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Heat transfer and flow characteristics in a circular tube fitted with rectangular winglet vortex generators

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ABSTRACT

In this paper, the heat transfer and flow behavior of a circular tube fitted with rectangular winglet vortex generators (RWVGs) are investigated numerically and experimentally with uniform heat flux boundary conditions for Reynolds number ranging from 5000 to 17,000. Water is employed as working fluid. The RWVGs are inserted into the tube, with the slant angle β of 10°, 20°, 30°, 35°, respectively. The asymmetric winglet height is set on the one side at $H_1/D = 0.5$, and on the other side at $H_2/D = 0.2$, 0.3, 0.4, and 0.5, respectively. The effects of β and H_2/D on the heat transfer and flow behavior are studied numerically by employing FLUENT software. The results show that the RWVGs can agitate the cold fluid from the core flow region to the tube wall, and therefore, enhancing the mixing of hot and cold fluids. The Nusselt number and friction factor increase with the increase of β, or H_2/D. Specifically, the Nusselt number and friction factor are increased at 1.16–2.49 times and 2.09–12.32 times, respectively, compared with the plain tube. The Performance Evaluation Criterion (*PEC*) increases first, and then decreases with the increase of β and H_2/D. The maximum *PEC* is found to be 1.18 for $\beta = 30°$, $H_2/D = 0.5$ and $Re = 5000$. Based on numerical data, new correlations of Nu and f by using four nondimensional parameters are also developed. The experimental platform is set up and the numerical results agree well with those of the experiment. In addition, the mechanism of heat transfer enhancement of RWVGs can be well explained by the principle of field synergy.

1. Introduction

Heat transfer enhancement technology has been widely used in heat exchangers, to achieve the required energy efficiency [1–3]. Heat transfer enhancement technology is now divided into two main categories [4]: active and passive heat enhancement technologies, where the common feature is to reduce the thickness of the boundary layer, so as to achieve an efficient surface heat transfer coefficient. Compared with active enhancement heat transfer technologies, passive heat transfer enhancement technologies, such as tube inserts, extended surface technology, and surface coating technology, do not need any extra power, and are cost efficient and easy to use. As a result, the study of passive heat transfer enhancement technology has attracted more attention [5–8].

In recent years, researchers have proposed various tubular inserts to obtain the maximum heat transfer rate at the expense of lower pressure drop losses. Liu et al. [9] studied the heat transfer characteristic and friction coefficient of the inclined rod inserted in the center of the tube under uniform heat flux conditions experimentally and numerically. They reported that the Nusselt number and friction factor are enhanced by 1.8–5.05 times and 2.49–6.92 times, respectively, compared to a plain tube. Liu et al. [10] numerically investigated the thermo-hydraulic characteristics of a heat exchanger tube fitted with a novel vortex rod insert with constant wall heat flux in a laminar flow. The results showed that the maximum *PEC* value of approximately 2.22 was obtained at rod length ratio 0.35, rod pitch ratio 1, and Reynolds number 1800. Tang et al. [11] numerically studied the heat transfer and friction characteristics of laminar flow through a circular tube with small pipe inserts. The results indicated that the nondimensional spacer length at 6.67 could achieve the best overall performance of enhanced tube. Deshmukh et al. [12] experimentally studied the effects of the pitch to projected length ratio, attack angle and circumferential

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Nomenclature

A	pipe surface area, mm^2
l_1	length of the rectangular winglet, mm
C_p	specific heat of water, J/kg·K
D	hydraulic diameter, mm
f	friction factor
f_0	friction factor of a smooth tube
H_1	height of one side rectangular winglet, mm
H_2	height of another side rectangular winglet, mm
h	height of the rectangular bar, mm
h_{conv}	convective heat transfer coefficient, W/m^2·K
k	thermal conductivity of water, W/m·K
L	length of test section, mm
l	length of rectangular rod, mm
m	thickness of rectangular winglet, mm
Nu	Nusselt number
Nu_0	Nusselt number of a smooth tube
P	spacing between rectangular winglets, mm
Pr	Prandtl number
PEC	Performance evaluation carition
Δp	pressure drop, Pa
Q	flow rate of liquid, L/min
Q_h	input power, W
q	heat flux, W/m^2
Re	Reynolds number
S	cross-sectional area of channels, mm^2
T_{in}	inlet fluid temperature, K
T_m	average fluid temperature, K
T_{out}	outlet fluid temperature, K
T_w	wall temperature, K
T_{wi}	wall temperature readings, K
ΔT	differential temperature, K
u,v,w	the velocity in the three dimensional space, m/s
W	width of rectangular rod, mm
w_m	average velocity of water, m/s
x, y, z	three coordinates shown in Fig. 1, m

