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Interaction of counter rotating longitudinal vortices and the effect on fluid flow and heat transfer

KeWei Song, Song Liu, LiangBi Wang *

School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou, Gansu 730070, China
Key Laboratory of Railway Vehicle Thermal Engineering (Ministry of Education), Lanzhou Jiaotong University, Lanzhou, Gansu 730070, China

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ABSTRACT

The flow with longitudinal vortices is an important phenomenon in fluid dynamics and heat transfer. As the longitudinal vortices can potentially enhance heat transfer with small pressure loss penalty, vortex generators (VGs) which can generate longitudinal vortices are widely used to enhance the heat transfer of compact heat exchanger. In order to obtain a better heat transfer performance, researchers always try to punch lots of VGs out of the fin surface. But the increasing number of VGs is not necessarily linked with the rise in heat transfer performance augmentation. This is because the longitudinal vortices will interact with each other when they meet in the flow channel and the interaction between the longitudinal vortices is always disadvantage for the heat transfer enhancement. In this paper, numerical simulation of the interaction between two counter-rotating longitudinal vortices was carried out for the plate–fin heat exchanger using two rows of delta winglet type vortex generators. The effect of the transversal distance between the two VGs on the interaction of vortices and the effect of such interaction on heat transfer enhancement are studied in detail. New and important understandings about the interaction of counter-rotating longitudinal vortices are obtained. The intensity of the longitudinal vortices and the heat transfer performance are sensitive to the interaction between longitudinal vortices. The interaction between counterrotating vortices decreases the average intensity of vortices, but does not necessarily decrease the heat transfer performance of longitudinal vortices. The common flow region formed between the counterrotating longitudinal vortices is beneficial to the heat transfer enhancement though interaction takes place in the common flow region between longitudinal vortices. An optimum arrangement of VGs exists for obtaining the best heat transfer performance. The arrangement of VGs with the transversal distance is zero must be avoided due to the serious interaction between longitudinal vortices.

1. Introduction

The study of heat transfer enhancement plays an important role in the fields of chemical industry, energy, transport, aerospace, electronics cooling, etc. Kinds of heat exchangers are the most widely used heat exchanger equipments. But the heat transfer performance is limited by the gas side due to its dominant thermal resistance. Developing and innovating new techniques to enhance the heat transfer of a new compact heat exchanger is not only useful but also necessary for energy saving. The published findings state that longitudinal vortices can potentially enhance heat transfer with small pressure loss penalty and a better heat transfer effect than that of latitudinal vortices [1].

The longitudinal vortices can cause bulk fluid mixing, boundary layer modification, flow destabilization, and thereby enhance convective heat transfer [2]. Setting protrusions that can generate longitudinal vortices on the fin surface is a promising technique to enhance the airside heat transfer. There are many protrusions that can generate longitudinal vortices. Vortex generators (VGs) are among the most popular actuators for the fin-side heat transfer enhancement. The effectiveness of a vortex generator in enhancing the heat transfer depends on the vortex strength generated per unit area of the vortex generator [3]. The winglet vortex generator is capable of enhancing heat transfer with less increase in pressure penalty compared with other type of protrusions [4,5]. Ahmad et al. [6] performed an overview on heat transfer augmentation using longitudinal vortex generators.

Longitudinal vortices are generated by flow separation along the side edges of the VGs due to the pressure differences between the upstream and downstream sides, and are perpendicular to the

* Corresponding author at: School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou, Gansu 730070, China. Tel.: +86 931 4956556.
E-mail address: lbwang@mail.lzjtu.cn (L. Wang).

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Nomenclature

A	surface area involved in heat transfer or cross sectional area (m^2)
$A(x)$	cross sectional area at position x (m^2)
b	longitudinal pitch between VGs (m)
c	transverse pitch between VGs (m)
c_p	specific heat capacity (J/(kg K))
d_h	hydraulic diameter, characteristic length (m)
f	friction factor
h	height of winglet-type VGs (m) or heat transfer coefficient (W/(m^2 K))
H	fin spacing (m)
J^n	vorticity flux in the normal direction of the cross section (1/s)
JF	surface goodness factor
l	base length of vortex generator (m)
L	stream-wise length of the simulation domain (m)
n	direction normal to the cross section
Nu	Nusselt number: $Nu = hd_h/\lambda$
P	Pressure loss (Pa)
Re	Reynolds number: $Re = \rho u_m d_h/\mu$
S	the width of the simulation domain
Se	secondary flow intensity
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)
x, y, z	coordinates

