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Heat transfer enhancement for laminar flow in a tube using bidirectional conical strip inserts

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A B S T R A C T

In the present work, a novel tube insert (bidirectional conical strip inserts) is proposed, and the heat transfer performance and flow characteristics of this insert are studied numerically. Effects of three geometric parameters (numbers of bidirectional conical strip (n), central angle (α) and pitch ratio ($P^* = p/D$)) are also investigated. The results indicate that cold fluid in the core region and the hot fluid near the tube wall are rapidly exchanged as the fluid flows through the bidirectional conical strip, and multiple longitudinal swirling flows are formed downstream of the bidirectional conical strip. Therefore, the heat transfer (the Nusselt number) is significantly enhanced by 2.35–9.85 times compared to the smooth tube. Moreover, because of the cooperation between the forward and the reverse conical strips, the formation of the dead zone and eddy on the back of the conical strips is inhibited. Thus, the increase in flow resistance is smaller than many other published works, as the friction factor is enhanced to 2.37–21.18 times of the smooth tube. The overall heat transfer performance (*PEC* value) is located in range of 1.75–3.93. Both the Nusselt number and friction factor increase with the increasing numbers of bidirectional conical strip, central angle and the decreasing pitch ratio. However, the friction factor is more sensitive to geometric parameters, so the maximum overall heat transfer performance (PEC value) is obtained at moderate geometric parameters ($n = 3$, $\alpha = 40°$ and $P^* = 3$). In addition, Correlation formulas for Nusselt number and friction factor are derived.

1. Introduction

Heat exchange tubes are common units in various heat exchangers, which are widely applied in many industries such as power generation, waste heat recovery, chemical industry, etc. Heat transfer enhancement techniques for heat exchange tube have a great significance for energy saving and environmental protection. With the development for several decades, a variety of techniques for heat transfer enhancement in tube flow have been proposed and investigated.

In general, the passive methods are widely used because of their requiring no external power [1,2]. There are two common passive methods to enhance the convective heat transfer in tube flow. One is shaped tube or modification of tube wall, which focuses on the heat transfer augmentation in tube boundary layer, such as corrugated tube [3–6], ribbed tube [7,8], grooved tube [9,10], helically-finned tube [11], elliptical axis tubes [12], etc. The other is tube inserts, which enhances the heat transfer in the core flow and is widely researched because of its ease of manufacture and installation. Twisted tape, the most widely used tube insert, can induce turbulence and vortex motion (swirling flow) and consequently result in a higher heat transfer coefficient. Since Manglik and Bergles et al. [13,14] conducted experimental investigations on heat transfer and pressure drop in a tube fitted with twisted tape in laminar and turbulent flow regime, researchers all over the world have proposed and investigated various modifications of twisted tape [15]. Saha et al. [16] experimentally investigated the friction and heat transfer characteristics of laminar flow in a tube with regularly spaced twisted-tape inserts. They found that compared to the full-length twisted-tape, the friction factor for regularly spaced twisted-tape inserts was substantially decreased. Wongcharee et al. [17] studied the heat transfer and friction characteristics of laminar flow in tube fitted with alternate clockwise and counter-clockwise twisted-tapes. Guo et al. [18] proposed a center-cleared twisted-tape and numerically studied its heat transfer and friction factor characteristics in laminar flow regime. They found that the friction factors of center-cleared or centrally hollow narrow twisted tapes were obvious less than that of the traditional twisted tapes. Some cut or perforated twisted tapes have been

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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 bidirectional conical strip, mm
d	proximal diameter of the bidirectional conical strip, mm
f	friction factor
f_0	friction factor of a smooth 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 smooth tube
n	the number of bidirectional conical strip
P	pressure of water, Pa
p	the pitch of bidirectional conical strip, mm
P^*	pitch ratio
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
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
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 bidirectional conical strip, °
δ	thickness of the bidirectional conical strip, mm
θ	the attack angle of bidirectional 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

proposed and reported to improve the overall heat transfer performance in tube flow, such as V-cut twisted tape insert [19], square-cut twisted tape [20], multiple square perforated twisted tape [21] and so on. In addition to the twisted tape inserts, researchers have proposed and reported a variety of tube inserts. Ozceyhan et al. [22] numerically studied the heat transfer enhancement in tube flow using circular cross sectional rings. Tu et al. [23] found the tube with small pipe inserts could obtain a better thermal performance due to the pipe inserts pushing the maximum velocity water to the wall side. Louvered strip inserts fitted in circular tube