Greek symbol

β	the slant angle, °
ρ	fluid density, kg/m^3
μ	dynamic viscosity of fluid, kg/m·s
θ	synergy angle, °
θ_m	average synergy angle, °

contact length to tube inner diameter ratio on the heat transfer enhancement in a circular tube in laminar flow. They reported that the average Nusselt number ratio with and without the insert could up to 15. Lin et al. [13] proposed a newly designed twisted tape having parallelogram winglet vortex generators (PWVGs) to enhance heat transfer. They reported that the heat transfer enhancement under identical pumping power condition was achieved.

Cao et al. [14] created new method to modulate the flow and heat transfer performance of a tube in which the consecutive conical-mesh inserts were suspended. The results indicated the excellent heat transfer enhancement of modulated heat transfer tube was obtained with lower pumping cost as the *PEC* was up to 2.2. Alia et al. [15] compared the enhanced heat transfer effect of flexible vortex generators with that of conventional non-deformable rigid vortex generators in a circular tube. The results showed that the heat transfer enhancement of the former case was 21% higher than that of the latter case. The heat transfer enhancement induced by a new type of porous metal cylinder inserts (PMCIs) was numerically investigated by Huang et al. [16]. The results showed that (1) the Nusselt number and friction coefficient increased with the decrease of the spacer length and (2) the smaller the porosity was, the better *PEC* values were. Ibrahim [17] experimentally investigated the heat transfer and flow performance of horizontal double pipes of flat tubes with helical screw inserts. The results showed that the Nusselt number decreased with the increase of twist ratio and spacer length.

Tang et al. [18] experimentally investigated the heat transfer performance and pressure drop of a circular tube with small pipe inserts in turbulent flow. They found that a high heat transfer rate with relatively low flow resistance can be obtained using pipe inserts. Subsequently, Tang et al. [19] numerically studied the heat transfer and friction factor of a circular tube with pipe inserts for Reynolds number ranging from 2892 to 28,915. The results showed that an excellent heat transfer performance can be obtained by introducing pipe inserts under turbulent boundary conditions. The heat transfer rate decreased with the increasing spacer length. However, the flow resistance increased with the decrease of the spacer length. Pourramezan and Ajam [20] numerically investigated thermo-hydraulic characteristics of a circular tube fitted with twisted conical strip inserts in turbulent region. They found that both the Nusselt number and friction factor increased with the decrease of the pitch and the increase of slant angle. Man et al. [21] experimentally investigated thermo-hydraulic performance of a dual-pipe heat exchanger. The alternation of clockwise and counterclockwise twisted tape (ACCT tape) and typical twisted tape (TT tape) were inserted into the inner tube. The results showed that ACCT tapes exhibited better heat transfer enhancement than the typical twisted tapes. In addition, compared with the other lengths of twisted tapes, the best effect appeared for the full-length of ACCT tape.

Bhuiya et al. [22] studied the heat transfer and fluid friction characteristics of a tube fitted with perforated double counter twisted tapes under uniform wall heat flux boundary conditions. The results showed that the hydro-thermal character increased with the reduction of porosity except porosity of 1.2%. And the heat transfer enhancement and friction factor augment were obtained around 80–290% and 111–335%, respectively, compared to the plain tube. Kumar et al. [23] studied the influence of circular perforated ring (CPR) inserts on the thermo-hydraulic performance in a circular cylindrical tube in turbulent region. The results indicated that the augmentation in heat transfer was different when perforation index and diameter ratio were taken different values. Skullong et al. [24] compared staggered-winglet perforated tapes (WPT) with the staggered-winglet typical non-perforated tapes (WTT) and revealed that the highest thermal enhancement factor of WPT was about 1.2 times higher than that of WTT. Li et al. [25] studied the turbulent flow of the tube fitted with the drainage inserts. The results showed that the slant angle of 45° and the pitch ratio of 3.3 were suggested as the optimal parameters. Chingtuaythong et al. [26] investigated the influence of V-shaped rings on heat transfer and flow resistance characteristics in a tube with uniform heat flux conditions. The results showed that the V-ring has considerably enhanced the heat transfer rate up to 5.8 times with the 82 times friction factor punishment above the plain tube. Promvonge et al. [27] investigated the enhancement of thermal performance in a square duct fitted with twisted-tape and winglet vortex generators combined under constant heat-fluxed