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Numerical simulation on heat transfer characteristics of rectangular vortex generators with a hole

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ABSTRACT

Vortex generators (VGs) can enhance the heat transfer of the channel, but it can also cause a certain pressure loss. In order to decrease the flow resistance of VGs, the VGs with a punched hole was proposed. In this research, three-dimensional numerical simulations of VGs are performed to analyze the heat transfer enhancement and the flow resistance in a rectangular channel with two-row rectangular vortex generators with and without a hole at the *Re* from 214 to 10,703. The heat transfer enhancement and the pressure drop are described by using the dimensionless factors Colburn factor *j*, friction factor *f*, and thermohydraulic performance factor $PEC = j/(f)^{1/3}$. Then, the effects of the hole diameter and the hole position were investigated. The results show that the values of *PEC* in the rectangular vortex generators with a hole are larger than those in the rectangular vortex generators without a hole. Through the analysis of the values of *PEC*, *j* and *f*, the optimal diameter of the hole is determined as $d = 5$ mm. In the vertical direction, the *PEC* increases with the increase of *c* and has the maximum value at $c = 4.5$ mm. In the lateral direction, the *PEC* first increases and then decreases slightly and has the maximum value at $e = 18$ mm.

1. Introduction

Heat transfer enhancement techniques are used in modern industries such as energy, power engineering, petroleum, chemical engineering, material engineering and metallurgy, etc., especially in heat exchangers. In general, heat transfer enhancement techniques are classified into active, passive and compound categories. The distinction between the active and passive methods is whether external power is required. The surface or geometrical modifications achieved by inserts or additional devices are usually applied in passive method [1]. Vortex generators (VGs), as a kind of passive heat transfer enhancement device, have been extensively applied to improve the heat transfer enhancement in heat exchangers [2–6]. The kinds of VGs have received considerable attentions such as triangular and rectangular form or any other combinations. However, the pressure drop is also tremendous with significant heat transfer enhancement.

Fiebig et al. [7] experimentally investigated three-tube-row heat exchanger element with delta winglets. The results show that the heat transfer enhancement is increased by 55–65% and the friction factor is increased by 20–45%. He et al. [8] studied the heat-transfer enhancement by punched winglet-type vortex generator arrays in fin-and-tube heat exchangers. He reported the discontinuous winglets significantly enhance heat transfer with a significant augmentation of up to 33.8–70.6% in heat transfer coefficient. It is achieved accompanied by a pressure drop penalty of 43.4–97.2%. Caliskan et al. [9] developed two new punched triangular vortex generators and punched rectangular vortex generators. Results show a 23–55% increase in heat transfer and an 18–195% increase in the corresponding pressure loss by punched triangular and rectangular VGs. Tabish et al. [10] studied the effect of geometrical parameters of the V-shaped perforated blocks on heat transfer and flow characteristics of rectangular duct by the experimental method. It found that the maximum enhancement in Nusselt and friction factor were 6.76 and 28.84 times to that of smooth duct, respectively. Chen et al. [11] studied on fluid flow and heat transfer in rectangular micro-channels with various longitudinal vortex generators. It found that heat transfer performance can be enhanced by 12.3–73.8% and 3.4–45.4% for micro-channels, while the pressure losses is increased by 40.3–158.6% and 6.5–47.7%, respectively. Hatami et al. [12,13] analyzed a vortex generator heat exchanger is used to recover exergy from the exhaust of an OM314 diesel engine by experimental and numerical. And fifteen HEX cases with different fins height, thickness and number are modeled numerically and the optimization is done to have the maximum heat recovery amount and minimum of pressure drop along the heat exchanger [14]. Azita et al. [15] achieved a maximum heat

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Nomenclature

A	inlet of VG distance calculation domain (m)
A_0	area of the effective heat transfer channel (m^2)
A_c	area of the cross section channel (m^2)
a, b	length, height of the vortex generator (m)
B	width of the rectangular channel (m)
C	longitudinal distance between two VGs (m)
c	height from the center of hole to bottom edge (m)
D	transverse distance between two VGs (m)
D_e	hydraulic diameter of the flow channel (m)
d	diameter of the hole
e	width from the center of hole to side edge (m)
f	friction factor
H	height of the rectangular channel (m)
h	heat transfer coefficient of the fluid ($W \cdot m^{-2} \cdot K^{-1}$)
j	Colburn factor
L	length of the rectangular channel (m)
Nu	Nusselt number
P	wetted perimeter (m)
p	Pressure (Pa)
Δp	pressure drop (Pa)
Pr	Prandtl number
PEC	thermohydraulic performance factor
Re	Reynolds number
S_ϕ	source term
T	temperature (K)
U	velocity vector
u	inlet velocity of the channel ($m^2 \cdot s^{-1}$)
V	kinematic viscosity of fluid ($m^2 \cdot s^{-1}$)
v, w	each direction velocity scalar

