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A numerical study on heat transfer enhancement and flow structure in enhanced tube with cross ellipsoidal dimples

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ABSTRACT

Flow characteristics and heat transfer performance of enhanced tube with cross ellipsoidal dimples are numerically analysed in this research work. The special arrangement is a conventional plain tube with longitudinal and transverse dimples at each cross-plane. The objective is to present details of flow field structure and heat transfer mechanisms for the dimpled tube. Additionally, effects of dimples depth, pitch and axis ratio on thermal–hydraulic performance also being discussed. The realizable k-ε turbulence model was employed in the numerical simulations with the *Re* range from 5000 to 30,000. The velocity contour, temperature contour, local streamlines, velocity vectors and *Nu* were presented to illustrated the heat transfer enhancement mechanisms. From this investigation, it is found that the transverse and longitudinal dimples cause downward flow, improve the flow mixing and reattachment, interrupt the boundary layer and form periodic impingement flows and then greatly improve the heat transfer. *Nu* of TCED increase with the increase of depth and axis ratio, and decrease with increase of pitch. Under operating condition and geometric parameters considered, the TCED with D = 2 mm, P = 20 mm, R = 2.2 and Re = 5000 obtained the largest *PEC* value about 1.58.

1. Introduction

In many industrial applications, such as cooling towers, aerospace industries 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 widely applications and potential promise [1].

For enhanced the heat transfer rate, several investigations have been carried out in passive technologies, including fins, ribs, twisted taps, wire coils, insert device, nanofluid, turbolentor and dimples, etc. [2,3]. 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. [4] and Leontiev et al. [5] studied the flat with dimples, Huang et al. [6] and Zahid et al. [7] investigated the enhanced tube with dimples. Wang et al. [8,9] and Liang et al. [10] 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 tubes (Fig. 1a and b). Chang et al. [11] experimentally studied the heat transfer performance of plain tube and hexagonal duct with dimples (Fig. 1c). Kumar et al. [12] 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. Zheng et al. [13] numerically studied the heat exchanger with discrete double inclined ribs (Fig. 1e). The results showed that the counter rotating vortices or longitudinal swirl flows were generated inside the tube. Zheng et al. [14] investigated the heat transfer performance in the circular and annular microchannel with dimples/protrusions (Fig. 1f). Kukulka et al. [15] conducted experiments on dimpled tube which have been named EHT (Fig. 1 g). They found that the EHT can enhancement the heat transfer rate, evaporation and condensation heat transfer coefficient. Li et al. [16,17] conducted experiment and simulation works

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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, ms^{-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

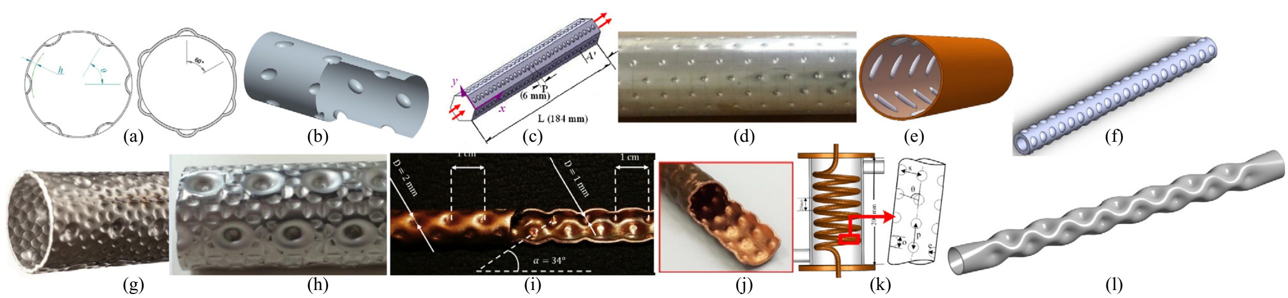

Fig. 1. The application of dimpled/protruded tubes: (a) dimpled and protruded tube [8]; (b) ellipsoidal dimpled tube [10]; (c) hexagonal ducts with dimples [11]; (d) shallow dimpled surface [12]; (e) discrete double inclined ribs [13]; (f) microchannel with protrusions [14]; (g) EHT tubes [15]; (h) dimpled surface by Li et al. [16]; (i) helically dimpled tube [18]; (j) dimpled surface by Aroonrat Li et al. [20,21]; (k) coiled tube with dimples [22]; and (l) enhanced tube with dimples and protrusions by Xie et al.[25].

on enhanced tube with dimples (Fig. 1h). 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. [18] and Mashouf et al. [19] experimentally studied thermal-hydraulic performance of helically dimpled tube (Fig. 1i). 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 and Wongwises et al. [20,21] experimentally studied investigates the heat transfer and pressure drop of R134a during condensation inside a dimpled tube (Fig. 1j). They proposed correlations for predicting heat transfer and pressure drop in the two-phase condition. Anand et al. [22] measured experimentally the heat transfer enhancement using dimple helically coiled tube. They discussed the transitions between different flow regimes, heat transfer coefficients and pressure drops (Fig. 1k). Chen et al. [23] and Vicente et al. [24] investigated heat transfer performance and friction factors of protruded tube by experiment. They proposed correlations for predicting the Nusselt number and friction factors. Xie et al. [25] numerically studied the enhanced tube with both dimples and protrusions (Fig. 1l). Similarly, Thianpong et al. [26], Garcia et al. [27] who worked on different dimpled or protruded tubes.

Previous research work showed that the enhanced tube with dimples/protrusions has a realizable heat transfer performance with relatively low pressure loss penalty. However, no investigations have been reported for the new designed of TCED (enhanced tube with cross ellipsoidal dimples). The main objective of this study was to provide a numerical investigation of thermal-hydraulic performance for the novel dimpled tubes at Reynolds number ranged from 5000 to 30,000. Flow field structure and heat transfer mechanisms of the TCED are investigated under the single phase condition. Effects of dimples depth, pitch and axis ratio on thermal-hydraulic performance also being discussed. Generally, this study may provide some theoretical guidelines and suggestions in the potential application of the TCED.

2. Physical model and numerical method

2.1. Physical model

Fig. 2 shows geometric schematic diagram of the TCED which used in the present research work. The cross ellipsoidal dimples mounted on the tube surface and the diameter of the plain tube is 19 mm. In addition, the cross ellipsoidal dimples contained four longitudinal and transverse dimples at each cross-plane, and parameters of the longitudinal and transverse dimples are equal. The main deign parameters contain dimple depth $\boldsymbol{D}$, dimple pitch $\boldsymbol{P}$ and axis ratio $\boldsymbol{R}$ (R = a/b, where $\boldsymbol{a}$ is the ellipse minor axis and is an invariant constant, $\boldsymbol{b}$ is major axis). The primary parameter is $\boldsymbol{D}$ = 1.7 mm, $\boldsymbol{P}$ = 20 mm, $\boldsymbol{R}$ = 2 ($\boldsymbol{a}$ = 4 mm, $\boldsymbol{b}$ = 8 mm), while various arrangements for different cases are presented in Table 1.