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The optimal arrangement of vortex generators for best heat transfer enhancement in flat-tube-fin heat exchanger

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ABSTRACT

The interaction of longitudinal vortices decreases the intensity of longitudinal vortices and inevitably affects the heat transfer performance of heat exchangers. In this paper, the effects of transverse distance of vortex generators (VGs) on the interaction of longitudinal vortices and the heat transfer performance are quantitatively studied. The increments of longitudinal vortex intensity, Nusselt number and friction factor resulted from the application of VGs are discussed in detail. The results show that the transverse distance of VGs obviously affects the interaction of longitudinal vortices, the heat transfer enhancement and the pressure loss characteristics of the heat exchanger. The interaction of co-rotating longitudinal vortices generated by VGs around the same tube is less affected by the transverse distance of VGs. While the interaction of counter-rotating longitudinal vortices generated by VGs around different tubes is closely related to the transverse distance of VGs. The interaction between counter-rotating longitudinal vortices plays a dominant role in the interaction process of longitudinal vortices. Optimal transverse distance of VGs exists for best heat transfer performance of the heat exchanger. Meanwhile, the transverse distance which leads to the worst heat transfer performance is also reported. For the largest Reynolds number studied in this paper, the maximum differences in the increments of intensity of longitudinal vortices, Nusselt number and friction factor for different transverse distance of VGs are 34.0%, 33.9% and 18.5%, respectively.

1. Introduction

Fin-and-tube heat exchanger is one of the most commonly used compact heat exchangers in locomotive engineering. The heat exchanger is usually used to cool the water using air. As the thermal conductivity of the air is inherently lower than that of water, the convective heat transfer coefficient is needed to be improved by using heat transfer enhancement techniques on the fin surfaces. Vortex generators (VGs) which can generate longitudinal vortices and enhance heat transfer efficiently have been widely studied and applied in many industrial application fields [1,2]. The VGs can not only disrupt the development of boundary layer, but also generate longitudinal vortices and speed up the exchange of fluid with different temperature, thereby enhancing the heat transfer between the fluid and the wall.

The heat transfer enhancement performance of VGs depends on many parameters such as geometric shape, size and attack angle. There are increasing number of researches focusing on this topic [3–19]. Tiggelbeck et al. [3] compared the heat transfer characteristics of four types of VGs and implied that the winglet VG has better heat transfer performance than wing VG. References [1,4] also indicated that the winglet is more attractive than wing as vortex generators for enhancing heat transfer. Promvonge et al. [5] reported that the larger attack angle leads to higher values of both heat transfer coefficient and pressure losing than the lower one, and convective heat transfer coefficient is heavily affected by attack angle. Lei et al. [6] also found that both the heat transfer coefficient and pressure loss increase with the increase of attack angle of VGs when the attack angle ranges from 10° to 50°. Kwak et al. [7] and Tang et al. [8] found that the increase of attack angle or length, or the decrease of height of VGs may enhance the heat transfer performance. Wu and Tao [9] also concluded that the geometry of VGs is important for heat transfer enhancement. They observed that heat transfer is improved better with an increase of base length and a decrease of height under the premise of fixed VGs areas. Huang and Chiang [10] studied the optimal shape and position of delta winglet vortex generators for heat transfer of pin-fin heat sinks. Their results showed that the cooling performance with the designed optimal vortex generators is indeed better than that with the original vortex generators. Song et al. [11] experimentally reported that geometric size

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Nomenclature

a	width of flat tube (m)
A	cross section area (m^2)
b	length of flat tube (m)
c	transverse distance between two VGs around tube (m)
c_p	specific heat capacity (J/(kg·K))
d	length of the extended domain (m)
d_h	hydraulic diameter (m)
H	height of vortex generator (m)
JF	surface goodness factor or thermal performance factor
L	base length of vortex generator (m)
L_s	length of simulation domain (m)
Nu	Nusselt number
p	Pressure loss (Pa)
Re	Reynolds number
S	heat transfer area (m^2)
S_1	transverse pitch between flat tubes (m)
S_2	longitudinal pitch between flat tubes (m)
Se	secondary flow intensity
T_p	fin spacing (m)
T	temperature (K)
U	characteristic velocity of secondary flow (m/s)
u_m	maximum average velocity of air (m/s)
u, v, w	components of velocity vector (m/s)
V	flow volume (m^3)
x, y, z	coordinates

Greeks

θ	attack angle of VG (°)
λ	heat conductivity (W/(m·K))
μ	viscosity (kg/(m·s))
ρ	density (kg/m^3)
ω	vorticity (1/s)

