International Journal of Thermal Sciences 134 (2018) 541–551

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Heat transfer enhancement of inclined projected winglet pair vortex generators with protrusions

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ARTICLE INFO

Keywords:
Heat transfer enhancement
Winglet pair
Vortex generator
Protrusions
Plate-fin heat exchanger
Numerical simulation

ABSTRACT

Heat transfer enhancement in parallel plate-fin heat exchanger is examined by performing three-dimensional numerical simulations of longitudinal vortex generators (VG) with protrusions. The turbulence is modeled using the shear-stress transport (SST) κ-ω model and validated with correlations and experimental data at Reynolds number equal to 4600. Hemi-spherical protrusions are inserted downstream two VG configurations: delta winglet type (DWP) and a new VG configuration named inclined projected winglet pair (IPWP), in various locations, leading to the definition of six different configurations. Based on the streamwise distribution of Nusselt number and friction coefficient criteria in addition to vorticity, the local performance is analyzed. Some VGs with protrusions are examined and show better performance relative to VGs standing alone. The present study highlights the different mechanisms involved in the convective heat transfer intensification by generating multiple interacting vortices while adding protrusions with low pressure drop penalty. Finally, it is found that the IPWP with protrusions, set downstream in the middle, bestows the best global performance with about 7.1% heat transfer enhancement compared to DWP configuration.

1. Introduction

Flow structure characteristics are fundamental for heat transfer augmentation in parallel plate-fin heat exchanger. In fact, the amount of surface heat transfer augmentation is controlled by the topology of secondary flows, three-dimensionality, shear-layer reattachment and turbulence transport induced by the devices employed on the walls of the internal passages. These devices may include cylindrical tubes [1,2], transverse vortex generators (TVGs) [3], longitudinal vortex generators (LVGs) [4,5], plane or curved VGs [6], dimples or protrusions [7], or even a combination of the above types [8,9].

These components are used in various industrial fields including electronics cooling, micro and macro-scale heat exchangers, combustion chambers and chemical reactors. This paper focuses on the addition of hemi-spherical protrusions downstream two types of LVGs, and on their capability in heat transfer enhancement caused by the generation of strongly interacting large scale longitudinal vortices. This heat transfer intensification results from the combination of three main mechanisms of heat transfer enhancement: the reduction of the laminar sub layer thickness near the wall, the development of three-dimensional turbulent layers and the swirl movement of the streamwise vortex that enhances the convective transfer, as described by Tiggelbeck et al. [10].

Protrusions downstream VGs show a significant effect on the heat transfer process since by disturbing the thin boundary layer at the wall, thus increasing the local Nusselt number as shown by Habchi et al. [11]. In fact, the addition of hemispherical protrusions between the vortex generator arrays greatly enhances the heat transfer with only a small increase in pressure drop [11]. This increase in local heat transfer is caused by increasing the temperature gradients and vorticity very close to the heated wall.

Ligrani et al. [12] reported that stronger secondary flows are present over a much larger portion of the channel cross section when protrusions are added. Secondary flow generated by protrusions enhances greatly the heat transfer process. Hwang et al. [13] explained how a dimple-protrusion patterned wall affects the heat transfer characteristics. Xie et al. [14], Li et al. [15] and Sangtarash et al. [16] showed in their investigation of flow and heat transfer in rectangular channel with dimple-protrusion geometry, that protrusions exhibit greater thermal enhancement with higher friction cost than dimples. Chen et al. [17] concluded that larger height of dimple-protrusion

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https://doi.org/10.1016/j.ijthermalsci.2018.08.032
Received 15 January 2018; Received in revised form 20 June 2018; Accepted 16 August 2018

