International Journal of Thermal Sciences 109 (2016) 323–333

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

# Numerical simulation on performances of plane and curved winglet – Pair vortex generators in a rectangular channel and field synergy analysis

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A R T I C L E I N F O

*Article history:*
Received 17 September 2015
Received in revised form
9 June 2016
Accepted 10 June 2016
Available online 20 June 2016

*Keywords:*
Curved trapezoidal winglet
Heat transfer enhancement
Vortex generator
Field synergy principle

A B S T R A C T

Thermal and flow characteristics of plane and curved longitudinal vortex generators (LVGs) are investigated and the corresponding mechanism is analyzed based on field synergy principle (FSP). 3 – D numerical simulations are carried out in a channel flow ($Re$ = 700–26500) embedded with a pair of plane and curved delta, trapezoidal and rectangular winglet – type LVGs, respectively. The effects of the these LVGs are examined and compared using the dimensionless parameters $Nu_m/Nu_{m0}$, $f/f_0$ and $R = (Nu_m/Nu_{m0})/(f/f_0)$. The results show that the curved trapezoidal winglet pair (CTWP) provides the best thermo – hydraulic performance with the value of $R$ ranging from 0.68 to 1.14 under the present conditions. Parametric study on CTWP reveals that the attack angle of $\beta = 45°$ and inclination angle of $\alpha = 20°$ perform better than other conditions. The heat transfer characteristics and flow structure are explored with the help of secondary velocity vectors, streamlines and isotherms. The volume – average synergy angle $\theta_m$ between velocity vector and temperature gradient first decreases with $\beta$, reaches the minimum value for $\beta = 45°$, and then rises back to the maximum value for $\beta = 90°$. Correspondingly, the $Nu_m/Nu_{m0}$ shows the opposite trend to $\theta_m$ while varying with $\beta$. It is confirmed that the maximum value of heat transfer augmentation is achieved at the minimum synergy angle, which indicates that the mechanism of heat transfer enhancement can be well explained by FSP.



## 1. Introduction

Heat transfer enhancement is of significant importance in such fields as power systems, automobile industry, heating, ventilation, air conditioning systems and aerospace, etc. However, as the heat transfer performance improves, the corresponding pressure drop also becomes tremendous for conventional passive methods such as adding fins or baffles.

As is known that the air side thermal resistance is inherently higher than that on the liquid side for air – to – liquid and phase – change heat exchangers (HXs). A passive strategy for air – side heat transfer enhancement is to use longitudinal vortex generators (LVGs), which can be stamped on or punched out from the surface of HXs. The earlier work using LVGs for heat transfer enhancement was reported by Johnson and Joubert in 1969 [1]. They found that the local $Nu$ (Nusselt number) was increased at the position of LVGs, while the overall $Nu$ was not much increased due to the decrease elsewhere on the cylinder. Tiggelbeck et al. [2] experimentally investigated the heat transfer enhancement and drag in transitional channel flow containing double rows of delta winglets. They reported that the critical angle of attack for the formation of longitudinal vortices behind the second row was smaller than that behind the first one, and heat transfer coefficient and drag were increased by 80% and 160%, respectively. Tiggelbeck et al. [3] compared several wing – type LVGs for heat transfer enhancement using liquid crystal thermograph method. They found the drag induced by LVGs was nearly proportional to the projected area and independent of $Re$ and the shape of LVGs. Fiebig et al. [4,5] studied the thermal – hydraulic characteristics of LVGs in the form of delta wing, delta winglet pair, rectangular wing and rectangular winglet pair in the rectangular channel flow. They quantitatively discussed the heat transfer enhancement mechanism in three ways: (1) developing boundary layers on the LVGs surface; (2) swirling; and (3) flow destabilization. The followed results were also presented: (1) winglets brought about higher heat transfer enhancement than wings for otherwise identical parameters; (2)

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.06.024
1290-0729/

**Nomenclature**

| | |
|---|---|
| $a$ | chord length of vortex generator (m) |
| $b$ | width of vortex generator (m) |
| $c_p$ | specific heat (J kg$^{-1}$ K$^{-1}$) |
| CDWP | curved delta winglet pair |
| CRWP | curved rectangular winglet pair |
| CTWP | curved trapezoidal winglet pair |
| $D$ | hydraulic diameter of the air channel (m) |
| DWP | delta winglet pair |
| $f$ | fraction factor |
| $f_0$ | friction factor of smooth channel |
| $h$ | height of vortex generator (m) |
| $H$ | channel height (m) |
| $h_c$ | convective heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $L$ | channel length (m) |
| LVGs | longitudinal vortex generators |
| $Nu$ | Nusselt number |
| $Nu_0$ | Nusselt number of smooth channel |
| $p$ | pressure (Pa) |
| $P$ | distance between leading edge of vortex generator and channel inlet (m) |
| $P_{in}$ | pressure of the inlet (Pa) |
| $Pr$ | Prandtl number |
| $R$ | overall performance factor $(Nu/Nu_0)/(f/f_0)$ |
| $Re$ | Reynolds number |
| RWP | rectangular winglet pair |
| $S$ | front edge pitch of a pair of vortex generators (m) |
| $T$ | temperature (K) |
| $T_\infty$ | free − stream fluid temperature (K) |
| TWP | trapezoidal winglet pair |
| $U$ | velocity profile (m s$^{-1}$) |
| $U_\infty$ | free − stream fluid velocity (m s$^{-1}$) |
| $\overline{U}$ | dimensionless fluid velocity |
| $u_i$, $u_j$, $u_k$ | $x$, $y$, $z$ velocity components (m s$^{-1}$) |
| $W$ | channel width (m) |
| $x$, $y$, $z$ | Cartesian coordinates |

