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The characteristics of heat transfer and flow resistance in a rectangular channel with vortex generators

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ABSTRACT

The vortex generators (VGs) are among the most popular actuators for the heat transfer enhancement of heat exchangers. Using pure water as the working fluid, the characteristics of heat transfer and flow resistance in a rectangular channel with novel types of VGs were studied numerically at the Reynolds number range of $Re = 8900–29{,}900$. Five types of VGs with the same frontal area were used in the present study and the corresponding mechanism of heat transfer was analyzed. The heat transfer enhancement and flow resistance were examined by using the dimensionless parameters j/j_0, f/f_0, $R = (j/j_0)/(f/f_0)$, and $R^* = Nu_c/Nu_0$. The results revealed that, when the thermohydraulic performance factor R and Performance Evaluation Criterion R^* were considered as the comprehensive evaluation criteria, the half-cylinder VG was the best. Then the effects of arrangement, length, radius, and spacing of the half-cylinder VGs on the heat transfer and flow resistance were investigated. When the half-cylinder VGs were arranged along the side-lined row, the thermohydraulic performance factor R was the largest. With the increase in the generator length, the thermohydraulic performance factor R increased at first and then decreased, and exhibited the maximum value at $A/B = 0.50$. With the increase in the radius and decrease of the spacing, the thermohydraulic performance factor R decreased.

1. Introduction

Since the 1990s, the vortex generator (VG) as a new heat transfer enhancement technique has received significant attention. Recently, the enhancement of convective heat transfer has become an interesting research topic. By expert joint efforts for years, its application gradually expanded to several industrial fields such as petroleum and chemical engineering, energy and power engineering, and material engineering, etc, especially in heating and air conditioning. Researchers have realized the trends and future directions of heat transfer enhancement by VG [1].

The VGs were first employed in the field of aerodynamics because they produce vortices to alter local aerodynamic effects. In 1960, Schubauer and Spangenberg [2] applied the concept of VGs to the study of enhanced turbulent boundary layer. In 1969, Johnson and Joubert [3] experimentally studied the effects of VG on heat transfer and fluid flow characteristic. Thus, the VG was first used in the field of heat exchanger for vortex-induced heat exchanger enhancement. The VG is a passive heat transfer element, which utilizes a special type of extended surface that mainly generate vortices parallel to the flow direction to achieve heat transfer enhancement [1,4,5]. The VGs which can produce longitudinal vortices are widely used to enhance the heat transfer of heat exchanger, because the longitudinal vortices can lead to the thinning and destruction of the wall boundary layer, which aids in achieving the heat transfer enhancement [6–11]. Wang et al. [12] studied a pair of VGs to enhance the impingement heat transfer. The results showed that the delta winglet provided worse heat transfer than the rectangular winglet due to weaker vortex flow. Zheng et al. [13] studied numerically a heat exchanger tube fitted with vortex rods insert under uniform heat flux conditions, and analysis of the flow structures indicated that the vortex rod inserts could generate pairs of counter-rotating vortices or longitudinal swirling flows in the tube. Velte et al. [14] investigated the patterns of vorticity in the wake of a single rectangular winglet VG embedded in a turbulent boundary layer by stereoscopic particle image velocimetry. Song et al. [15] studied the effect of the interaction between two counter-rotating longitudinal vortices and the intensity of vortices and heat transfer by using numerical method for two rows of delta winglet type VGs. Salviano et al. [16] studied, based on the SIMPLEX method, the effects of seven independent parameters of the VG arranged in the finned tube heat exchanger on the heat transfer enhancement and resistance loss. The results indicated that for the two objective functions JF and $JF^{1/3}$, which are based

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Nomenclature

A	the length of the vortex generator (mm)
A_0	area of the effective heat transfer channel (mm^2)
A_c	area of the cross section channel (mm^2)
a, b	height, width of the vortex generator (mm)
B	width of the rectangular channel (mm)
D	the spacing between two vortex generators (mm)
D_e	hydraulic diameter of the flow channel (mm)
E, F	inlet, outlet extending zone (mm)
f	friction factor
H, L	height, length of the rectangular channel (mm)
h	heat transfer coefficient of the fluid ($W{\cdot}(m^{-2}{\cdot}K^{-1})$)
j	Colburn factor
Nu	Nusselt number
P	wetted perimeter (mm)
p	Pressure (Pa)
Δp	pressure drop (Pa)
Pr	Prandtl number
R	thermohydraulic performance factor
Re	Reynolds number
S_ϕ	source term
u	average velocity of the channel ($m^2{\cdot}s^{-1}$)
U	velocity vector
V	kinematic viscosity of the fluid ($m^2{\cdot}s^{-1}$)

