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Field synergy analysis for helical ducts with rectangular cross section

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ABSTRACT

This paper proposes a new approach based on VSP method (Vorticity–Stream function–Poisson equation method), to study numerically fully developed laminar flow characteristics and heat transfer behaviors of helical ducts with rectangular cross section. The aim is to guide heat transfer enhancement for helical rectangular ducts. Based on the numerical results, synergies between velocity field and temperature field have been investigated through field synergy principle. The effects of curvature, torsion, aspect ratio, Reynolds number, and Prandtl number on velocity field, temperature field and field synergy have been examined. The results show that the secondary flow of the central regions is weaker than that in other locations of the cross section. With reference to the entire cross section, the best values of synergy between velocity field and temperature field can be found in the center of the section. Increasing the curvature, Reynolds number and Prandtl number causes the mean synergy angles of the cross section to increase. This result indicates that it is more important to improve the field synergy for high Prandtl number fluid, especially at high Reynolds number. As the torsion increases, the average synergy angles decreases. The mean synergy angles reach the maximum value when the aspect ratio is equal to one; therefore, one can conclude that the field synergy of helical ducts with square cross section is the worst. To enhance heat transfer performance of helical rectangular ducts, for small aspect ratio, the main important aspect is to improve the secondary flow in the center of the cross section. On the contrary, for moderate values of the aspect ratio, the most important aspect is to improve the field synergy of the region near the upper and the lower wall. The correlations of friction factor and Nusselt number have been also developed for helical ducts with rectangular cross section.

1. Introduction

Helical ducts are frequently used in industrial applications, as in heat transfer equipment. The generation of a secondary flow in helical duct leads to higher heat and mass transfer rates compared with straight ducts. Helical ducts with rectangular cross section can be found in external cooling jacket of reactors, with helical baffles. In case of a reactor with fixed length, sometimes the pitch of helical baffles must be shortened to transfer heat in a certain amount of time for safety. In this case, the overall pressure drop of the helical channels becomes very high for the long distance fluid flowing through. Thus, the application of compound heat transfer enhancement could be a better solution for heat removal at moderate pressure drop. To apply compound heat transfer enhancement efficiently, some topics should be investigated. For laminar convective heat transfer, heat transfer performance depends not only on the temperature gradient and on the values of the velocity, but also on the synergy between velocity field and temperature field. This is in agreement with the field synergy principle for the boundary-layer flow first proposed by Guo et al. [1]. The main idea of the principle is that the reduction of the intersection angle between the velocity and the temperature gradient allows enhancing convective heat transfer. A comprehensive review of recent studies of the field synergy principle is provided by Guo et al. [2]. Moreover, Wu and Tao [3] analyzed the field synergy of the rectangular channel with vortex generators and verified the field synergy principle. Liu et al. [4] introduced the application of the field synergy principle in laminar flow field. Guo et al. [5,6] investigated the field synergy of curved square channel to enhance heat transfer. All these studies reported that the field synergy principle provides an alternative way to explain the heat transfer enhancement mechanism for curved rectangular channel flows. It is worth mentioning that Chen et al. [7] optimized the design of decontamination ventilation using the field synergy principle. The results of the researches above mentioned show that the field synergy principle is an effective tool for guiding convection heat

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Nomenclature

a	half-width of duct, m
A	heat transfer area, m^2
b	half-height of duct, m
$\mathbf{B}$	binormal of centerline ($=\mathbf{T}\times\mathbf{N}$)
d_h	hydraulic diameter, m
Dn	Dean number
f	friction factor
G	axial pressure drop
Gn	Germano number
$2\pi K$	pitch of helical duct, m
M	intermediate variable ($=1-\kappa x$)
N	normal of centerline
Nu	Nusselt number
Pr	Prandtl number
p	pressure
R	radius of helical duct
Re	Reynolds number
$\mathbf{r}$	position vector
$\mathbf{r}_c$	position vector of centerline
s	arc length of centerline, streamline coordinate
S	source item
$\mathbf{T}$	tangent of centerline
T	temperature
u	secondary flow velocity, m/s
v	secondary flow velocity, m/s
v	velocity vector
w	axial flow velocity, m/s
x	coordinate along **N**, m
y	coordinate along **B**, m

Greek symbols

γ	synergy angle, degree
δ	diviation
η	aspect ratio
κ	curvature
ϑ	kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
τ	torsion
ϕ	general variable
Γ	general diffusion coefficient
ψ	stream function
ω	vorticity

Subscript and superscript

*	dimensional variable
max	maximum value
m	mean value
b	characteristic variable
w	wall

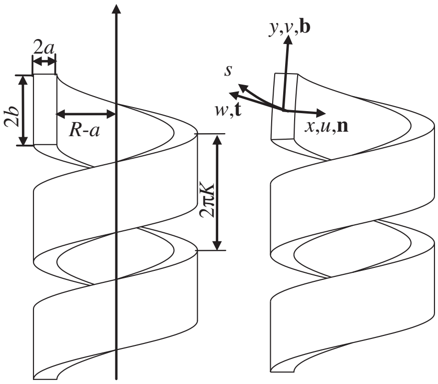

Fig. 1. Helical ducts with rectangular cross section.

Table 2
Effect of curvature on pressure drop and heat transfer.

κ	G	fRe	w_{max}	Nu_m	
				$Pr = 3$	$Pr = 10$
0.01	5776.4	14.44	2.0963	4.46	5.82
0.05	6630.1	16.58	1.9879	6.38	8.11
0.1	7246.4	18.12	1.8676	7.20	9.23
0.15	7660.1	19.15	1.7978	7.71	9.98
0.2	8007.6	20.02	1.7544	8.13	10.58

and mass transfer enhancement. This paper deals with the investigation of the synergy between velocity field and temperature field for some helical ducts with rectangular cross section at different parameters. The results of this research can provide guidance for the application of compound heat transfer enhancement.

Table 1
Grid test and comparison between present work and references.

Grids			41 × 41	51 × 51	61 × 61	References
	G		5683	5696.3	5696.9	
$\kappa = 0.0001$	fRe		14.21	14.24	14.24	14.26 [22]; 14.23 [23]
$\tau = 0$	w_{max}		2.099	2.098	2.097	
$\eta = 1$		$Pr = 0.7$	3.597	3.600	3.603	3.608 [10]
$Re = 200$	Nu_m	$Pr = 7$	3.600	3.600	3.606	
		$Pr = 10$	3.602	3.600	3.608	
	G		8190	8076.5	8004.4	
$\kappa = 0.2$	fRe		20.48	20.19	20.01	19.69 [10]; 19.62 [24]
$\tau = 0$	w_{max}		1.746	1.751	1.755	
$\eta = 1$		$Pr = 0.7$	6.118	6.031	5.581	5.595 [23,24]; 5.636 [10]
$Re = 200$	Nu_m	$Pr = 7$	10.698	10.087	9.601	
		$Pr = 10$	11.917	11.084	10.426	10.697 [10]
	G		8326.5	8194.4	8108.8	
$\kappa = 0.2$	fRe		20.82	20.49	20.27	19.86 [25]
$\tau = 0.2$	w_{max}		1.747	1.750	1.754	1.7594 [25]
$\eta = 1$		$Pr = 0.7$	5.865	5.766	5.408	
$Re = 200$	Nu_m	$Pr = 7$	10.892	10.257	9.333	
		$Pr = 10$	12.260	11.404	10.291	