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Improving the thermal hydraulic performance of a circular tube by using punched delta-winglet vortex generators

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ABSTRACT

A new circular tube with delta-winglet vortex generators is proposed in order to improve the thermal hydraulic performance for energy conservation. The delta-winglet vortex generators are punched out from the fin which inserted in the center of the circular tube. Three-dimensional numerical investigation is performed to study the thermal hydraulic characteristics of the circular tube with delta-winglet vortex generators. The effects of attack angle (β = 15 deg, 30 deg, 45 deg, and 60 deg) and pitch ($P = 1D$, $P = 2D$, $P = 3D$, and $P = 4D$) of delta-winglet vortex generators on heat transfer and fluid flow are examined in detail. The mechanism of heat transfer enhancement is analyzed based on the viewpoint of field synergy principle. The results demonstrate that delta-winglet vortex generators generate swirling motion of flow to enhance the fluid flow mixing in circular tube resulting in heat transfer augmentation with a moderate pressure drop penalty. It was found that the Nusselt number increase with the increasing attack angle and decreasing pitch of the delta-winglet vortex generators. The mechanism of heat transfer enhancement in circular tube by using delta-winglet vortex generators can be well explained by field synergy principle.

1. Introduction

Heat exchangers are widely used in heating, ventilation, air conditioning, and refrigeration (HVACR) system. Improving the performance of heat exchangers is crucial to meet energy costs and environment impact. As the basic heat transfer elements, heat transfer tube play a important role for the integrated performance of heat exchangers. Hence, enhancing heat transfer for heat transfer tube is of great significance for energy conservation and environmental protection. Many kinds of enhanced heat transfer tubes such as corrugated tube [1–4], grooved tube [5–7], dimpled tube [8,9] and tube with twisted tapes [10–13] have been designed and investigated for heat transfer augmentation. It is obvious that the penalty of pressure drop is associated with heat transfer enhancement, which causes the increase of pumping power. Therefore, the proper strategy of heat transfer enhancement is challenging task to increase heat transfer coefficient with a reasonable increase of pressure drop penalty.

Appling wing-type vortex generators, which can be mounted or punched on the heat transfer surface, is a innovation strategy to augment heat transfer with small increases of pressure drop penalty. Longitudinal vortices can be generated by the utilization of the wing-type vortex generators causing boundary layer modification, flow swirl and destabilization that resulting in heat transfer enhancement [14–17]. The early report of utilization of vortex generators on heat transfer was presented by Johnson and Joubert [18]. Since then, the investigations of the heat transfer impact of vortex generators have been carried out extensively. In general, the vortex generator can be divided into wing and winglet. The span of wing is attached to the wall and the chord of winglet is attached to the wall. It was found that the type of winglet cause higher heat transfer enhancement at same pressure drop [19–21]. So, the use of winglet-type vortex generators for heat transfer augmentation has received considerable attentions. Over the past several decades, winglet-type vortex generators for heat transfer enhancement in channel and fin-and-tube heat exchanger have been studied numerically and experimentally.

There are many investigations of heat transfer characteristics and fluid flow structure in channel with winglet-type vortex generators. Deb et al. [22] carried out numerical studies on heat transfer performance and flow structure of laminar and turbulent flows in a rectangular channel with built in delta winglets. Biswas et al. [23] studied the flow structure and heat transfer effects of

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Nomenclature

A	heat transfer area of tube (m^2)
a	length of delta-winglet vortex generator (m)
b	height of delta-winglet vortex generator (m)
C_p	specific heat (J kg^{-1} K^{-1})
D	tube diameter (m)
f	friction factor
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number
P	pitch of delta-winglet vortex generator
p	pressure (Pa)
Δp	pressure drop in flow direction (Pa)
Pr	Prandtl number
Q	heat transfer capacity (W)
Re	Reynolds number
T	temperature, K
ΔT_m	log-mean temperature difference (K)
u, v, w	x, y, z velocity components (m s^{-1})
$\vec{u}$	velocity vector
x, y, z	Cartesian coordinates

Greek symbols

β	attack angle (deg)
θ	the local intersection angle (deg)
μ	dynamic viscosity (Ns m^{-2})
ρ	density (kg m^{-3})

