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Experimental investigation of heat transfer in a channel with new winglet-type vortex generators

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ABSTRACT

Both new punched triangular vortex generators (PTVGs) and punched rectangular vortex generators (PRVGs) have been developed. Both the triangular and rectangular vortex generators were directly punched from the longitudinal winglet at attack angles of 15°, 45° and 75°, respectively. Measurements were carried out for a rectangular channel of an aspect ratio of AR = 2, for a winglet transverse pitch (S) to a longitudinal winglet height (e) ratio of S/e = 0.59, and a winglet height (e) to a channel height (H) ratio of e/H = 0.6. The parameters included the location of the punched vortex generator on the longitudinal winglet, the geometric shapes of the punched vortex generators, and the attached angle of punched vortex generators. The Reynolds numbers considered for the channel flow case (based on the hydraulic diameter) ranged from 3288 to 37,817. The heat transfer results were obtained using the infrared thermal imaging technique. The heat transfer results of the vortex generators were compared with those of a smooth plate. The best heat transfer performance was obtained with the PTVGs. The presence of the vortex generators produced higher heat transfer coefficients than the smooth plate surfaces. Correlations were developed for the averaged Nusselt number for the PTVGs and PRVGs. Results showed a 23–55% increase in heat transfer due to the use of vortex generators. These vortex generators show a more significant increase in heat transfer coefficient for channel flows.

1. Introduction

A longitudinal vortex generators (LVGs) on a heat transfer surface is one of the most widely employed heat transfer enhancement techniques. This technique is used for thermal equipment such as a heat exchanger and internal blade cooling of a gas turbine. The mechanism of heat transfer enhancement is based on flow separation and reattachment. In general, flow reattachment introduces a strong shear flow on the surface behind each rib or winglet, resulting in an effective disruption of the thermal boundary layer and thus the improvement of the heat transfer [1–10].

Tigglebeck et al. [11] found that in a rectangular channel flow, a pair of delta winglets performs slightly better heat transfer than a pair of rectangular winglets at higher attack angles and Reynolds numbers. Biswas et al. [12] reported that a winglet pair has less loss of flow than that of a single winglet, and winglet pairs can eliminate zones of poor heat transfer.

Two kinds of vortex generators, a delta winglet pair (DWP) and a rectangular winglet pair (RWP), were numerically compared by Ferrouillat et al. [13]. Torii et al. [14] proposed a common-flow-up delta winglet configuration, which was effective in delaying boundary layer separation from the tube, reducing form drag, and removing zones of poor heat transfer from the near-wake of the tube. Tian et al. [15] numerically investigated the effects of RWP and DWP with two different configurations, such as common-flow-down and common-flow-up heat transfers along with fluid flow characteristics. Fiebig et al. [16] studied the heat transfer enhancement of delta wings and winglets in flat plate channels for Reynolds numbers based on plate spacing between 1360 and 2270. Qualitative data was recorded using a laser-sheet flow visualization technique, and the heat transfer behavior was measured using unsteady, liquid crystal thermography. They concluded that the local heat transfer was enhanced up to 200% and the delta winglet caused the highest local enhancement. When the Reynolds number was 1360, the Colburn j factor was increased by 20–60%.

Min et al. [17] developed a modified rectangular LVG obtained by cutting off the four corners of a rectangular wing. Their experimental results of this LVG mounted in a rectangular channel suggested that the modified rectangular wing pairs (MRWPs) have better flow and heat transfer characteristics than those of rectangular wing pairs (RWP). A numerical study by Biswas and

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Nomenclature

A	convection heat transfer area of channel (m^2)
AR	aspect ratio of channel (–)
b	distance of punched winglet from the channel bottom (m)
c	punched winglet length (m)
D_h	hydraulic diameter (m)
e	height of winglet (m)
f	friction factor (–)
g	spacing between punched winglet (m)
H	channel height (m)
h	averaged heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity of air (W/m K)
L	length of test channel (m)
Nu	Nusselt number (–)
Nu_{avg}	averaged Nusselt number (–)
S	spacing between longitudinal winglet (m)
ΔP	pressure drop (Pa)
Pr	Prandtl number (–)
PTVGs	punched triangular vortex generators
PRVGs	punched rectangular vortex generators
Re	Reynolds number (–)
Q	heat transfer (W)
T	temperature (K)
t	thickness of longitudinal winglet (mm)
U	mean velocity (m/s)
V	voltage (V)
W	width of channel (m)
$\dot{V}$	volumetric flow rate (m^3/s)
x/D_h	dimensionless distance along the streamwise (–)
y/D_h	dimensionless distance along spanwise (–)

