2010

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Air-Side Heat Transfer Enhancement by a V-Formation Delta-Winglet Array in a Developing Channel Flow

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ABSTRACT

Inspired by group movement of animals in nature, a new vortex generator (VG) array deployed in a “V” is proposed in this study, aiming to create constructive interference between vortices and improve VG performance. Its impact on surface convection enhancement is experimentally assessed in a developing channel flow. A large-aspect-ratio duct of 6 mm high is constructed to model a single passage of plain-fin heat exchangers. The frontal air velocity ranges from 0.9 to 2.5 m/s, corresponding to a Reynolds number range based on channel height of 340 to 940. The proposed V-array demonstrates superiority to a conventional multi-row configuration in that it affects a much larger heat transfer area, and the boost effect by the trailing pair is manifest even at relatively small Reynolds numbers. A two-pair V-array deployed at 30º yields 12-36% augmentation in the total heat transfer for the current channel flow, and is considered an appropriate design for implementation in prototype heat exchangers.

1. INTRODUCTION

Vortex generation has emerged as one promising technique for enhancing air-side convection. In this method, wing-like vortex generators (VGs) are punched or mounted on a heat-transfer surface to generate longitudinal vortices. As the vortices are advected downstream by the main flow, they cause bulk fluid mixing, boundary-layer modification and flow destabilization, and thus improve convective heat transfer. This enhancement technique has the advantage of low cost and ease of implementation, accompanied by a usually modest pressure drop penalty.

Considerable research has been directed at vortex-enhanced channel flows, because of their relevance to heat exchanger geometries. Gentry and Jacobi (2002) used naphthalene sublimation to measure vortex strength and local convective coefficients in a developing channel flow with a delta wing placed at the leading edge. They revealed that the tip vortices had a significant impact on heat transfer behavior of both walls and local enhancement by a factor of 3 was acquired in regions where a vortex induced a normal inflow. The average enhancement of 20-55%, along with an additional pressure loss of 50-110%, was reported for Reynolds numbers ranging from 400 to 2000. Tiggelbeck et al. (1993) considered two delta-winglet pairs in an aligned geometry and a staggered geometry. In both configurations, the qualitative flow structure, the number of developing vortices per VG, and their streamwise development were found to be independent of the nature of the flow approaching the VG. Vortices generated by the second row were less stable than those by the first row. Nevertheless, the local heat transfer enhancement behind the second row was higher in the aligned geometry due to a boost effect on the incoming vortical flow. Dietz et al. (2006) employed the commercial software FLUENT to compute heat transfer and velocity field in a turbulent channel flow embedded with up to three delta-wing VGs. Over the considered parametric range, variation in the longitudinal displacement had very little impact on the average Nusselt number for two VGs, and addition of a third VG did not improve heat transfer appreciably. The first to-scale heat-exchanger implementation of winglets to generate a common-up-flow for tube wake management was investigated by Joardar and Jacobi (2008). They assessed the overall heat transfer and pressure drop performance of a compact plain-fin-and-tube heat exchanger mounted with a three-row VG set for Reynolds numbers in the range 220-960. The arrangement achieved a maximal heat transfer increase of 69% with a pressure drop penalty of 26% at Re=960. Their study suggested that careful orientation and deployment of VGs can lead to significant thermal-hydraulic improvement for fin-tube heat exchangers.
It is interesting to observe a V-like or echelon (i.e. half V) formation in group movement of animals in nature, among which bird migration is most commonly encountered (Figure 1). Lissaman and Shollenberger (1970) applied aerodynamic theory to predict that 25 birds in a “V” formation could have a flight range increase of about 70% over a solo bird, with the trailing birds “riding” on the upwash of tip vortices generated from the upstream members. Although the inherent mechanisms may be different, the essential idea of grouping individuals in advantageous positions for favorable interaction could be utilized in human fluid-flow technology. As a preliminary realization, this study proposes a new delta-winglet array deployed in a “V” to try to exploit the constructive inference between vortices. Its impact on surface convection enhancement is experimentally evaluated in a developing channel flow using infrared (IR) thermography. Measurement is performed at three incoming air velocities, 0.9, 1.5 and 2.5 m/s, corresponding to Reynolds numbers based on channel height of 340, 570, and 940, respectively. A single winglet pair is firstly examined at various attack angles, followed by multipair VGs placed at the optimal angle. The present work aims to demonstrate the effectiveness of the proposed array as compared to a single pair or conventional multiple VG rows. It also provides an appropriate array design for implementation in prototype heat exchangers.

