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Experimental and numerical investigation on particulate fouling characteristics of vortex generators with a hole

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ABSTRACT

In this study, the particulate fouling characteristics in a heat exchange channel with a rectangular wing vortex generator were investigated both experimentally and numerically. First, the fouling and flow resistance characteristics of the smooth channel, vortex generator without a hole, and vortex generator with a hole were compared experimentally. Subsequently, the fouling characteristics of the rectangular vortex generator with and without a hole were compared under turbulent conditions via numerical simulations. Finally, the effects of the hole diameter, and the lateral and vertical hole distances in the vortex generator on the particulate fouling characteristics were evaluated. The results show that both the vortex generator with a hole and without a hole could inhibit the formation of particles on the heat transfer surface. Compared with the vortex generator without a hole, the vortex generator with a hole could better inhibit particulate fouling, and it had a low flow resistance loss. The asymptotic fouling resistance decreased first and then increased with increasing hole diameter, it decreased as the lateral distance of the hole increased, and increased as the vertical distance of the hole increased.

1. Introduction

The heat transfer enhancement and fouling characteristics of heat exchangers have generally been of marked research interest. Heat transfer surface fouling inevitably causes heat loss to the heat exchange equipment, which compromises the safe operation of the heat exchange equipment. Beside deterioration of heat transfer, the growing fouling layer is leading to a reduction of channels cross-section that increase the pressure loss in the heat exchanger [1]. Vortex generators (VGs), as the most representative heat transfer enhancement component, have been the focus of significant global study [2].

Currently, many studies have indicated that vortex generators can enhance the heat transfer ability of the heat transfer surface [3–6]. However, a literature survey found that regardless of the type of vortex generator used, a certain pressure drop loss occurs while enhancing the heat transfer ability of the channel. For example, Chu et al. [7] studied the effects of a triangular winglet vortex generator on the heat transfer of a finned elliptical tube heat exchanger under laminar flow. It was found that the triangular winglets increased the average Nusselt number of the heat exchanger by 13.6%–32.9%, but the pressure loss also increased by 29.2%–40.6%. Chen et al. [8] studied the heat transfer characteristics in rectangular micro-channels with different number of pairs and dimensions longitudinal vortex generators. It was found that the heat transfer performance of the micro-channels with vortex generators was enhanced by 12.3–73.8% and 3.4–45.4% for microchannels with aspect ratios of 0.0667 and 0.25, respectively, while the pressure losses were increased by 40.3–158.6% and 6.5–47.7%, respectively. Gallegos and Sharma [9] investigated the heat transfer characteristics of rectangular channels equipped with a flapping flag as a vortex generator. Their results showed that the inclusion of a flapping flag in the channel leads to a Nusselt number enhancement as high as 1.34 to 1.62 times the bare channel levels, and the friction factor was as high as 1.39 to 3.56 times the bare channel levels.

To ensure the heat transfer enhancement of the vortex generator while reducing the flow resistance, many new designs have been proposed for the vortex generator. Tang et al. [10] proposed various types of vortex generators, compared with the common-flow-down configuration, the Nusselt number of the common-flow-up configuration increase by 2.7–2.9% and the friction factors reduced by 7.8–10.0%. Biswas and Chattopadhyay [11] determined that punching holes under the airfoil vortex generator would have an effect on the heat transfer and resistance characteristics. Wu et al. [12] found that the structure was not only easy to implement by arranging the rectangular vortex generator with punched holes on the surface of the fin heat exchanger but also helped to im-

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Nomenclatures

a	length of the vortex generator (m)
b	height of the vortex generator (m)
c	hole vertical direction distance (m)
C_{MgO}	particle concentration (kg/m^3)
C_∞	bulk particle concentration (kg/m^3)
C^+	dimensionless particle concentration
d	hole diameter (m)
D_B	Brownian diffusivity (m^2/s)
D_T	turbulent diffusivity (m^2/s)
d_p	particle diameter (m)
e	hole lateral direction distance (m)
J	deposition flux (kg/(m^2•s))
k	removal constant (–)
m_f	fouling mass per unit area (kg/m^2)
$\dot{m}_f$	total mass rate (kg/(m^2•s))
$\dot{m}_d$	deposition mass rate (kg/(m^2•s))
$\dot{m}_r$	removal mass rate (kg/(m^2•s))
p	pressure (Pa)
R_f	fouling resistance (m^2•K/W)
S	particle-fluid density ratio (–)
S_p	sticking portability (–)
T	temperature (K)
T_l	Lagrangian integral time scale (s)
t	fouling time (s)
U	velocity vector (–)
u_d	particle deposition velocity (m/s)
v	fluid velocity (m/s)
x_f	thickness of fouling layer (m)
y	distance from wall (m)
Greek symbols	
ε	deposit porosity (–)
λ	thermal conductivity (W/(m•K))
λ_f	thermal conductivity of the deposit (W/(m•K))
μ	dynamic viscosity (kg/(m•s))
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_{dep}	density of the deposit (kg/m^3)
τ_p	particle relaxation time (s)
τ_w	wall shear stress (MPa)
ψ	the bond strength factor (–)
Subscripts	
d	deposition
f	fouling
in	inlet
l	liquid phase
out	outlet
p	particle phase
r	removal

