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Laminar thermal and fluid flow characteristics in tubes with sinusoidal ribs

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ABSTRACT

The article presents the effect of novel sinusoidal ribs transversely mounted in a tubular heat exchanger on convective heat transfer and flow pressure loss characteristics. The numerical study was performed under a constant heat flux condition for laminar water flow with Reynolds number (*Re*) ranged from 400 to 1800. The employment of sinusoidal ribs in the tube was aim to induce longitudinal vortex streams to give more intense flow mixing and to interrupt thermal boundary layer at the tube wall. The sinusoidal rib tubes (SRTs) were investigated at four rib height to diameter ratios (H/D = 0.026, 0.042, 0.058 and 0.074), three rib amplitude to diameter ratios (A/D = 0.211, 0.316 and 0.421), four rib width to diameter ratios (W/D = 0.158, 0.263, 0.368 and 0.474), three rib pitch to diameter ratios (P/D = 1.053, 1.316 and 1.579) and six circumferential rib numbers (N = 1, 2, 3, 4, 5 and 6). The obtained results reveal that increasing rib height, decreasing rib amplitude, decreasing rib width and decreasing rib pitch at most of *Re* lead to increase of both Nusselt number (*Nu*) and overall thermal performance evaluation criterion (*PEC*) while *Nu* and *PEC* increase from N = 1 to 3 and then decrease from N = 3 to 6. The enhanced heat transfer rate up to 4.89 times above that of the plain tube is found in the SRTs and the augmented friction loss is up to 5.62 times. The *PEC* is gained in the range of about 1.03–2.75 in the case studies and can be further improved by combined employing of the optimized individual geometric parameters in the preliminary trend analysis with the maximum value being about 3.64. The well organized flow patterns in the SRTs imply the probability in active controlling heat transfer characteristics by geometries. In addition, the obtained results indicate that the dimensionless absolute vorticity analysis, the entransy dissipation extremum principle and the field synergy theories could well depict and evaluate the heat transfer behaviors. At last, by comparing the present work with previous studies, the SRTs possess a potential promise in laminar heat transfer enhancement.

1. Introduction

Laminar flow is encountered in many industrial applications. Due to its low velocity, non-interfering in fluid mass, and flow calming in flow structures, the tube/duct/channel heat transfer in this circumstance always give poor performance. In order to reduce volume size and decrease equipment investing cost as well as improve heat transfer in heat exchangers under laminar flow, wide interests were triggered for augmentations in thermal performance and energy efficiency, including oil coolers for lubricating oil or engine [1], fin-and-oval tube compact heat exchangers [2] for air conditioner, nanofluids in an automotive cooling system [3,4], thermal improvement in micro-channels [5,6], microencapsulated PCM slurry in thermal storage system [7], solar energy water heaters [8,9], and etc. In these issues, enhanced devices/fluids were employed individually or simultaneously to enhance laminar heat transfer, such as ribs, corrugations, inserts, nanofluids, micro-tube/channels and etc., giving full play to enhanced tubes with geometric merits or fluids with high thermal conductivity characteristics.

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Nomenclature

A	rib amplitude, mm
C_p	specific heat at constant pressure, J/(kg·K)
C_v	specific heat at constant volume, J/(kg·K)
D	diameter, mm
E_{diss}	entransy dissipation, W·K
f	friction factor, dimensionless
h	convective heat transfer coefficient, W/(m^2·K)
H	rib height, mm
$J^n_{ABS,V}$	absolute vorticity, s^{-1}
k	thermal conductivity, W/(m·K)
L	tube length, mm
N	rib number in the circumference direction
Nu	Nusselt number, dimensionless
P	rib pitch, mm
Pr	Prandtl number, dimensionless
PEC	performance evaluation criterion, dimensionless
ΔP	pressure drop along the length of the tube, Pa
q	heat flux, W/m^2
Q	average heat transfer rate, W
r	radius, mm
R	radius, mm
Re	Reynolds number, dimensionless
Se	absolute vorticity, dimensionless
T	temperature, K
u	velocity, m/s
V	volume, m^3
W	rib width, mm
Z	axial distance, mm
Ω	trajpar
α	synergy angle between velocity and velocity gradient
β	synergy angle between velocity and temperature gradient
θ	synergy angle between velocity and pressure gradient
ρ	density, kg/m^3
μ	dynamic viscosity, kg/(m·s)

