolds number ranged from 5000 to 30,000 and the validated realizable k-ε turbulence model was employed on the numerical simulations. The local streamlines, velocity contour, temperature contour and Nusselt number were presented to illustrate the heat transfer enhancement mechanisms. From this investigation, it is found that the varying geometric parameters of ETDP play an important role in thermal-hydraulic characterises. The main findings are that the ETDP have an advantage for augmented heat transfer rate and PEC compared with the plain tube, due to improved flow mixing, interrupted the boundary layer, formed periodic jet flows and swirl flows induced by dimples and protrusions. The Nusselt number and friction factor increase and *PEC* decrease with an increasing protrusion depth. Among the investigated different protrusion pitch, it is found that the friction factor first decrease and then increase with the increase of protrusion pitch. For varying the protrusion radius, the ETDP with $R = 3$ mm have the largest PEC at the most *Re*. Under operating condition and geometric parameters considered, the ETDP with $D = 3$ mm, $P = 30$ mm and $R = 4$ mm offers the largest PEC value of about 1.65.

1. Introduction

In many industrial applications, such as cooling towers, aerospace industries, oil and gas flow in reservoirs and chemical processing, heat exchangers play an important role in heating and cooling. However, to reduce the energy consumption and increase economic benefit, the traditional heat exchangers with plain tube are always not competent enough due to they have low and inefficient thermal performance. In order to overcome this problem, the technologies of heat transfer enhancement were put forward. According to whether it needs external additional power, the heat transfer enhancement technologies can be classified into active and passive. Generally, due to reliability in operation, low energy input and inexpensive cost in maintenance, the passive technologies have more wide applications and potential promise [1].

In passive technologies families, fins, ribs, twisted taps, wire coils, insert device, dimples, etc. are commonly used to enhance the heat transfer rate. The protrusions/dimples surface can improve the heat transfer performance with relatively low pressure loss penalty. Therefore, during a few decades, heat transfer enhancement technologies utilize protrusions/dimples surface have received much attention for enhancing heat transfer. Xie et al. [2] and Leontiev et al. [3] studied the flat with dimples, Zheng et al. [4] and Zahid et al. [5] investigated the plain tube with dimples. Chen et al. [6] and Vicente et al. [7] investigated heat transfer performance and friction factors of protruded tube by experiment. They proposed correlations for predicting the Nusselt number and friction factors. Thianpong et al. [8] conducted experimental work on dimpled tube with twisted tape inserts. The results show that the pitch ratio and twist ratio have the significant influence on heat transfer performance. Wang et al. [9,10] and Liang et al. [11] investigated the spherical dimpled tube and ellipsoidal dimpled tube by experiment and simulation. They reported that the ellipsoidal dimpled tube provides a better performance than spherical dimpled

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Nomenclature

A	heat transfer area, m^2
c_p	special heat, $J\ kg^{-1}\ K^{-1}$
D	protrusion depth, mm
D_h	equivalent diameter, mm
f	friction factor
P	protrusion pitch, mm
Pr	Prandtl number
p	pressure, Pa
Δp	pressure drop, Pa
m	mass flow rate, $kg\ s^{-1}$
Nu	Nusselt number
R	protrusion radius, mm
Re	Reynolds number
T	temperature, K
u	velocity, $m\ s^{-1}$
u^*	friction velocity
y^+	mesh resolution indicator

Greek symbols

ρ	fluid density, $kg\ m^{-3}$
μ	dynamic viscosity, Pa s
μ_t	turbulent viscosity
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
Φ	total heat rate, W
Θ	temperature gradient

