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The mechanism of heat transfer enhancement using longitudinal vortex generators in a laminar channel flow with uniform wall temperature

Qiang Zhang [a, b], Liang-Bi Wang [a, b, *], Yong-Heng Zhang [a, b]

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

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A B S T R A C T

Heat transfer enhancements are used extensively to improve the performance of heat exchangers and to reduce their running cost. Longitudinal vortices can enhance heat transfer greatly. To enrich the mechanism of heat transfer enhancement produced by longitudinal vortices, this paper addresses the mechanisms of heat transfer enhancement enforced by longitudinal vortices generated by vortex generators (VGs) from another view point. The view point is based on the convective transport equation of heat flux, a description of convective heat transfer process in the process parameter of heat flux **q**. Based on this view point, the heat transfer enhancement mechanism is explained by the contributions of the combinations of flux with velocity gradient and velocity with flux gradient to the heat transfer. To find these contributions the heat transfer in a channel with and without VGs is studied numerically, and the differences of these contributions under conditions with and without VGs are compared in the frame of the convective transport equation of heat flux. The results show that longitudinal vortices greatly enhance the local convection contribution terms that promote the local transport of heat flux in span direction, which enforces the transports of heat flux along the main flow direction and heat flux along the normal direction by enlargements of the values of the corresponding convection contribution terms. The later results in the increase of the heat flux per unit temperature difference on the top and the bottom surfaces, and hence the heat transfer enhancement is enforced by longitudinal vortices. The local terms intensify the local transport of heat flux in span direction, but do not do so in an average measure in the presently studied case.

1. Introduction

Heat exchangers are widely used in many fields. It is very important to reduce their energy and material consumption, and to improve their efficiency. To design heat exchangers with good performance, many methods of heat transfer enhancement are used. Thus, the investigations on heat transfer enhancement have been intensified. Heat transfer enhancement with small energy consumption may be achieved by generating structured secondary flow via longitudinal vortices [1–45]. This method has received more attention because it introduces relatively small friction loss of fluid flow with enhanced heat transfer [1–45]. The reason is that the wall friction loss depends mainly on the wall normal gradient of the velocity component along the main flow direction, and does not depend on the gradient of the velocity components formed by secondary flow, so this method has been attributed to the heat transfer enhancement methods of the third generation [11,12,16].

The effects of a single longitudinal vortex embedded in one side of the wall in the turbulent boundary layer on heat transfer were experimentally studied by Eibeck and Eaton [3,8]. Pauley and Eaton [7] studied the effects of a longitudinal vortex pair embedded in one side of the wall in a turbulent boundary layer on heat transfer characteristics. The results show that the vortex pair decays slower in a longer distance than a single vortex does, which has a great impact on heat transfer. Russell [4] carried out an experimental study of a pair of embedded vortex generators (VGs) on the channel and compared their heat transfer and pressure drop characteristics. It is found that a pair of embedded vortex generators is a superior

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

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Nomenclature

a	height of rectangular winglet, m
A	area of heat transfer, m^2
b	base length of winglet, m
B	width of the channel, m
c_p	specific heat capacity, kJ/kgK
d_e	hydraulic diameter of flow channel, m
f	friction factor: $f = \Delta p\ d_e/(L_x \rho u^2{}_{max}/2)$
g	height of vortex generator
h	convective heat transfer coefficient, W/m^{2}K
H	height of channel, m
J	heat transfer enhancement factor
l	span length of the rectangular winglet, m
L	length of the channel, m
n	normal direction
Nu	Nusselt number: $Nu = hd_h/\lambda$
p	static pressure, Pa
q	component of heat flux, W/m^2
$\mathbf{q}$	heat flux vector, W/m^2
Re	Reynolds number: $Re = \rho \cdot u_{max} \cdot d_e/\mu$
S	distance between the tips of rectangular winglet, m
SW	span average convection contribution term, W/m^{2}s
T	temperature, K
t	time, s
u, v, w	components of velocity vector, m/s
W	convection contribution term, W/m^{2}s
X_v	axial distance from the entrance to the wing tip, m
x, y, z	coordinates, m

