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Novel design of delta winglet pair vortex generator for heat transfer enhancement

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A B S T R A C T

Heat transfer is a naturally occurring phenomenon that can be greatly enhanced with the aid of vortex generators (VG). Three-dimensional numerical simulations of longitudinal vortex generators are performed to analyze heat transfer enhancement in parallel plate-fin heat exchanger. The shear-stress transport (SST) κ-ω model is adopted to model the flow turbulence. Empirical correlations from the open literature are used to validate empty channel simulations. First, numerical simulations are conducted for the classical delta winglet pair (DWP) which is introduced as the reference case in this study. Then, an innovative VG configuration, named inclined projected winglet pair (IPWP), is examined and it shows superior performance relative to the DWP. The IPWP exhibits similar heat transfer rates than that of the DWP but with lower pressure drop penalty due to its special aerodynamic design. The local performance is analyzed based on the streamwise distribution of Nusselt number and friction coefficient criteria in addition to vorticity. This study highlights the different mechanisms involved in the convective heat transfer intensification by generating more vortices using more aerodynamic VG shape while decreasing the pressure drop penalty.

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1. Introduction

The use of vortex generators (VG) in the various industrial fields is widespread ranging from compact heat exchangers to aeronautics [1–4]. In the field of heat exchangers, the role of the VG is the enhancement of the heat exchange process between the wall and the working fluid. This enhancement relies on generating a secondary flow in form of complex streamwise and transverse vortices. The vortices disrupt the growth of the boundary layer and eventually serve in enhancing the heat transfer [5]. For this intention, two enhancement methods can be implemented: the active VG method and the passive VG method [6]. Passive VG are more commonly used since they are characterized by their efficiency, economy, manufacturing simplicity and maintenance ease, opposite to active VG which are energy consumers and less easy to implement. These VG have various types which include helical and twisted inserts [7,8], dimples or protrusions [9,10], cylindrical tubes [11–14], transverse vortex generators (TVG) [10,15,16], longitudinal vortex generators (LVG) [17–23], plane or curved surface of VG [24,25] or a combination of the above types [10,22,26–29].

Transverse vortices are two-dimensional flows with axes normal to the flow direction, while longitudinal vortices rotate about an axis in the streamwise direction, implying a three-dimensional swirling flow. When pressure losses are taken into account, LVG are found to have an advantage over TVG in terms of global mixing and heat transfer performances [30].

This paper focuses on the study of LVG and their unique capability in heat transfer enhancement through the generation of large scale longitudinal vortices. This enhancement is a result of the combination of the main mechanisms of heat transfer intensification: the reduction of the laminar sub layer thickness near the wall, the development of three-dimensional turbulent layers and the swirl motion of the streamwise vortices that enhances convective transfer [31,32].

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Nomenclature

A	cross-sectional area
B	channel width, m
C_p	specific heat at constant pressure, J $(\text{kgK})^{-1}$
D_h	hydraulic diameter, m
f	Fanning friction factor, *dimensionless*
H	channel height, m
h	convective heat transfer coefficient, W $(\text{m}^2\text{K})^{-1}$
j	Colburn factor, *dimensionless*
k	thermal conductivity, W$(\text{mK})^{-1}$
L	channel length, m
l	Vortex generator span, m
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number, *dimensionless*
Pe	Péclet number = *Re Pr*, dimensionless
Po	Poiseuille number, *dimensionless*
Pr	Prandtl number, *dimensionless*
ΔP	pressure drop, Pa
q''	heat flux
Re	Reynolds number, *dimensionless*
s	distance between tips of winglet pair, m
$T_{b,x}$	bulk temperature at position x, K
T_i	inlet temperature, K
T_o	outlet bulk temperature, K
T_s	surface temperature, K
U	mean flow velocity across the cross section, m s^{-1}
u	flow velocity in x direction, m s^{-1}
v	flow velocity in y direction, m s^{-1}
w	flow velocity in z direction, m s^{-1}
x_v	distance of wingtips from the channel entrance, m
z	Vortex generator height, m

Greek letters

μ	dynamic viscosity, Pa s
ν	kinematic viscosity, m^2 s^{-1}
ρ	fluid density, kg m^{-3}
β	angle of attack, °

Abbreviations

VG	Vortex Generator
DWP	Delta Winglet Pair
RWP	Rectangular Winglet Pair
IPWP	Inclined Projected Winglet Pair
LVG	Longitudinal Vortex Generator
TVG	Transverse Vortex Generator
CFD	Computational Fluid Dynamics
SST	Shear-Stress Transport
TEF	Thermal Enhancement Fraction, *dimensionless*

Winglet pairs exist in two configurations, one is the common flow-down and the other is the common flow-up. When the transverse distance between leading edges is less than that of trailing edges, the configuration is known as common flow-down and vice-versa [33]. Common flow-down vortices create down-wash in between, and up-wash flow in the outside regions. Along the streamwise direction, the vortices' velocity vectors decrease while the distance between vortex cores increases which leads to the thinning of the thermal boundary layer [33]. Tian et al. [34] compared delta-winglet pair (DWP) with rectangular winglet pair (RWP) for common flow-down and common flow-up configurations and deduced that DWP in common flow-down geometry is more efficient than other configurations. Biswas et al. [5] studied the performance of a delta winglet type VG and concluded that such VGs show great promise for enhancing the heat transfer in plate-fin heat exchangers. Meanwhile, common flow-up configuration also seems to be important to study as future work in some applications. In fact, Jain et al. [35] proposed a common flow-up configuration delta winglet that causes significant separation delay, reduced form drag and removes the zones of poor heat transfer.

The present work focuses on designing a better aerodynamic VG shape that can provide the same heat transfer with a reduced pressure drop when compared to the DWP as a reference case. The new VG increases the global thermal enhancement with an average of about 6% and the averaged global pressure drop decreases by about 10% over a wide range of Reynolds numbers. Moreover, the effect of the new VG geometry on the flow structure and thus on the heat transfer mechanism is analyzed.

The numerical method, computational domain and mesh sensitivity analysis are presented in the problem statement in section 2. Numerical validation, global performance followed by local examination of the heat transfer phenomena and compactness comparison are discussed in section 3. Finally, section 4 is devoted to the concluding remarks.

2. Problem statement

2.1. Numerical model

The flow field is governed by the three-dimensional (3D) steady-state Reynolds averaged Navier-Stokes (RANS) equations. The continuity and momentum equations for an incompressible Newtonian fluid are:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2_{u_i}}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \tag{2}$$

where the term - $\overline{u_i' u_j'}$ is the Reynolds stress tensor resulting from the averaging procedure on the nonlinear convective terms in the momentum equations.

The heat transfer is governed by the energy equation given below:

$$\frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial x_i}\left(\lambda_{eff}\frac{\partial T}{\partial x_i}\right) \tag{3}$$

where E is the total energy and λ_{eff} the effective thermal conductivity.

The solver used for the flow computation is the ANSYS Fluent 15, which is based on an Eulerian approach to solve the Cauchy equations through cell-centered finite volume discretization [10]. The code computes the conservation equations for mass and momentum in addition to the energy equation [36]. Turbulence models allow the calculation of the mean flow without first calculating the full time-dependent flow field.

In this study, for laminar flows (Re = 270, 540 and 1080) the laminar model is used whereas for turbulent flows (Re = 2800,

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