Figure 1: Migrating birds in V-formation
(Reproduced by courtesy of Tom Samoden, www.castlelakeestates.com/castlednn)

2. EXPERIMENTAL METHOD

Infrared (IR) thermography has been widely used in convective heat transfer research because it is noninvasive, and it provides full-field data with the ability to resolve temporal and spatial temperature distributions (Yang, 2001). In this work, the IR technique was adopted for surface temperature measurement in a rectangular high-aspect-ratio channel, specifically designed to model a single passage of plain-fin heat exchangers. A thin metallic foil was used to provide a uniform heat flux on the surface of the channel floor by Joule heating. The top channel wall was made of a transparent material, carefully selected to maximize transmission of radiant energy emitted from the heating foil. Experiments were performed for Reynolds numbers based on channel height between 340-940, representative of many HVAC&R applications and compact heat-exchanger designs.

2.1 Wind Tunnel
The experiments were conducted in an open-loop, induction wind tunnel, shown schematically in Figure 2. The flow was driven by an axial fan and frequency-controlled 1.5 kW AC motor. The airflow entered the wind tunnel through a square, bell-mouthed inlet and then passed through a series of hexagonal-cell, aluminum honeycomb and stainless steel screens to achieve uniform velocity profile. A 9:1 contraction was used to reduce free-stream turbulence and provide a smooth transition into the test section (152×152 mm). Using a 20-μm hot-wire anemometer, the velocity profile at the entrance of the test section, was determined to be flat to within 3%, with a turbulence intensity below 2% (as reported elsewhere (Gentry and Jacobi, 2002)).

2.2 Test Section
The test section, with reference to Figure 3, consisted of a second one-dimensional contraction with a 25.3:1 area ratio and the test channel. The velocity of the airflow was measured at channel entrance using an 8355 TSI hot-wire anemometer with an accuracy of ± 0.01 m/s. The Plexiglas channel was 305 mm long, 6 mm high and 152 mm wide. A heated section of 170 mm was immediately downstream from the secondary contraction, followed by an extended unheated section of 135 mm (not shown in Figure 3). Due to the position of the IR camera, mounting
surfaces, etc., only a portion of the channel floor from \( x=5 \) to 150 mm was in the field of view of the thermal imager. The channel floor was constructed of Plexiglas that was 3 mm thick, and its exterior surface was covered with a 60 mm layer of rigid PVC foam insulation. The channel ceiling was constructed by attaching a thin, transparent plastic sheet on the lower surface of a 5 mm, opaque insulating material at the channel entrance. The sheet was made of 0.46 mm thick polyethylene which was selected to minimize absorption losses in wavelengths from 8 to 14 \( \mu \text{m} \) (Tsilingiris, 2003). The total emissivity, reflectivity and transmissivity were estimated to be 0.45 (Fujikura et al., 1982), 0.07 (Il’yasov and Krasnikov, 1973) and 0.48 (Tsilingiris, 2003), respectively. Electric power was provided to a 25 \( \mu \text{m} \) Inconel 625 alloy foil from a Mastech HY3030E DC power supply, imposing an isoflux condition by Joule heating. In order to reduce reflected energy and enhance thermal-image detection, the foil surface facing the camera was coated with matte black paint to raise its emissivity to 0.98. A Scotch double-sided tape was applied on the back side to ensure the foil was smooth and fixed to the Plexiglas. The IR system included a computer-controlled Mikron MIDAS thermal imager and the processing software MikroView™. The sensing system was an uncooled microbolometer detector of 320×240 pixels. During operation, IR radiation emitted from the channel floor was captured, converted it into an electrical signal and displayed as a color or monochrome image. The camera was capable of recording 30 frames per second and digitally storing the 16-bit images. The instantaneous field of view was 1.6 mrad, and the minimum focal distance was 305 mm. The measurement resolution was \( \pm 2.0\% \) of full scale, with a thermal sensitivity of 0.08 °C at 30 °C. During the experiments, the camera was placed 356 mm away from the heated surface throughout the calibration and measurement process. Using a closer viewing distance to achieve higher spatial measurement resolution was not possible, due to geometric constraints in the apparatus.

