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An experimental and numerical study on the laminar heat transfer and flow characteristics of a circular tube fitted with multiple conical strips inserts

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ABSTRACT

In this work, numerical simulations on the flow structures and heat transfer enhancement of laminar flow in a heat exchanger tube fitted with multiple conical strips inserts have been carried out. And stereoscopic particle image velocimetry (SPIV) measurements on the flow structures have been conducted to verify the numerical results. Both the experimental and numerical results show that multiple longitudinal vortexes are generated in tube, and the flow structures obtained by simulations agreed well with those of the PIV measurements. Numerical results show that heat transfer and friction factor were respectively enhanced by approximately 2.54–7.63 and 2.40–28.74 times compared to the plain tube, and the overall heat transfer performance (performance ratio *R3*) was located in the range of 1.23–6.05. Moreover, effects of the number of conical strips (n), central angle (α), slant angle (θ) and the pitch (p) have been investigated. It is found that both the heat transfer rate and flow resistance increase with the increasing number of conical strips, central angle and the decreasing pitch, and they both increase first and then decrease with the increase of slant angle. Compared with the previous published works, the tube with multiple conical strips inserts can obtain a moderate heat transfer and low flow resistance, and thus achieve a high overall heat transfer performance.

1. Introduction

Heat transfer equipment is indispensable devices in a variety of engineering areas and industrial fields such as power generation, chemical industry, and waste heat recovery [1]. Heat exchanger tubes exist in a wide variety of heat transfer equipment. To increase the heat transfer rate of the tube flow, numerous studies on heat transfer enhancement techniques have been carried out. Among the heat transfer enhancement techniques for tube flow, tube inserts are widely researched because of their ease of manufacture and installation. In previous work, the twisted tape insert has been extensively studied. Manglik and Bergles [2,3] experimentally investigated the heat transfer and pressure drop of a tube fitted with typical twisted tape inserts. They presented the predictive correlations of Nusselt number and friction factor for laminar, transition, and turbulent flows. It was found that the inserts could effectively enhance the heat transfer in the tube by disturbing the flow and creating a thinner thermal boundary layer. However, a drawback of this insert is the sharp increase of pressure drop in the tube, which means more pump power consumption. Motivated by the goal of minimizing the increased flow resistance and improving thermal-hydraulic performance, researchers have proposed various modifications of typical twisted tape inserts. Saha [4,5] conducted an investigation of heat transfer enhancement in a circular tube fitted with regularly spaced twisted tape elements. Guo [6] and Bhattacharyya [7] studied, numerically and experimentally, the characteristics of heat transfer and friction factor in a tube with a center-cleared twisted tape insert under laminar flow, respectively. The numerical results showed that the twisted tape with a central clearance ratio of 0.3 obtained the best thermal-hydraulic performance. A centrally hollow, narrow, twisted tape insert under laminar flow in a tube was numerically studied by Li et al. [8]. The results indicated that the flow resistance decreased with the increase of the hollow width, and the best overall heat transfer performance was achieved with a moderate hollow width. Saysroy [9] carried out an investigation on heat and fluid flow behaviors of turbulent flow in a tube with square-cut twisted tape inserts. Their results showed that the highest thermal enhancement factor was 1.32 times higher than that of the classical twisted tape. Helical screw tape and wavy-tape are other forms of tape inserts. Physical quantity synergy and entropy generation

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Nomenclature

c_p	specific heat at constant pressure of water, J/kg K
D	inner diameter of the tube, mm
D_1	distal diameter of the conical strip, mm
d	proximal diameter of the conical strip, mm
f	friction factor
f_0	friction factor of a plain tube
h	heat transfer coefficient, W/m^2 K
L	the full length of tube, mm
Nu	Nusselt number
Nu_0	Nusselt number of a plain tube
n	the number of conical strip
P	pressure of water, Pa
p	the pitch of conical strip, mm
PIV	particle image velocimetry
PEC	comprehensive heat transfer performance coefficient
q	heat transfer rate per unit area, W/m^2
R	inner radius of the tube, mm
r	the distance between the fluid particle and the center of the tube, mm
$R3$	comprehensive heat transfer performance coefficient
Re	Reynolds number
T	temperature of water, K
T_c	temperature at the center position of inlet Cross-section, K
u_i	the velocity component in the three-dimensional space, m/s
T_w	temperature on the tube wall, K
T_m	fluid bulk temperature inside tube, K
T_{in}	mass average temperature of inlet, K
T_{out}	mass average temperature of outlet, K
u	flow velocity, m/s
u_c	velocity at the center position of inlet Cross-section, m/s

