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The effect of delta winglet attack angle on the heat transfer performance of a flat surface

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A B S T R A C T

The heat transfer performance of a flat plate behind a 10 mm high (h) and 20 mm long delta winglet was studied at a distance up to 30h in a wind tunnel at a Reynolds number based on h of 6000. The focus was on the role of the attack angle, which was varied from 30 to 60° in 15-degree increments. The bottom side of the flat plate was uniformly heated by condensing steam at 100 °C. Surface thermal imaging results indicated that the peak Nusselt number (Nu) increases with the attack angle, and this augmentation was attributed to the larger share of the transverse vortex at the larger attack angles. Peak Nu dropped sharply in the near wake ($X/h < 10$), presumably due to the rapid fading of the transverse vortex. It subsequently decreased more gradually and became less sensitive to attack angle farther downstream. This extended heat transfer enhancement was postulated to be caused by the slowly-decaying longitudinal vortices which persisted beyond the studied span. The prevailing longitudinal vortex induced heat transfer enhancement was explained in terms of the detailed flow characteristics scrutinized via a triple hot wire at 20h. The Inflow region, where cooler freestream air was brought into the hot plate, corresponded to the maximum Nu boost; while the Outflow region, where heated air began to leave the hot surface, correlated with the Nu valley. Further analysis revealed Nu relations with the local near-surface streamwise velocity, out-of-plate velocity, and turbulence intensity. The specific heat-flow correlations subtly differed between the Inflow and Outflow regions, and thus also the effect of the winglet attack angle.

1. Introduction

In typical engineering applications, liquid-to-air and two-phase-to-air heat exchangers have their heat transfer 'bottleneck' on the air side [1]. Extending heat transfer surface and perturbing the flow are familiar means for boosting heat transfer efficiency. To perturb the flow, either main-flow disturbing or secondary-flow inducing can be applied [2]. Louvers and strip fins are examples of main-flow enhancement methods, while the secondary-flow augmentation is to intentionally generate vortices via vortex generators (VGs). The investigations on the application of VGs in plate-fin heat exchangers [3–5], fin-tube heat exchangers [6–11], louvered fin heat exchanger [12–14], circular tubes [15,16], triangular ducts [17] and rectangular channels [18–20] have revealed that VGs are effective heat transfer enhancers. Vortex generators are typically incorporated into a surface by means of punching, embossing, stamping, or attachment process, with an attack angle [21]. As described by Fiebig [22], when the attack angle is 90°, generated vortices are mainly transverse. As the attack angle decreases, the longitudinal vortices dominate over the transverse ones. Noting that it is impossible to generate pure longitudinal vortices, since transverse vortices spawn naturally unless the attack angle is zero, in which case no vortices, longitudinal or transverse, are created [21]. Transverse vortices have their rotating axes normal to the main flow direction and the flow is primarily two-dimensional, whereas the rotation direction of longitudinal vortices is parallel to the main flow direction which makes the flow three-dimensional. Some studies [22,23] found longitudinal vortices showing less flow loss and better heat transfer characteristics than transverse vortices. Extensive reviews of the longitudinal vortex generators are available from a number of sources [2,24–26]; nevertheless, a brief highlight of pertaining literature is due.

A delta winglet, as shown in Fig. 1, is an effective vortex generator. In several comparison studies, this type of vortex generator posted itself as potentially the best longitudinal vortex generator with simple geometry. In Edwards and Alker [27], the heat transfer enhancements by cubes (typical transverse vortex generators) and delta winglets (typical longitudinal vortex generators) were compared. The winglets vortices could achieve a higher overall