Figure 2: Schematic of the wind tunnel: 1) inlet, 2) flow conditioning, 3) contraction, 4) test section, 5) diffuser, 6) blower, 7) exit plenum, and 8) discharge to outside of lab (adopted from Gentry and Jacobi (2002) with modification)

Figure 3: Diagram of the test section, all dimensions in mm
2.3 VG Geometry
The investigated VG geometries included a single delta-winglet pair (Figure 4a), a two-pair V-formation array (Figure 4b), conventional two-row winglet pairs (Figure 4c), and a three-pair V-formation array (Figure 4d). Each winglet was 5.4 mm in height and 16.2 mm in chord, which translated to an aspect ratio of 3. The leading pair had zero tip spacing following the recommendation by Fiebig (1998) and was placed 17.5 mm away from channel entrance. In a V-formation design, a preliminary investigation suggested positioning the trailing pair immediately adjacent to the preceding one. Conventional two-row pairs were considered for the purpose of comparison, where the longitudinal displacement of the second pair remained the same as that in the two-pair array design. Note that addition of VGs resulted in less than 1% increase in the total heat transfer area. Therefore surface convection enhancement can be predominantly ascribed to the generation of longitudinal vortices.

![Figure 4: Test VG geometries: a) single winglet pair, b) two-pair V-array, c) conventional two-row pairs, and d) three-pair V-array](image)

2.4 Experimental Procedure
The IR imaging system was first calibrated over the desired temperature range by comparing direct measurement of the heated surface without the transparent sheet in place to those obtained by viewing through the sheet. In this study, the temperature distribution along the heated surface was measured at three air velocities, 0.9, 1.5, and 2.5 m/s, corresponding to Reynolds numbers based on channel height of 340, 570, and 940, respectively. An experiment was initiated by adjusting the wind-tunnel fan speed to the desired flow rate, as indicated by the anemometer. Air entered the channel at the ambient temperature, 294 K, and its transport properties were evaluated at 300 K (approximate average temperature). The metallic foil was continuously supplied with a fixed current of 12 A, generating a constant heat flux of 257 W/m². After a transient period of around 20 minutes, a steady state was deemed to prevail when all temperature readings varied within the experimental uncertainty over at least three minutes. The thermal image and temperature data of the heated surface were then recorded for post analysis.

The baseline experiments were firstly conducted in the plain channel without VGs. Next, a single winglet pair was embedded on the heated surface at 15º, 30º and 45º (see Figure 4a), respectively, aiming to find an appropriate deployment with respect to the angle of attack. The investigation concluded after testing various multipair designs placed at the optimal angle (see Figures 4b-4d).

2.5 Data Reduction
The local Nusselt number is defined as

\[
Nu = \frac{q_{\text{conv}} H}{(T_e - T_0) k_f}
\]

where the convective flux, \(q_{\text{conv}}\), is determined by the external heating flux, \(q_e\), less conduction flux to the substrate, \(q_{\text{cond}}\) and radiation loss in the channel, \(q_{\text{rad}}\)

\[
q_{\text{conv}} = q_e - q_{\text{cond}} - q_{\text{rad}}
\]