*Greek letters*

| | |
|---|---|
| $\alpha$ | inclination angle of LVGs (°) |
| $\beta$ | attack angle (°) |
| $\delta_t$ | thermal boundary layer thickness (mm) |
| $\Delta p$ | pressure difference between inlet and outlet of the channel (Pa) |
| $\theta$ | synergy angle (°) |
| $\lambda$ | thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\rho$ | density (kg m$^{-3}$) |
| $\omega$ | secondary flow intensity (s$^{-1}$) |
| $\Omega$ | dimensionless secondary flow intensity |

*Subscripts*

| | |
|---|---|
| m | average value |
| s | cross section − average value along flow direction |
| *i, j, k* | $x$ direction, $y$ direction and $z$ direction, respectively |
| in | inlet |

the heat transfer enhancement was higher in laminar flow than that in turbulent flow; (3) for single vortex generators, heat transfer enhancement increased with the angle of attack and peaked at around 45°. Biswas et al. [6] studied the flow structures of LVGs in channel flow in numerical and experimental methods. They found the vortices were complex and consisted of a main vortex, a corner vortex and induced vortices. The combined effect of these vortices distorted the temperature field in the channel and ultimately brought about the heat transfer enhancement between the fluid and its neighboring surface. Torii and Kwak [7,8] proposed a common − flow − up configuration of winglets, which could augment heat transfer but nevertheless reduce pressure loss in a fin − tube heat exchanger. The results showed that heat transfer was increased by 10–30% and meanwhile the pressure loss was reduced by 34–55% for a single row of winglets placed in staggered arrangement compared with the situation without winglets. Kim and Yang [9] studied the flow and heat transfer characteristics of a pair of embedded counter − rotating vortices using thermo − chromatic liquid crystal method and they found that the common − flow − down cases showed better heat transfer characteristics than the common − flow − up cases. Different arrangements of LVGs to optimize the heat transfer enhancement and flow loss have been experimentally studied in Refs. [10–12] and the results showed that specially designed configuration could optimize the heat transfer coefficient. In addition to the study on configurations of LVGs, the development of new shape of LVGs attracts many researchers in recent years. Min et al. [13] experimentally investigated the modified LVGs by cutting off the four corners of a rectangular wing and the heat transfer performance was reported to be improved. Zhou et al. [14,15] proposed a kind of LVG called curved trapezoidal winglet and experimentally investigated its performance of heat transfer enhancement and flow resistance by comparison with those of traditional vortex generators − rectangular winglet, trapezoidal winglet and delta winglet. The results indicated that curved trapezoidal winglet pair performed better in fully turbulent region with higher heat transfer enhancement and lower pressure loss. Caliskan [16] studied the heat transfer enhancement of punched LVGs using the infrared thermal image technique. He reported 23–55% increase in heat transfer performance and correlations for $Nu$ were developed for corresponding LVGs.

Wang et al. [17] numerically studied the hydrodynamic performances from a rectangular channel fitted with LVGs and found the heat and mass transfer were intensified for a transient − state flow. Wu and Tao [18] investigated four horizontally placed plates with a pair of delta winglets punched directly from the plates at an attack angle of 15°, 30°, 45°, 60°, respectively. And the results revealed that the average $Nu$ on the plate increased with the increase of attack angle. Du et al. [19] numerically studied the flow structure and heat transfer enhancement of LVGs applied in direct air − cooled condenser using RNG $k$–$\varepsilon$ model and found that the delta winglet pair with attack angle of 25° could reach the optimum thermal and flow performances. Gong et al. [20] fitted curved rectangular vortex generators in the wake regions of a fin − tube exchanger and found that the heat transfer performance was significantly improved.

The inherent mechanism of heat transfer enhancement by LVGs can be explained in two folds from the above literature: (1) the secondary flow induced by LVGs swirls and disturbs the fluid flow; (2) the boundary layer is distorted and thinned, which are mainly