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Numerical study on fully-developed turbulent flow and heat transfer in inward corrugated tubes with double-objective optimization

Wei Wang [a], Yaning Zhang [a], Yongji Li [a], Huaizhi Han [b], Bingxi Li [a,*]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China

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ABSTRACT

In this study, numerical calculations are employed to investigate the effect of swirl and spiral flow on enhanced heat transfer and pressure drop in internal transversal and helical corrugated tubes with Reynolds numbers in the range of 10,020–40,060 at a constant wall temperature condition. Additionally, a double-objective optimization is employed to obtain the optimal solutions that balance the improvement of heat transfer and flow resistance and relevant design parameters. The results indicate that two reasons exist for heat transfer enhancement. The first reason corresponds to the transformation of convective heat transfer into a jet impingement heat transfer form at corrugation windward. The second reason corresponds to the severely turbulent pulsation and boundary-layer redevelopment at the corrugation leeside. The spiral flow exerts a low inhibiting effect on the heat transfer performance and causes a significant reduction in the pressure drop. Additionally, the Pareto front is obtained by the genetic algorithm, and equilibrium points with respect to the optimization values of Nu and f_{Re} correspond to 154.6 and 1663.8, respectively, and the design parameters corresponded to $Re = 39{,}596$, $Hl/D = 0.024$, and $pl/D = 1.38$. Thus, decision-making is performed based on the weight requirement of heat transfer and pressure drop. Optimal solutions are selected from points C–E if heat transfer performance is dominant, and otherwise they are selected from points A–C.

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1. Introduction

The passive enhanced heat transfer technologies are widely used in compact heat exchangers, and these can improve heat transfer efficiency and reduce their sizes, such as special shaped pipes [1–9] and pipes with kinds of inserts [10–12]. The corrugated tubes have a significant improvement on heat transfer compared with smooth tube, and the increasement of pressure drop is much less than pipes with inserts and some finned tubes. Recently, several studies considered various factors, such as different corrugation shapes [1,2], Reynolds number (Re) [3,4], Prandtl number (Pr) [5], and geometrical parameters [6–9], to determine an optimal design parameter and operation conditions. Most studies focus on the liquid heat transfer process, because of the higher heat transfer coefficients of denser fluids. The gas-gas heat exchangers often cost a lot of metal materials and space due to the low thermal conductivity, few scientists and engineers pay attention to this. But the gas waste heat takes up more than half of the industrial waste heat [13], so it is meaningful to employ the passive enhanced heat transfer technology on the gas-gas heat exchangers.

Rozzi et al. [4] used working fluids including whole milk, cloudy orange juice, apricot puree and apple puree, and performed experimental study on a shell and helically corrugated tube heat exchanger. The results confirm that helical corrugated tubes are especially effective in enhancing convective heat transfer for low Reynolds number values ranging from approximately 800 to the limit of the transitional flow regime in which a helical corrugated tube significantly enhances overall heat transfer performance. Vicente et al. [5] extended the experimental analysis to include a wide range of turbulent flow conditions with Re ranging from 2000 to 90,000 and Prandtl number (Pr) ranging from 2.5 to 100 in 10 types of corrugated tubes. Corrugated tubes present higher-pressure drop and heat transfer performance when compared with those of a smooth tube under the same flow conditions. Increases were observed in the friction factor coefficient from 20% to 300% and increases in Nusselt number up to 250%. A numerical investigation was performed by Mohammed et al. [6] to examine the effects of different geometrical parameters on thermal and flow fields through transversely corrugated circular tubes with Re ranging from 5000 to 60,000 and a heat flux corresponding to 50 W/cm^2.

* Corresponding author.
E-mail address: libx@hit.edu.cn (B. Li).