An ongoing numerical study (He et al., 2010) for the baseline flow revealed that \(q_{\text{cond}}\) contributed around 5% of the total flux for the first 7 mm in the measured section (i.e. from \(x=5\) mm to \(x=12\) mm), and then dropped rapidly to less than 1% downstream. For this reason, conduction effects were neglected in the current analysis. The study also showed that due to the significant loss of energy to ambient via radiation through the transparent sheet, there was no appreciable rise on the temperature of the top wall (less than 6 K). Evaluation of \(q_{\text{rad}}\) was thus justifiable using the net-radiation analysis (Siegel and Howell, 2002) in a parallel-plate configuration. Radiation exchange occurred between finite areas on the wall surfaces, and with the inlet and exit apertures. Local temperature of the heated
plane, \( T_n \), was measured from the camera and all the surrounding surfaces were assumed to be at the ambient temperature, \( T_0 \). Using a 95% confidence interval and standard error-propagation method (Taylor and Kuyatt, 1994), the average uncertainties in \( Re \) and \( Nu \) were estimated to be 2.5% and 8.0%, respectively. Note that data interpretation on the span-averaged \( Nu \) and the overall \( Nu \) followed the standard procedure on a fixed area (Fiebig et al., 1991), and was different from the affected-area-based approach by Gentry and Jacobi (2002).

### 3. RESULTS AND DISCUSSION

#### 3.1 Visualization of Thermal Pattern

False-color images of the steady-state temperature distribution on the heated surface at \( Re=340 \) are presented in Figure 5 for the base flow and various VG arrangements at 30°. At a focal distance of 356 mm, the 248×120 pixel image corresponds to an area of 145×70 mm. Thus, each pixel represents a 0.59-mm-square unit on the heated surface. The width of the area selected for data reduction is large enough to incorporate all the spanwise effects of longitudinal vortices yet sufficiently small to avoid edge effects. The base flow clearly illustrates the anticipated thermal development effects, with a smooth increase of temperature in the streamwise direction. The addition of VGs induces areas of increased heat transfer, as shown in the regions where the temperature is lower than that of the base flow. Through enhancing bulk mixing, modifying the boundary layer, and potentially causing flow destabilization, the vortices result in a net effect of augmented surface convection. Local enhancement is most pronounced immediately after the VGs and exists in a nearly parallel pattern downstream. For the V-formation arrangement, the affected area increases with the number of winglet pairs. When the second pair is moved closer to zero tip spacing as in the conventional two-row configuration (Figure 5d), the affected area is significantly reduced compared to the two-pair V-formation array (Figure 5c).

![Figure 5: 2D thermal images for the steady-state temperature distribution at Re=340 for the base flow and various VG arrangements at an attack angle of 30°](image)

#### 3.2 Span-Averaged Nu

The span-averaged Nusselt number distributions for a single winglet pair are presented in Figure 6 at varying Reynolds numbers and angles of attack. In accordance with the observation in Figure 5, the vortices are at their strongest immediately after the VGs where local enhancement of over 100% is achieved at \( Re=570 \) and 940. The characteristic is also evident by noting in Figure 6a that the peak of \( Nu \) occurs firstly at 45° and lastly at 15°. The presence of VGs may induce destabilization drastically (Fiebig, 1998), which could be a possible explanation for the fluctuations observed in Figures 6b and 6c. The vortices become stronger as the attack angle increases from 15° to 30°. However, further increase to 45° probably causes breaking down of vortices since the peak at 30° is seen to be the highest at all Reynolds numbers.

The span-averaged Nusselt number distributions for multipair geometries are presented in Figure 7, where all VGs are deployed at the optimal angle of 30°. The multiple peaks associated with the series of winglet pairs are again clearly exhibited. Due to a much less area influenced, the local \( Nu \) downstream the generators in the conventional
Figure 6: Span-averaged $Nu$ distributions for a single winglet pair

Figure 7: Span-averaged $Nu$ distributions for multipair VG geometries
configuration is consistently smaller than that in the V-formation arrangement. It is also interesting to note that while the magnitude of the two peaks is fairly comparable over the entire Re range in the array arrangement, the second peak is noticeably lower at Re=340 in the conventional configuration. This behavior indicates the effectiveness of the proposed array for relatively small Re applications such as low frontal velocities or compact heat-exchanger designs.