prove the overall heat transfer and reduce pressure loss. He et al. [13] studied the effects of the enhanced heat transfer on a perforated winglet vortex generator in a finned tube heat exchanger. Their results showed that a significant increase of up to 33.8–70.6% in the heat transfer coefficient was achieved and was accompanied by a pressure drop of 43.4–97.2% for the 30° case compared to the plain fin. The performances of plane and curved winglet vortex generators with and without punched holes have been investigated experimentally by Zhou and Feng [14]. Their results showed that punched holes could enhance the heat transfer in both the laminar and turbulent flow regions and decrease the flow resistance. Qi et al. [15] investigate the effects of round hole diameter and pitch-row on thermal and hydrodynamic characteristics of nanofluids based on triangular tubes with perforated turbulator inserted, and apply thermal and exergy efficiency to assess the comprehensive thermal and hydrodynamic characteristics. Jeong et al. [16] proposed a crescent-shaped protrusion was mounted as a vortex generator on the downstream of the dimple. The dimpled channel with a vortex generator shows better normalized thermo-performances than the general dimpled channel. Experimental and numerical of vortex heat transfer in turbulent air flow around the plate with permeable transverse rectangular ribs have been made by Kong et al. [17]. It is shown that the presence of a slit can eliminate secondary separation zones on the plate and decrease recirculation flow regions behind a rib.

Vortex generators have been extensively studied for heat transfer enhancement, however, research on fouling is relatively sparse. Hasan et al. [18] studied the crystallization fouling characteristics of the delta-wing vortex generator, and proposed that the structural design of the vortex generator should be considered in conjunction with antifouling and pressure drop. Zhang et al. [19] proved experimentally that the vortex generator could effectively improve the heat transfer coefficient and also destroy the boundary layer near the wall surface, thus inhibiting fouling. Furthermore, our recent work [20] demonstrated that induced vortexes could inhibit fouling formation. Therefore, in this work, the fouling characteristics of a new type of vortex generator with a hole were studied experimentally and numerically. First, a comparison of a rectangular vortex generator with and without a hole was carried out. Then, the effects of the hole diameter, and the lateral and vertical hole distances of the VGs on the particulate fouling characteristics were studied.

2. Experimental procedure

A schematic diagram of the experimental system is shown in Fig. 1 [21]. The system was composed of a working fluid circulation loop, a cooling cycle loop, and a data acquisition system. The temperature in the experimental section was controlled using a Pt100 thermal resistance and thermostat control. All the relevant experimental data were collected through the data acquisition system and sent to a computer. The test section used a rectangular channel with a size of 1000 mm × 100 mm × 8.5 mm. The test section consisted of a polypropylene (PP) plastic plate, a silica gel sheet, and a 304 stainless steel plate. The thickness of the stainless steel plate was 0.5 mm, which was the main heat exchange surface for the test section, and the fouling was mainly deposited on it. Its geometrical dimensions were 1000 mm × 100 mm as shown in Fig. 2. The PP plastic plate was anti-hygroscopic, had acid and alkali corrosion resistance, and was resistant to oxidation under high temperature conditions. Therefore, the surface materials were constructed using PP plastic plates. The silica gel sheet had large elastic deformation because of its soft texture and pressure, and therefore had good sealing abilities and functioned as a seal in the test section. The test section was well insulated to minimize the heat loss.

The schematic diagram of the test section and vortex generator with a hole is shown in Fig. 2. The arrow indicates the direction of fluid flow. The VGs with two rows and nine columns were placed in the channel at an attack angle of 90°. The first VG pair was located 150 mm from the leading edge. The lateral spacing between two VGs was 20 mm. The longitudinal spacing between the two VGs was 90 mm. The sizes of rectangular VGs with a hole are shown in Fig. 2(a). The VGs were made of a steel plate with a = 25 mm long and b = 6 mm high. A hole was punched on the VG surfaces at different positions. The height from the center of the hole to the bottom edge was c. The width from the center of hole to the side edge was e. The diameter of the punched hole was