Greek symbols

α	central angle of single conical strip, (°)
δ	thickness of the conical strip, mm
θ	the attack angle of conical strip, (°)
λ	thermal conductivity of water, W/m K
μ	dynamic viscosity of water, kg/m s
ρ	density of water, kg/m^3

analysis were performed to study the mechanism of heat transfer enhancement in a tube fitted helical screw tape by Zhang et al. [10]. Zhu et al. [11] proposed the wavy-tape insert for pipe heat transfer augmentation under laminar flow. They discussed the effects of the wavy-tape amplitude and width on the thermal-hydraulic performance. Longitudinal vortex generators are another type of insert elements. Eiamsa-ard [12] and Fan [13] conducted investigations on heat transfer and pressure loss of louvered strip inserts in the tube with water and air as the working fluids, respectively. The convective heat transfer behavior of a tube fitted with baffle turbulators under turbulent flow was experimentally and numerically studied by Nanan et al. [14]. They found that compared with other baffle turbulators, twisted cross-baffles gave the highest heat transfer enhancement and the overall thermal performance because of the high longitudinal vortices created in the tube core. Tu et al. [15,16] experimentally and numerically investigated the heat transfer and flow resistance characteristics of a tube fitted with small pipe inserts for laminar and turbulent flows. A circular heat exchange tube equipped with drainage inserts was experimentally and numerically studied by Li et al. [17] to analyze the heat and flow behaviors in turbulent flow. You [18] carried out a study on thermo-hydraulic characteristics of flow in a tube with conical strip inserts. Recently, Deshmukh [19] experimentally investigated the curved delta wing vortex generator insert in a tube to analyze the heat transfer enhancement performance for laminar flow. A numerical simulation on the thermo-hydraulic characteristics of turbulent flow in a circular tube fitted with twisted conical inserts was performed by Pourramezan et al. [20]. They found that the higher slant angle generated a swirling flow within the tube and resulted in higher *PEC* values. The conical ring is another type of tube insert element that can direct the fluid to scour the tube wall, thus reducing the thickness of the thermal boundary layer. Promvonge [21,22] conducted studies on heat transfer enhancement performance of tube with different configuration of conical-nozzle turbulators. Promvonge [23] experimentally investigated the effects of the conical ring turbulator inserts on the heat transfer rate and friction factor. The results indicated that the Nusselt number was enhanced up to 333% with the comparison of the plain surface tube. However, a substantial increase in friction factor was caused by conical ring inserts. Attempts have been made to reduce the flow resistance. Experimental investigation of heat transfer and turbulent flow friction in a tube fitted with perforated conical rings was carried out by Kongkaitpaiboon [24]. Somchai et al. [25] numerically studied the heat transfer and flow resistance behaviors in a exchanger tube with hexagonal conical-ring inserts. Their results showed that both the modifications of

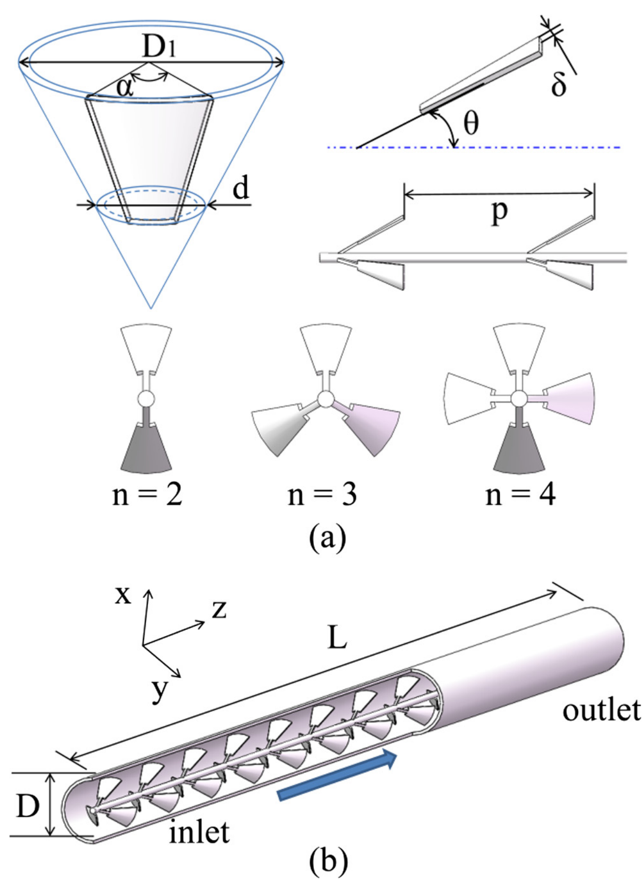

Fig. 1. (a) Geometry model of multiple conical strips inserts, (b) schematic diagram of a tube with multiple conical strips inserts.