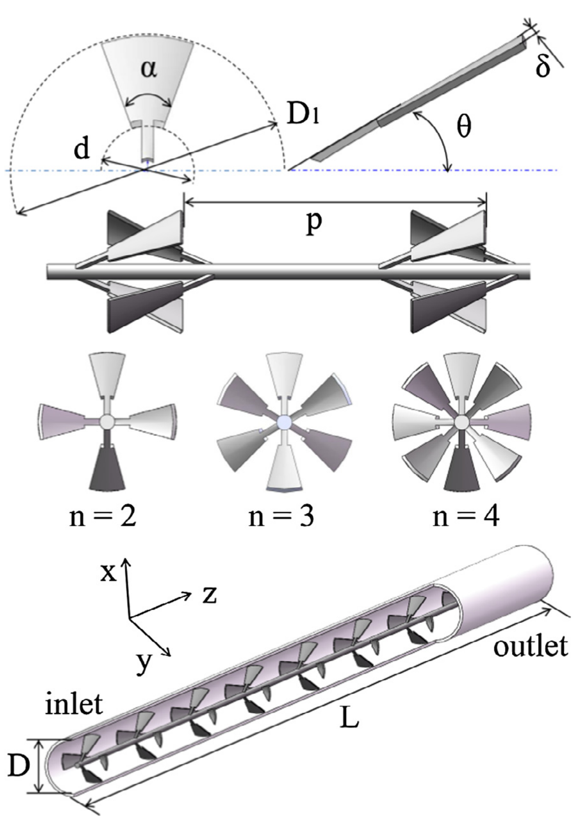

Fig. 1. Geometry model of bidirectional conical strip inserts, and the schematic diagram of a tube with bidirectional conical strip inserts.

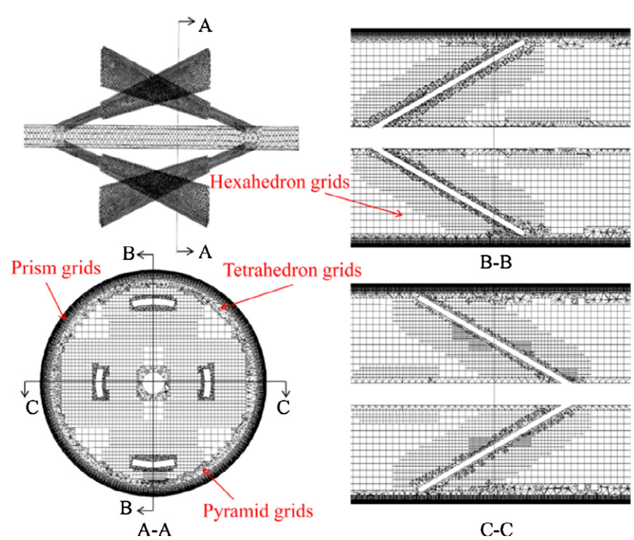

Fig. 2. Grids generated for computation domain.

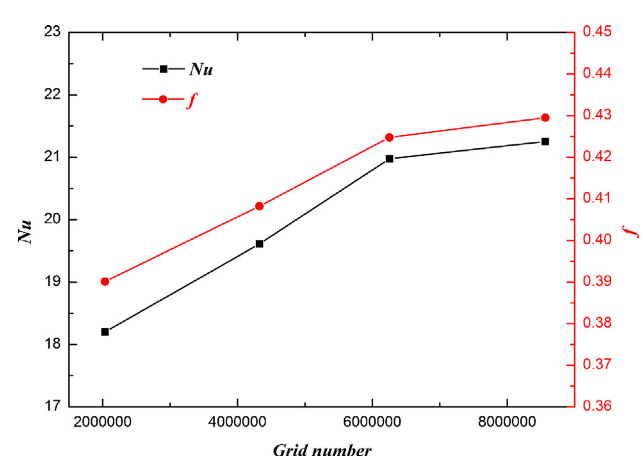

Fig. 3. Nusselt number and friction factor obtained by different grid systems for bidirectional conical strip insert with $n = 2$, $P^* = 2$ and $\alpha = 30°$, at $Re = 900$.