Greek symbols

α	attack angle of punched winglet (°)
ρ	density of the fluid (kg/m^3)
η	thermal enhancement factor (–)
ν	kinematic viscosity (m^2/s)

Subscripts

a	augmented
avg	average
b	bulk
0	channel without vortex generator
pp	pumping power

Chattopadhyay [18] on a delta wing with a punched hole in the base wall showed that the heat transfer enhancement and the friction factor at the exit were both relatively lower than those of the case without any punched hole.

Akbari et al. [19] studied the heat transfer enhancement effects of two different configurations of delta winglet pair vortex generators in a narrow rectangular channel by experiment. Chen et al. [20,21] explored the punched longitudinal vortex generators in the form of winglets in both in-line and staggered arrangement, both of which could enhance heat transfers in a finned oval tube heat exchanger.

Gentry and Jacobi [22,23], experimentally studied the heat transfer enhancement characteristics of delta wing vortex generators in a flat-plate channel flow. Results showed that the averaged heat could be enhanced by 50–60% at a low Reynolds number in comparison with the original configuration. Chung et al. [24] investigated the combined effect of the angle of attack and the louver angle of a winglet pair on heat transfer enhancement where the punched holes were considered but the thickness of the winglet pair was neglected. Results showed that the best performance was achieved when the angle of attack was at 30° and the louver angle was at 15°. Eiamsa-ard et al. [25], in an experiment, investigated the fluid flow and heat transfer characteristics in a tube fitted with delta winglet twisted tape, which resulted in a higher Nusselt number and friction factor in comparison with the typical twisted tape. Zhou and Ye [26], experimentally investigated the heat transfer performance of a new vortex generator called curved trapezoidal winglet and compared the results with the rectangular winglets.

Promvonge et al. [27], experimentally studied the effects of combined ribs and winglet type of vortex generators (WVGs) on forced convection heat transfer and friction loss behaviors for turbulent air-flow through a constant heat flux channel. Zhu et al. [28] calculated three-dimensional turbulent flows and a heat transfer in a rectangular channel with a rectangular winglet on one wall and rib-roughened elements on the other wall by using the k–ε model. They found that the combined effect of rib-roughened, vortex generators can enhance the averaged Nusselt number by nearly 450%. Zhou and Feng [29], experimentally studied the performance of both plane and curved winglet (rectangular, trapezoidal and delta) vortex generators (VGs) both with and without the punched holes. They found that curved winglet type VGs (CRWP, CTWP and CDWP) have both a better heat transfer enhancement and lower flow resistance than corresponding plane winglet VGs in both laminar and turbulent flow regions.

In the work currently being done, both new punched triangular vortex generators (PTVGs) and punched rectangular vortex generators (PRVGs) have been designed. In order to investigate the convective heat transfer performance of PTVGs and PRVGs, an experimental set-up was established. The effects of the attack angle and distance of both PTVGs and PRVGs from the channel bottom on the heat transfer and pressure drop characteristics were examined. In plate-fin heat exchangers the flow between the plates can be considered as a channel flow. For the reduction of the thermal resistance, the heat transfer coefficient needs to be augmented.

2. Experimental apparatus and procedure

The heat transfer experiments were conducted in an open rectangular channel as shown in Fig. 1. The experimental system consisted of a honeycomb, an entrance section, a test section, a centrifugal blower, an infrared thermography system, vortex generators, and devices for measuring flow velocity, temperature and pressure difference. The triangular and rectangular vortex generators were directly punched from the longitudinal winglets. Air was drawn in by a variable speed fan and passed through the test section of the channel. The channel inner cross section dimensions were 100 mm (wide) and 50 mm (height). The entrance channel was 2500 mm long. The channel was constructed with 9 mm thick plexiglass plates. The dimensions of the heating plate were 100 mm (width) and 270 mm (length). In the experiments, the heating plate was made of stainless steel foil. It was firmly clamped and stretched between two copper bus bars. The foil was electrically heated by means of a high current DC power supply to provide a constant heat flux surface. In order to confirm the equal temperatures at the bottom and upper side of the 0.02 mm thick