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Nomenclature

C_1, C_2	k-ε model constants
D	inner diameter of tube (m)
E	inner energy (J/kg)
f	Darcy fraction factor
f_{Re}	Poiseuille number
Hl	corrugation height (m)
I	turbulent intensity
pl	corrugation pitch (m)
PEC	performance evaluation criterion
k	turbulent kinetic energy (J/kg)
L	tube length (m)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
tl	tube wall thickness (m)
u	streamwise velocity component (m/s)
v	transverse velocity component (m/s)
V	velocity (m/s)
wl	corrugation width (m)
w	vertical velocity component (m/s)
y^+	dimensionless distance from the cell center to the nearest wall

Greek letters

ρ	density of fluid (kg/m^3)
ε	turbulence dissipation rate (m^3/s^2)
μ	dynamic viscosity (kg/m/s)
Φ	scalar quantities
λ	thermal conductivity (W/m/K)

Subscripts

s_ave	smooth tube average value
in	inlet
i, j, k	directions of the coordinate system
local	local value
out	outlet
s	smooth tube
t	turbulence
wall	tube wall

Additionally, Nu increased with increases in roughness height, width, and Re and with a decrease in roughness pitch. Maximum PEC was achieved with $Hl/D = 0.025$ for a pitch-to-tube diameter ratio of $pl/D = 0.5$ and a height-to-tube diameter ratio of $wl/D = 0.2$. More recently, Harleß et al. [14] performed an experimental study with gas-liquid heat exchangers relying on cross-corrugated tubes. The highest heat transfer enhancement was obtained with a corrugation height of 1.86 mm and a corrugation angle of 38.4°, and the optimal corrugation angle was expected

Table 2
Properties of working fluids.

Variable	Unit	Helium
Density (ρ)	kg/m^3	2.1659
Specific heat (C_P)	J/(kg·K)	5191
Thermal conductivity (λ)	W/(m·K)	0.2724
Dynamic viscosity (μ)	kg/(m·s)	3.46E−5
Pr	–	0.659

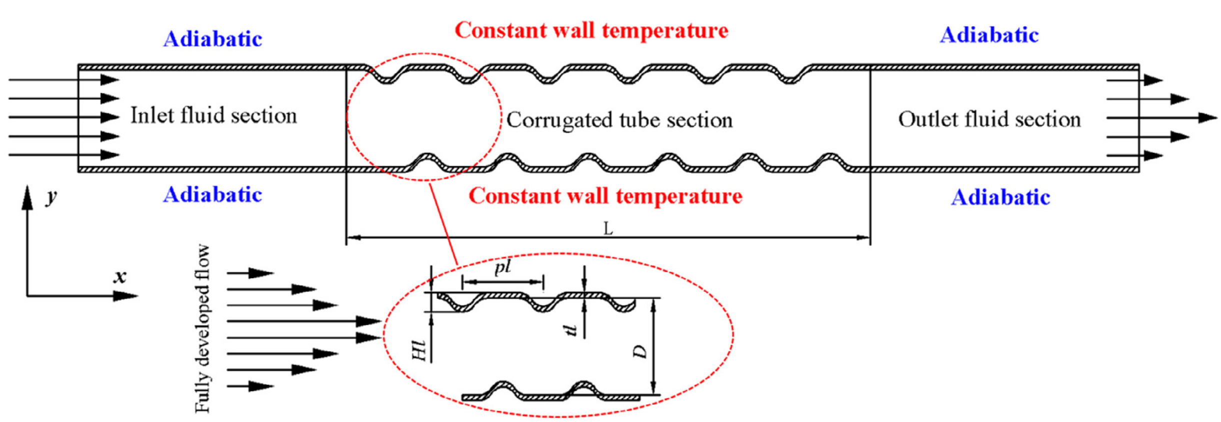

Fig. 1. Schematic diagram of the computational domain.

Table 1
Geometrical dimensions of the simulation tubes.

	D (mm)	Hl (mm)	pl (mm)	Hl/D	pl/D
Smooth	20	–	–	–	–
TCT-1	20	1	30	0.05	1.5
HCT-1	20	1	30	0.05	1.5
HCT-2	20	0.4	30	0.02	1.5
HCT-3	20	1.6	30	0.08	1.5
HCT-4	20	1	40	0.05	2.0
HCT-5	20	1	20	0.05	1.0

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