Subscripts

m	average value
in	inlet parameter
out	outlet parameter
w	wall conditions

longitudinal vortices produced by a delta winglet in a fully developed laminar channel. A performance quality factor was also defined to indicate the heat transfer enhancement at a given pressure loss penalty. The thermo-chromatic liquid crystal was used to measure the local heat transfer coefficient for a pair of embedded delta winglets by Kim and Yang [24]. They found that the common-flow-down cases has better heat transfer performance than the common-flow-up cases. Hiravennavar et al. [25] numerically simulated flow structure and heat transfer enhancement in a hydrodynamically developed and thermally developing laminar channel with a delta winglet pair of non-zero thickness. They found that a winglet of finite thickness is superior to the idealized zero thickness winglet. Yang et al. [26] numerically studied the effect of the common-flow-up winglet-type vortex generators on flow structure and heat transfer in a rectangular channel. Secondary velocity vectors and turbulent kinetic energy contours of the common-flow-up pair were reasonably predicted. Tian et al. [27] conducted a numerical investigation to compare the laminar heat transfer and fluid flow characteristics of a channel with delta winglet pair and rectangular winglet pair. The results also indicated that the channel with delta winglet pair show better overall performance than rectangular winglet pair. Promvonge et al. [28] experimentally studied the air flow friction and heat transfer in a constant heat flux channel fitted with the combined triangular rib and delta winglets for the turbulent regime. They reported that utilizing both the triangular rib and delta winglets causes considerable heat transfer augmentations with moderate pressure drop. Min et al. [29] proposed a new combined longitudinal vortex generator, which consist of a rectangular wing mounted with an accessory rectangular wing. Wu and Tao [30] experimentally and numerically studied the effect of attack angle on heat transfer characteristics in rectangular channel equipped with delta winglets. The results show that the average Nusselt number increase with the increase of attack angle of delta winglet pair. Zhou and Feng [31] presented curved winglet of rectangular, trapezoidal and delta vortex generators with and without punched hole. Caliskan [32] developed both novel triangular vortex generators and rectangular winglet vortex generators for heat transfer augmentation in a rectangular channel under uniform heat flux condition. Experimental results indicated a 23–55% increase of heat transfer by using vortex generators. Min and Zhang [33] numerically investigated the flow and mass transfer in narrow membrane channels placed with delta winglets. They suggested the parametric optimization of the delta winglets under equal pumping power.

In recent years, utilization of winglet-type vortex generators in fin-and-tube heat exchangers received more and more attention. Extensive investigations have been done on heat transfer augmentation of fin-and-tube heat exchanger with winglet-type vortex generators. The impact of geometric parameters, placement and orientation of vortex generators on heat transfer enhancement and fluid flow were examined in detail. Winglet-type vortex generators have been proved to have a high performance for heat transfer augmentation in air side of fin-and-tube heat exchangers. Torii et al. [34,35] proposed a new strategy for a fin-tube heat exchanger with delta winglet-type vortex generators placed beside the tubes. The experimental results showed that the configuration can augment heat transfer and reduce pressure loss at relatively low Reynolds number. Tiwari et al. [36] performed numerical study on laminar flow and heat transfer of a heat exchanger using oval tubes and multiple delta winglets mounted on the fin surface. O'Brien et al. [37,38] presented the local heat transfer distribution of a single passage in a fin-and-tube heat exchanger with delta-winglet vortex generators using a transient technique. Allison and Dally [39] reported a experimental study of the effect of a delta winglet vortex pair on the performance of a tube-fin heat exchanger. Joardar and Jacobi [40,41] explored the flow and heat transfer of multirow inline-tube heat exchangers equipped with different delta winglet configurations in common-flow-up arrangement. Details of the local flow patterns, local and overall heat transfer were presented. It was found that the vortex generator arrays can significantly improve the performance of fin-tube heat exchangers. Tian et al. [42] performed numerical simulation on heat transfer enhancement of fin-and-tube heat exchangers by using punched delta-winglet-type vortex generators. Lei et al. [43] carried out a numerical investigation to study the heat transfer and fluid flow characteristics of fin-and-tube heat exchangers with delta-winglet vortex generators in common-flow-up orientation. Chu et al. [44] conducted a investigation to study the effect of geometric parameters on heat transfer and fluid flow of fin-and-oval-tube heat exchangers with delta-winglet longitudinal vortex generators. Lemouedda et al. [45] carried out a optimization investigation based on the strategy of Pareto optimality for the angle of attack of delta-winglets in an elementary model of plate-fin-and-tube heat exchangers.

Wu and Tao [46] presented a fin-tube surface with two rows of tubes in different diameter. Delta winglet pairs are fitted in the larger fin area around the first transerverse row of tubes in smaller size. He et al. [47] numerically investigated the effect of punched