3.3 Overall Heat Transfer Performance
The overall heat transfer performance of various VG geometries is evaluated in terms of the enhancement ratio, \( \frac{\bar{Nu}}{\bar{Nu}_0} \), i.e. VG-enhanced area-averaged \( Nu \) over the baseline area-averaged \( Nu \). The results are presented in Figure 8. It is consistent with established findings that the overall enhancement increases with Re, and with the angle of attack until vortices break down. For the V-formation array, increasing the number of winglet pairs from two to three does not improve heat transfer much, yet the additional pressure loss may or may not be commensurately large. Taking also other factors such as manufacturing cost and spatial constraints into account, this study recommends the two-pair V-array deployed at 30° as an appropriate geometry for implementation in prototype heat exchangers. The design yields 12-36% augmentation in the total heat transfer over the Reynolds number range considered for the current channel flow, as compared to 8-26% obtained by the conventional two-row configuration.

As a final remark, it is advised that the recommended design is based on heat transfer results. At this stage, the associated pressure drop penalty is not quantified. However, the concern may be alleviated by noting that the additional pressure drop is usually small relative to the overall losses in typical air-handling equipments. For example, Joardar and Jacobi (2008) reported an incremental fan power of as little as 0.8 W when attaching three-row winglet pairs in a fin-and-tube heat exchanger for air-cooling and refrigeration applications.

![Figure 8: Enhancement ratio of overall Nusselt number, \( \frac{\bar{Nu}}{\bar{Nu}_0} \)](image)

4. CONCLUSIONS
Inspired by group movement of animals in nature, a new VG array deployed in a “V” is proposed in the present study. Its impact on surface convection enhancement is experimentally evaluated in a developing channel flow using IR thermography. Heat transfer measurement is performed in a large-aspect-ratio duct of 6 mm high over a Reynolds number range based on channel height of 340 to 940. A single winglet pair is firstly examined at three angles of attack, 15°, 30° and 45°, followed by multipair VGs consisting of a two-pair V-array, a conventional two-row configuration and a three-pair V-array. The major findings of this work are summarized as follows:

- Longitudinal vortices are at their strongest immediately after the generators and very persistent throughout the channel. Local enhancement of over 100% is observed at relatively high Reynolds numbers.
- For a single winglet pair, an appropriate angle of attack is found to be 30°. The vortices may suffer from breaking down at higher angles.
- As compared to the conventional multi-row configuration, the proposed V-array demonstrates superiority in that it brings about a broadened affected area, and the boost effect by the trailing pair is manifest over the
entire Reynolds number range investigated. The array is expected to find particular use for small Re applications such as low frontal velocities or compact heat-exchanger designs.

- A two-pair V-array deployed at 30º yields 12-36% augmentation in the total heat transfer for the current channel flow, and is considered an appropriate design for implementation in prototype heat exchangers.

**NOMENCLATURE**

$$
egin{align*}
b & \quad \text{winglet height} \\
c & \quad \text{winglet chord} \\
H & \quad \text{Channel height} \\
k & \quad \text{thermal conductivity} \\
Nu & \quad \text{Nusselt number} \\
q & \quad \text{Heat flux} \\
Re & \quad \text{Reynolds number} \\
T & \quad \text{Temperature} \\
x & \quad \text{x-coordinate} \\
z & \quad \text{z-coordinate} \\
\beta & \quad \text{attack angle}
\end{align*}
$$

Subscripts

- cond: conduction
- conv: convection
- f: fluid
- rad: radiation
- s: heated surface
- 0: ambient or baseline

**REFERENCES**


**ACKNOWLEDGEMENT**

This work is financially supported by the Air Conditioning and Refrigeration Center (ACRC) at the University of Illinois. The authors are grateful to CTS (Creative Thermal Solutions) Co. for providing the infrared thermal imager, and to Tom Samoden for granting permission on the use of his photograph.

International Refrigeration and Air Conditioning Conference at Purdue, July 12-15, 2010