Greek symbols

Δ	increment value
ρ	densities, $kg{\cdot}m^{-3}$
ϕ	generalized variable
λ	thermal conductivity ($W{\cdot}(m^{-1}{\cdot}K^{-1})$)
Γ_ϕ	diffusion coefficient

Subscripts

in	inlet
out	outlet
0	smooth rectangular channel
c	augmented case

on Colburn factor and Friction factor, the optimal configuration of the VG was more affected by the tube arrangement than the Reynolds number.

Recently, some new types of VGs have been studied [17–23]. The hydrothermal performance of smooth wave fins and elliptical tube heat exchangers by using the new types of VG from the viewpoint of the field synergy principle was analyzed. A three-dimensional (3D) computational fluid dynamics CFD numerical simulation was successfully carried out on thermohydraulic characteristics of a new smooth wavy fin and elliptical tube heat exchanger with three new types of VGs [17]. Caliskan [18] investigated heat transfer enhancement in a channel with new punched triangular VGs and punched rectangular VGs. Tu et al. [19] studied the effect of a circular tube with small pipe inserts on the heat transfer enhancement and resistance loss characteristics of turbulent flow. Aliabadi et al. [20] proposed and studied a new design of the plate-fin heat exchangers with corrugated/VG plate-fin. Promvonge et al. [21] introduced an inclined vortex ring turbulator for heat transfer enhancement in a heat exchanger tube. Asadi et al. [22] studied a new design of cylindrical VG arranged along the bottom of the channel. Based on the thermal hydraulic performance parameter, small radius VGs exhibited better heat transfer efficiency in micro-channels. Compared to the full-span VG, the full-span half-circle VG showed a greater reduction in the heat transfer resistance, while also showed a smaller increase in the pressure drop. Deshmukh and Vedula [23] presented the fabrication of a special insert, for which the central rod side was connected to a curved delta wing VG, and studied the influence of height to tube inner diameter ratio, pitch to projected length ratio and angle of attack on the heat transfer characteristic. It was found that the average heat transfer enhancement of the surface with VG was significantly higher than that of the surface without the VG.

Above mentioned studies indicate that most of the researches focus on the application of wing-type VGs placed along the base of the channel. In order to investigate the effect of the profile of VG on the heat transfer enhancement, the characteristics of heat transfer and flow resistance in a rectangular channel with five types of VGs were studied numerically in the range of the Reynolds number Re = 8900–29,900 in the present study. The effects of arrangement, length, radius, and spacing of the half-cylinder VGs on the heat transfer and flow resistance were systematically investigated.

2. Geometry description and mathematical model

2.1. Geometry description

The rectangular channel with VGs is shown in Fig. 1. The channel has a length L = 420 mm, width B = 30 mm, and height H = 10 mm. Number of VGs are equally distributed along the base of the rectangular channel. The spacing between two VGs is D. In order to maintain the stability of the inlet velocity, and to avoid the backflow of the outlet, the actual computational domain is expanded to include an inlet extending zone of E = 50 mm; and an out extending zone of F = 150 mm. The length of the VG is A = 30 mm, the height is a, the width is b. The profiles and size of the five types of VGs with the same frontal area are shown in Fig. 2. Table 1 lists the geometrical dimensions of rectangular channel with five types of VGs.

2.2. Mathematical model

The governing equations for continuity, momentum and energy in the computational domain can be generally expressed as follows:

$$\mathrm{div}(\rho U \phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi) + S_\phi \tag{1}$$

The detailed equations are as follows:
Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0$$

Momentum equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j u_i - \mu \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_i} \qquad (i = 1, 2, 3)$$

Energy equation:

$$\frac{\partial}{\partial x_j}(\rho c_p u_j T) = \frac{\partial P}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right)$$

FLUENT provides many choices of turbulence models, such as the standard k–ε model, realizable k–ε model, RNG k–ε model, and LES model [24]. The RNG k–ε model has been successfully applied to simulate the flow structure induced by VGs [25–27].