Special characters

ρ	density, kg/m^3
μ	Viscosity, kg/(ms)
λ	thermal conductivity, W/mK
Δ	difference value
B	attack angle of vortex generator, °
ξ, η, ζ	coordinates, m

Subscripts

a	air
bulk	cross-section averaged value
c-x,c-y,c-z	related to velocity
e-x,e-y,e-z	related to velocity gradient
f	fluid
in	inlet
local	local value
m	average value
plain	channel of without VGs
s	span average value
w	wall
x, y, z	along the coordinate directions

method to enhance heat transfer. The capacity of heat transfer enhancement of VGs depends on their shape [10,19,22,31,34,37,44] and other parameters such as the angle of attack [1–20,23,24,27,28,32,33,36,39,40], the height of VGs [1–20,23,24,27,28,32,36,39,40], the arrangement of VGs [21,25,35,38], the ratio of the size of VGs to the size of the channel [26] and the manufacturing type of VGs (VGs are mounted or punched) [26,27]. According to the reports of Tiggelbeck et al. [10], the best performance is given by the delta winglets, closely followed by the rectangular winglets. For the flat tube bank fin heat exchanger, the optimum attack angle of VGs is 40° [45], and the optimum height of VGs is 0.8 times the net fin spacing [20]. Didarul [25] found that heat transfer with rectangular VGs of jagged arrangement is better than that of the same angle arrangement. Wang et al. [26] found that heat transfer is enhanced significantly when the longitudinal vortex generators are mounted in the narrow channel, Wu et al. [27] studied heat transfer enhancement by punching rectangular winglets and triangular winglets of rectangular channel in laminar fluid flow, the results show that strong heat transfer enhancement and low coefficient of flow friction in the zone near the winglet is affected by punching holes in the wall. Wang et al. [29] found that mounted VGs have no obvious difference with punched VGs.

The longitudinal vortices can be classified as secondary flow, which is the flow on the cross section normal to the main flow. Recently, our group found that the intensity of secondary flow determines the heat transfer characteristics of the fin side of tube bank fin heat exchanger having VGs on the fin surface [30,41–44]. A dimensionless parameter of the intensity of secondary flow is given by Song et al. [42]. This literature indicates that in many cases of using VGs as the measure to enhance heat transfer, the intensity of secondary flow determines the heat transfer characteristics.

The above mentioned literature is only a small part of the literature that addresses the heat transfer enhancement using VGs. This literature mainly presents the characteristics of the heat transfer enhancement enforced by VGs, and VGs' parametric effect on heat transfer enhancement. Above mentioned literature demonstrates that longitudinal vortices can enhance the momentum and heat exchanges between vortices and the boundary layer, produce strong flow instability, and also increase the mixture of fluid in different temperatures. These are the presently acknowledged heat transfer enhancement mechanisms produced by longitudinal vortices. Unfortunately, these acknowledged mechanisms are too vague to be discovered in detail. Until now, they have not been strictly proven by some suitable terms in available equations describing convective heat transfer. Motivated by this fact, the present paper tries from another view point to address the mechanisms of heat transfer enhancement enforced by longitudinal vortices. The view point is based on the recent works done by our group [46–51], which have reported a description of the convective heat transfer process in the process parameter of **q**: convective transport equation of heat flux. This equation shows that the velocity gradient and the velocity have different contributions to convective heat transfer, and also these contributions are dependent on the heat flux transferred and its gradient itself. To find these contributions, the heat transfer in a channel with and without VGs is studied numerically in this paper, and the differences of these contributions under conditions with and without VGs are compared in the frame of the convective transport equation of heat flux. Based on these differences the mechanism of heat transfer enhancement enforced by longitudinal vortices is disclosed.

2. Physical model and mathematic formulation

Regarding the motivation of this paper, it does not try to repeat the studies performed by available literature, such as studying the parameter effects of VGs on heat transfer characteristics. Instead, this paper tries to compare the differences of heat transfer under