Subscripts

i	inside
max	maximum
s	plain tube
ref	reference

tubes (Fig. 1a, b). Chang et al. [12] experimentally studied the heat transfer performance of plain tube and hexagonal duct with dimples (Fig. 1c). They suggested that the hexagonal duct with dimples provided the higher flow momentum compared to rectangular dimpled channels. Heo et al. [13,14] numerically studied the manufacturing process and thermal performance of flat with dimples. Garcia et al. [15] experimentally studied three types of enhancement techniques, consisting of inclined corrugate tubes, dimpled tubes and wire coils. Their study provided some recommendations for choosing an enhancement tube at different Reynolds numbers. Kumar et al. [16] experimentally studied the enhanced tube with the protruded surface (Fig. 1d). The results indicated that the protruded surface tube showed a significant enhancement in heat transfer rate and friction factor over conventional tube. Kukulka et al. [17] conducted experiments on dimpled tube which have been named EHT (Fig. 1e). They found that the EHT can enhancement the heat transfer rate, evaporation and condensation heat transfer coefficient. Li et al. [18,19] conducted experiment and simulation works on enhanced tube with dimples (Fig. 1f). The results indicated that the dimples could disturb and mix the boundary layer and generate secondary flows that improve the turbulence level. Shafaee et al. [20] and Mashouf et al. [21] experimentally studied thermal-hydraulic performance of helically dimpled tube (Fig. 1g). The experiment shows that the heat transfer coefficients of dimpled tube are 1.29–2 times larger than plain tube, and the dimples have significantly impacts on the two-phase flow pattern. Aroonrat et al. [22] experimentally studied investigates the heat transfer and pressure drop of R-134a during condensation inside a dimpled tube. They proposed correlations for predicting heat transfer and pressure drop in the two-phase condition (Fig. 1h).

Even though previous research work have shown that the addition of dimples or protrusions on tube can provide a realizable heat transfer enhancement with relatively low pressure loss penalty. However, only a few researchers pay attention to the ETDP (enhanced tube with both dimples and protrusions) at the same time. The main objective of the present study is to present a numerical investigation of thermal-hydraulic performance of ETDP at Re (Reynolds number) ranged from 5000 to 30,000. Flow field characteristics and heat transfer mechanisms of the ETDP are investigated under the single phase condition. Effects of protrusion depth, pitchs and radius on thermal-hydraulic performance also being discussed. Generally, this study may provide some theoretical guidelines and suggestions in potential application of the ETDP.

2. Physical model

Fig. 2 shows the research processing for constructed the ETDP geometric model. The geometric model of the ETDP is too complicate to construct by 3D (Three-dimensional) software, such as Por/E, UG, Solidwork. Therefore, plastic forming method is employed

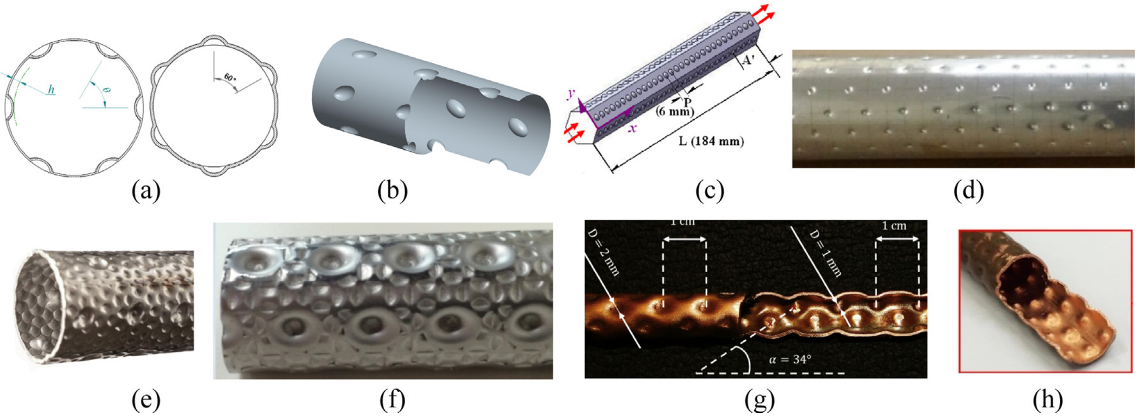

Fig. 1. The application of dimples on enhanced tubes: (a) dimpled and protruded tube [9]; (b) ellipsoidal dimpled tube [11]; (c) hexagonal ducts with dimples [12]; (d) protruded tube by Kumar et al.[16]; (e) EHT tubes [17]; (f) enhanced dimpled tube by Li et al.[18]; (g) helically dimpled tube by Shafaee [20]; (h) dimpled tube by Aroonrat Li et al. [22].