Superscript

n	direction normal to the cross section

Subscripts

local	local value
s	span average value
w	solid surface
0	value for plain fin without VGs

and location of curved vortex generators has obvious effect on heat transfer enhancement, and the change of fin pitch has less effect on Colburn factor and obvious effect on friction factor. Lu et al. [12] compared the performances of plane and curved winglet pair vortex generators in a rectangular channel and reported that the curved trapezoidal winglet pair provides the best thermo-hydraulic performance. Oneissi et al. [13] recently reported an inclined projected winglet pair vortex generators which exhibits similar heat transfer rate as the classical delta winglet pair vortex generators with lower pressure drop penalty. Khanjian et al. [14] studied the effect of roll angle of rectangular winglet vortex generator on the heat transfer enhancement in laminar channel. They found that the optimal values of the roll-angle are not necessarily 90° degrees and an optimal roll angle 70° is reported for Re = 911.

Considering the requirement of compact heat exchanger with high energy efficiency, low weight and low cost, the optimization of fin and vortex generator parameters for the existing heat exchanger is still a hot issue. The position of VGs plays an important role in the heat transfer performance of tube-fin heat exchanger. Wu and Tao [9] carried out an extensive parametric study about the effect of type, shape, attack angle and height of VGs on heat transfer performance. They found that Nusselt number decreases with the increase of VG distance from the channel inlet and the decrease of space between VGs pair. While the location of VGs has no significant influence on total pressure drop of channel. Wu and Tao [15] also reported that reasonable arrangement of vortex generator's position, geometry and size can improve the heat transfer characteristics and reduce the pressure drop. Mamourian et al. [16] recently studied the distance between two vortex generators on the heat transfer performance, and they stated that the mean Nusselt number increases with the increase of distance which varies from 10 mm to 20 mm. Jang et al. [17] numerically investigated the optimal transverse location of VGs with a simplified conjugate-gradient method. They found that the strength of the longitudinal vortex, j factor and f factor increase with the increase of transverse location. Salviano et al. [18] numerically studied the optimization of winglet-type vortex generator positions and angles in plate-fin compact heat exchanger. They reported that the optimized VGs configurations lead to heat transfer enhancement higher than those reported in literature. Jayavel and Tiwari [19] made an investigation of effects of longitudinal tube pitch and transverse tube pitch on fin-tube heat exchanger with delta winglet vortex generators. Xu et al. [20] numerically investigated the effect of different set of winglet vortex generator on the thermal performance in a circular pipe. The best set of parameters for thermal performance enhancement is achieved at a blockage ratio of 0.1 and an attack angle of 30°. Lemouedda et al. [21] reported the best attack angle and the best arrangement of vortex generators in conditions of different tubes rows and different Reynolds numbers.

Although well developments have been achieved by many optimization studies focusing on the fin, tube and VG geometry, few researches dealt with the thermal-hydrodynamic optimization considering the interaction between longitudinal vortices generated by VGs. There are a few researches focusing on the interaction between longitudinal vortex and boundary layer [22–25]. These studies indicated a similar conclusion that boundary layer is strongly distorted by vortex and local heat transfer is locally enhanced when the fluid is induced toward the heat transfer wall. Salviano et al. [18] referred to the important flow interaction between longitudinal vortices and mentioned that both Colburn factor and friction factor are influenced by the flow interaction. But they did not discuss the details about this phenomenon. Zhu et al. [26] qualitatively analyzed the interaction of longitudinal vortices and their effects on flow field and heat transfer. Their results showed that the interaction has an obvious influence on vortex intensity and heat transfer performance. Song et al. [27] quantitatively studied the interaction of longitudinal vortices and its effect on the characteristics of periodically developed fluid flow and heat transfer. Valuable results were reported for the optimization of flat-tube-fin heat exchanger. The interaction of counter-rotating longitudinal vortices was quantitatively studied recently by Song [28]. The effects of transverse distance between two winglet VGs on the interaction of longitudinal vortices and heat transfer performance were studied and valuable results for the optimum arrangement of VGs were reported.

From the aforementioned review we can find that few researches were carried out aiming at the interaction between longitudinal vortices. Deeper understanding of the interaction between longitudinal vortices and their corresponding effect on heat transfer performance can not only explore the potential features of longitudinal vortices for heat transfer enhancement but also exploit their full potential for heat exchanger. In this paper, the effects of interaction of longitudinal vortices on flow field and heat transfer performance in the fin-side of flat-