Greeks

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

Subscripts

ABS	absolute value
bulk	bulk temperature on the cross section
local	local value
s	span-average or cross-section-average value
w	solid surface

main flow direction. A description of the typical vortices structure formed by VG is given in some publications [7,8]. There is a main vortex that is formed as a result of the flow separating in the tip of the half-delta wing and rolling up due to the lower pressure in the back side of the vortex generator. Then there is a corner vortex that is horseshoe-like vortices formed in the corner between the front side of the wing and the fin. Finally there is an induced secondary vortex which is formed in the corner between the back side of the wing and the fin as a result of the redirection of the near wall flow caused by the lower pressure behind the generator.

In order to obtain a better heat transfer performance, researchers always try to punch lots of VGs out of the fin surface [9–16]. However, the increasing number of VGs is not necessarily linked with the rise in heat transfer performance augmentation. This is because the longitudinal vortices can interact with each other when they meet in the flow channel and the interaction of longitudinal vortices affects the intensity of vortices and their effect on heat transfer enhancement [17]. Experimental and numerical studies focusing on the interactions between vortices and boundary layers have been carried out in Refs. [18–23]. These results about the effect of interaction between the vortices and the boundary layer on the heat transfer indicated that in the region where two neighboring vortices induced flow toward the heat transfer surface, local heat transfer was locally enhanced. Conversely, in the regions where neighboring vortices induced outflow departs the heat transfer surface, the local heat transfer was decreased. Close proximity of other vortices strongly affects the spreading of the vorticity and the heat transfer modification produced by the vortex was strongly dependent on vortex interaction [17]. These previous works have shown that the strength of the vortices interaction with the wall is strongly dependent on the arrangement of vortices in the array. However, seldom works consider the interaction of longitudinal vortices and their effect on heat transfer. Yang et al. [24] numerically analyzed the effect of flow field and heat transfer created by interaction between a pair of vortices generated by vortex generators in rectangular channel. Song et al. [25] experimentally studied and found that the longitudinal vortices intensity decreases due to the interaction between two counter-rotating longitudinal vortices. Zhu et al. [26] qualitatively analyzed the effect of interaction of longitudinal vortices generated by winglet vortex generators on heat transfer enhancement of a flat tube bank fin heat exchanger. The arrangement of the VGs affects the interaction between the longitudinal vortices and the heat transfer performance of the VGs. But the quantitative study of the interaction of longitudinal vortices was seldom reported due to the lack of parameter that can define the intensity of longitudinal vortices. Song et al. [27] recently defined a secondary flow intensity parameter which provides a powerful tool for the quantitative study of the interaction between longitudinal vortices.

Above mentioned papers show that most of the researches focus on the application of longitudinal vortices to enhance heat transfer, but quantitative study about the interaction between longitudinal vortices and the effect of interaction on fluid flow and heat transfer was seldom reported. Until today there exists very little work and much less is known about the interaction between the longitudinal vortices. Therefore it is necessary to research into the interaction of longitudinal vortices and their effect on heat transfer enhancement. In this paper, the interaction of two counter-rotating longitudinal vortices was numerically studied. The effect of transverse distance of the VGs on the intensity of the vortices and the effect of interaction on fluid flow and the intensity of vortices and heat transfer were analyzed quantitatively. New and important understanding about the interaction of counterrotating longitudinal vortices is obtained.

2. Physical model

As stated above, the longitudinal vortices can provide good performance for fluid flow and heat transfer enhancement. As the intensity of the longitudinal vortices decreases along the main flow direction, in order to obtain a high intensity of longitudinal vortices in the flow field, lots of VGs are always protruded into the flow field. Different arrangements of VGs will generate longitudinal vortices with different intensity and different rotating directions. These vortices with different rotating directions will inevitably meet and interact with each other when they are flowing downward. The interaction between these vortices affects not only the intensity of the vortices but also the heat transfer enhancement of the