Greek Symbols

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

Subscripts

in	inlet
out	outlet
0	smooth rectangular channel
c	augmented case

transfer enhancement and a minimum pressure drop, and the optimal values of these parameters are calculated using the Pareto optimal strategy. Babak et al. [16] successfully carried out a new smooth wavy fin-and-elliptical tube heat exchanger with three new types of vortex generators on thermo-hydraulic characteristics. The result demonstrates that with increasing Reynolds number and wavy fin height, decreasing the tube ellipticity ratio, the heat transfer performance of the SWFET heat exchanger is enhanced. Anupam et al. [17] studied the air flow through fin-tube type heat exchangers with rectangular winglet pairs of half the channel height as vortex generators. And the result shows the heat transfer performance improves significantly due to the nozzle-like flow passages created by the winglet pair and the region behind the circular tube which promotes accelerating flow. Song et al. [18] studied the interaction of two counterrotating longitudinal vortices and the effect of interaction of counterrotating longitudinal vortices on the intensity of vortices and heat transfer by using numerical method.

The above literature review shows that the vortex generators are widely studied on the heat transfer enhancement and the flow resistance. Available literatures have disclosed deeper insights on the other most important role of VGs, which can be used as a reasonable method to reduce the area of wake region on the basis of vortex generator. Biswas et al. [19] has determined the effect of a punched hole, beneath the wing-type vortex generator, on the heat transfer and skin friction characteristics. Wu et al. [20,21] are numerically studied the effect of the punched holes and the thickness of the rectangular winglet pair to the fluid flow and heat transfer and experimentally studied on the performance of a novel fin-tube air heat exchanger with punched longitudinal vortex generator. Zhou and Lu et al. [22,23] investigated the performance of plane and curved winglet (rectangular, trapezoidal and delta) vortex generators with and without punched holes by experimental and numerical methods.

From above reviewed literature we can find that as the longitudinal vortices can potentially enhance heat transfer with pressure loss penalty, VGs which can generate longitudinal vortices are widely used to enhance the heat transfer of heat exchanger. In order to obtain a better heat transfer performance, researchers always try to punch lots of VGs out of the surface. However, a large number of VGs will cause greater pressure loss. Therefore, the rectangular vortex generator with a punched hole was studied in this paper. Numerical simulations of longitudinal vortex generators are performed to analyze the heat transfer enhancement and the flow resistance in rectangular channel with two types of rectangular vortex generator at the Re from 214 to 10,703.

2. Physical and mathematical model

2.1. Physical model

3D numerical simulations are conducted in a rectangular channel. The length of the vortex generator is a = 25 mm, and the height is b = 6 mm. The thickness of the winglet is often neglected for simplification in most simulation studies. A hole is punched on the vortex generator surfaces at different positions. The diameter of the punched hole is d. The width and height from the center of the hole to the side edge and bottom edge are e and c, respectively. The size of the rectangular vortex generator without and with a punched hole is shown in Fig. 1.

The computational domain with the built-in winglet in a channel is presented in Fig. 2. The dimension of the main channel is 1000 mm × 100 mm × 8.5 mm ($L \times H \times B$). In order to ensure the fluid can form the largest jet when the fluid flows out of the hole. The VGs with 2 rows and 9 columns are placed in a common-flow-down configuration axisymmetric arrangement at an attack angle 90°. The winglet pair with the transverse distance between the leading edge D = 20 mm are located at A = 140 mm downstream from the entrance of the channel. The spacing between two vortex generators is C. In addition, in order to ensure the development of the entrance flow, the actual computational domain is expanded to

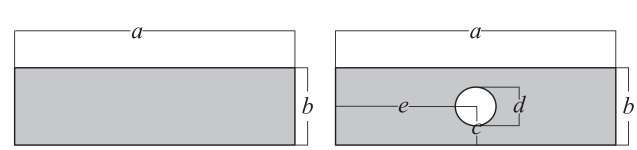

Fig. 1. The size of the rectangular vortex generator without and with punched a hole.