Subscripts

b	bulk
c	center
in	inlet
out	outlet
p	plain tube
w	wall

The thermo-hydraulic performance optimization in tubes/ducts with various enhancement technologies under laminar flow has attracted increasing attentions in the past few years. Krishna et al. [10] studied the use of straight full twist with different arrangements for improving heat transfer in a circular tube under laminar and turbulent flows. Promvonge et al. [11–13] performed successive works on laminar heat transfer and frictional losses of air in square/rectangle channels with inclined baffles/V-baffles. Akhavan-Behabadi et al. [14] compared the effect of wire coils with seven coil pitches and two wire diameters on the thermal performance of engine oil in tube laminar flow. Saha et al. [15–17] have conducted a series of studies to examine heat transfer augmentation in the co-use of axial corrugations/integral axial rib roughness/integral helical rib roughness with center-cleared twisted-tape as well as the use of individual enhancement devices in laminar flow with viscous oil as working medium. At Re = 300–1800, Zhang et al. [18] numerically investigated the convective heat transfer in a tube inserted with triple and quadruple twisted tapes. In their results, heat transfer rates increased up to 171% and 182% compared with the plain tube were respectively obtained by the former and the latter. You et al. [19] reported tube heat transfer enhancement behaviors under laminar flow by using conical strip insert and obtained the maximum PEC of 2.97. Song et al. [20] numerically analyzed influences of microencapsulated phase change material slurry with twisted tape inserts on laminar thermal characteristics in a tube. Cao et al. [21] proposed a mesh cylinder in the core region of the tube to yield higher heat transfer rate for the plain tube in the laminar flow and observed that the increased velocity and velocity gradient in the near wall region were the heat transfer enhancement mechanisms. Esmaeilzadeh [22] experimentally investigated thermal and flow characteristics at Re = 150–1600 in a tube with twisted tapes by using γ-Al_2O_3/water nanofluids as working fluid with two volume concentrations in nanofluids and three kinds of thicknesses in twisted tapes considered. They reported that the heat transfer rate increased with increasing in both nanofluids volume concentration and tape thickness. Jedsadaratanachai et al. [23] numerically reported laminar thermal-hydraulic characteristics in a plain tube with 45° V-baffles at tandem and in-line arrangements by a periodic model and pointed out longitudinal twisted vortices accounting for heat transfer enhancement. Simultaneous use of vortex generator and nanofluids adopted by Ahmed et al. [24] were aimed to give heat transfer augmentation in an equilateral triangular duct and the effects of Al_2O_3 and SiO_2 nanofluids with two particles concentrations were considered. Convection heat transfer behaviors under Re = 290–2024 by using water as working fluid in tubes inserted with wire-net cylinder inserts were studied by Tu et al. [25] to investigate the effects of different spacer length and open area rate. Xu et al. [26] examined laminar heat transfer and frictional losses of therminol heat transfer fluids in a rifled tube by both simulations and experiments. At Re = 200–2000, Sadeghi et al. [27] employed helical tapes with two nanofluids of Al_2O_3 and SiO_2 to enhance heat transfer in a tube. Vortex rods were numerically explored by Zheng et al. [28] to improve heat transfer under laminar water flow at Re = 300–1800 with effects including rod length ratios and rod pitch ratios being analyzed, and the obtained results gave the maximum PEC of about 2.22. Cheng et al. [29] numerically investigated water heat transfer and flow characteristics in twisted oval tubes at Re = 50–2000 with varying flattening ratios and twisted pitch ratios and gained the maximum PEC of 1.7. Huang et al. [30] designed porous metal cylinder inserts with varying porosity, pore types, spacer length and clearance to augment thermal performance of laminar heat transfer in a tube with water as working fluid. Feng et al. [31] reported laminar thermal enhancement using wire coil inserts in rectangular microchannel heat sinks with investigating effects of the length and arrangement on wire coils. Amin Ebrahimi and Benyamin Naranjani [32] reported a numerical study involved with thermal characteristics investigations of pyramidal protrusions in a flat-plate under Re = 135–1430 and examined the influences of the protrusion shape, size and arrangement. It was found that the heat transfer and pressure loss were augmented up to 277.9% and 179.4%, respectively. Lim et al. [33] employed various performance criteria such as the pumping power ratio, heat duty ratio, effectiveness ratio and etc. on twisted tape induced laminar swirl flow to investigate thermo-hydraulic performance. Khanjian et al. [34] presented secondary flow structures in a rectangular channel mounted with rectangular winglet pair vortex generators with varying