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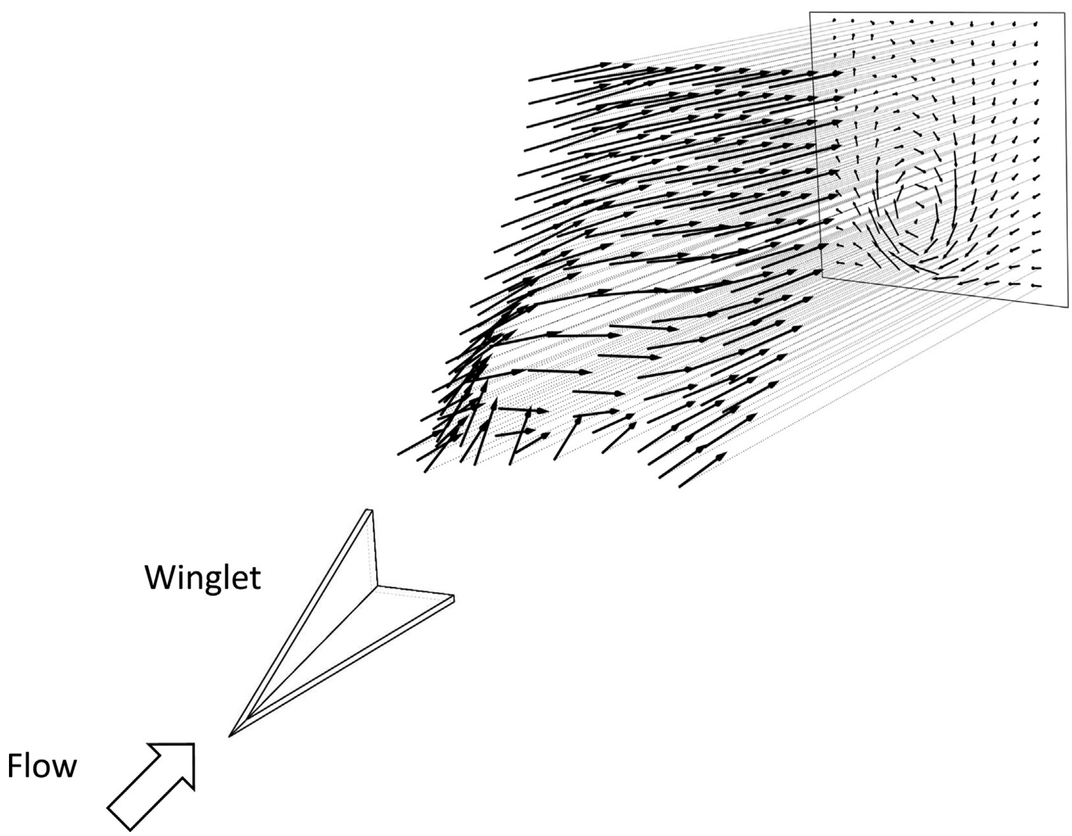

Fig. 1. Delta winglet vortex generator.

enhancement by persisting over a greater distance, though cubes furnished greater local enhancements. Zhou and Ye [28] studied the heat transfer improvement by rectangular winglet, trapezoidal winglet, delta winglet and curved trapezoidal winglet. The curved trapezoidal winglet gave the best performance in fully turbulent flow, while the delta winglet showed the best performance in the laminar and transitional flow. In Fiebig [22], systematical comparison of rectangular and delta wings and winglets were conducted. The results showed that winglets were better than wings in terms of heat transfer enhancement and pressure penalty. Tian et al. [21] numerically compared the heat transfer augmentation by rectangular and delta winglet pairs in a flat-plate channel. They concluded that the delta winglet pair was better than the rectangular winglet pair on overall performance.

Since the attack angle of the delta winglet essentially dictates the transverse/longitudinal vortices ratio, its effect on heat transfer performance has attracted heightened interest. Lei et al. [29] conducted CFD simulation on the hydrodynamics and heat transfer of a delta winglet in a fin-and-tube heat exchanger. Winglets with a thickness of 0.2 mm, aspect ratio from 1 to 4 and attack angle from 10 to 50° were studied. The heat transfer coefficient increased with the increase of attack angle and aspect ratio. Chen et al. [30] numerically studied the heat transfer enhancement of delta winglets in a finned oval tube heat exchanger. Three attack angles (20, 30 and 45°) and two aspect ratios (1.5 and 2) were investigated. The normalized Nusselt number had a higher value for larger attack angle and smaller aspect ratio cases.

Most of the aforementioned studies were conducted inside fin-and-tube heat exchangers, where the heat transfer performance was highly influenced by the interaction between the winglet and the tube, rather than the winglet itself. At the more fundamental level, a winglet placed on an unconfined flat surface can unambiguously elucidate the impact of attack angle on the resulting flow and heat transfer characteristics, without the complication of confinement. A larger attack angle, from 30 to 60°, may enable the differentiation of the relative contribution of transverse versus longitudinal vortices; for the longitudinal vortices are expected to diminish at larger attack angles. In short, the objective of this study is to examine the effect of winglet attack angle on the convective heat transfer from an unconfined flat surface. The heat transfer performance is interpreted in terms of the transverse-longitudinal vortex structures, streamwise velocity, velocity boundary layer thickness, and turbulence fluctuation.

2. Experimentation

Fig. 2 shows the experimental facilities. The experiments were conducted in a 1.8 m long wind tunnel test section with a 0.76 m by 0.76 m cross-section. A Polytetrafluoroethylene (PTFE) plate with a thermal conductivity of 0.25 W/(m K) and emissivity of 0.92 was inlaid in the center of the 10 mm thick test section base. The PTFE was 3 mm thick, 295 mm wide and 380 mm long. The test section base was made of 10 mm thick fiberglass with a very low heat conductivity of 0.04 W/(m K) to minimize the conduction heat loss. A water tank underneath the PTFE plate was heated to produce steam to evenly heat up the bottom surface of the PTFE plate at a temperature of 100 °C. An infrared thermal camera (Fluke TiX520) mounted on the top of the test section was employed to capture the temperature distribution of the top surface. The thermal photograph had 240 × 320 pixels, resulting in approximately 1 mm resolution. The thermal camera has a thermal sensitivity of 0.05 °C. It was calibrated using type-T thermocouples with an accuracy of 0.5 °C over the studied temperature range on the PTFE plate. The temperatures on both sides of the PTFE plate were verified by type-T thermocouples during the test. The camera cap-