Nomenclature

A	Cross-sectional area, m^2
A_f	Fin area, m^2
B	Channel width, m
C_p	Specific heat at constant pressure, $J\ kg^{-1}K^{-1}$
D_h	Hydraulic diameter, m
f	Friction factor
H	Channel height, m
h	Convective heat transfer coefficient, $W\ m^{-2}K^{-1}$
j	Colburn factor
k	Thermal conductivity, $W\ m^{-1}K^{-1}$
L	Channel length, m
l	VG span, m
$\dot{m}$	Mass flow rate, $kg\ s^{-1}$
Nu	Nusselt number
Pe	Péclet number = $Re.\ Pr$
Po	Poiseuille number
Pr	Prandtl number
ΔP	Pressure drop, Pa
$q"$	Heat flux, $W\ m^{-2}$
Re	Reynolds number
s	Distance between tips of winglet pair, m
$T_{x,b}$	Bulk temperature at position x, K
T_i	Inlet bulk temperature, K
T_o	Outlet bulk temperature, K
T_s	Surface temperature, K
U	Mean flow velocity, $m\ s^{-1}$
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	VG height, m

Greek letters

μ	Dynamic viscosity, $Pa\ s$
ν	Kinematic viscosity, $m^2\ s^{-1}$
ρ	Fluid density, $kg\ m^{-3}$

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 factor
PRO	Protrusion
HS	High Spacing
M	Middle

induces higher friction factor and Nusselt number. Bilir et al. [18] studied the optimization of the fin-tube and protrusion geometries of finned tube heat exchanger and investigated the cumulative effect of three protrusions. They concluded that the use of several protrusions provides better heat transfer performance, but increases the pressure drop, compared to the case with only one protrusion. Barik et al. [19] investigated turbulent heat transfer and fluid flow characteristics of a small rectangular channel with different protruded surfaces. An air jet impinging normal to the main flow is activated and this hybrid cooling strategy increases the pumping power in the cases with protrusions compared to that of without protrusions. The heat transfer enhancement rate is highlighted in the cases of protrusions, especially the increase with triangular protrusions is found to be more important when compared to other protrusion shapes.

The aim of the present study is to analyze the effect on the flow structure and heat transfer mechanisms of adding protrusions downstream two types of VGs. The originality of the present study lies in the way protrusions have been located downstream the VGs. In fact, their location was based on a thorough local analysis of the flow structure downstream the VG as discussed later in sections 2.2.3 and 2.2.4. Moreover, this study is performed for a novel VG designed in a previous study by Oneissi et al. [20].

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 analysis of the heat transfer phenomena and compactness comparison are discussed in section 3. Finally section 4 is dedicated to the concluding remarks.

2. Problem description

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:

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

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

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, and the energy equation is:

$$\rho c_p \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{x_i}} = \frac{\partial}{\partial \boldsymbol{x_i}}\left(\lambda_{eff}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{x_i}}\right) \tag{3}$$

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

The solver used for the flow computation is the code ANSYS Fluent 15, which is based on an Eulerian approach to solve the Navier-Stokes equations through cell-centered finite volume discretization [11]. The code solves the conservation equations for mass and momentum in addition to the energy equation for flows involving heat transfer [21]. RANS turbulence models allow the calculation of the mean flow without first calculating the full time-dependent flow field.

For turbulent flows, Re = 4600 is used in this study, the shear-stress transport (SST) κ-ω model developed by Menter [22] is used. This model solves two additional partial differential equations, a modified version of the turbulence kinetic energy equation κ used in κ-ε model and a transport one for the specific dissipation ω. Also, the shear stress transport (SST) combines the use of κ-ω formulation in the inner parts of the boundary layer and the switching to a κ-ε behavior in the free-stream thus avoiding the κ-ω sensitivity to the inlet free-stream turbulence properties. In addition to that, it is characterized by its good behavior in adverse pressure gradients and separating flows while attaining accuracy and reliability [21].

The preceding attributes give the SST κ-ω model additional accuracy and reliability thus providing it an advantage over the standard κ-ω model. Moreover, the SST κ-ω model was used by many researchers in previous works that gave a fair matching with experimental results, as discussed by Yongsiri et al. [23] and Tang et al. [24].

This approach necessitates assessment of the wall adjacent cell size