Experimental Thermal and Fluid Science 88 (2017) 46–54

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

An experimental study of turbulent flow behind a delta winglet

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ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form 15 May 2017
Accepted 15 May 2017
Available online 20 May 2017

Keywords:
Longitudinal vortex generator
Turbulence
Wind tunnel
Hotwire

ABSTRACT

The vortical turbulent flow generated by a 10 mm high and 20 mm long delta winglet on a flat surface was experimentally studied in a wind tunnel. The flow field at 10 winglet heights downstream was measured using a triple wire probe at a Reynolds number of 5000, based on winglet height. Main vortex and induced vortex structures were observed in the form of the cross-stream velocity vector and the vorticity contour. Boundary layer thickness, streamwise velocity distribution, turbulence intensity and Taylor microscale were compared at the inflow and outflow regions as well as in the base flat plate case. The inflow region was postulated to have a larger potential for heat convection; since the vortex penetrated into the boundary layer, the boundary layer thickness increased, while maintaining high turbulence intensity. At the core of both the main vortex and the induced vortex, both the streamwise velocity deficit and the turbulent intensity were enhanced.

1. Introduction

Convective heat transfer by air commonly exists in many engineering applications such as heat exchangers and the cooling of solar photovoltaic panels. In most cases, it is desirable to enhance the heat transfer, either passively or actively [1]. The passive enhancement of convective heat transfer that does not require any external power can be accomplished by extending the heat transfer surface, perturbing the flow, or adding additives to the fluid flowing across the surface. Active techniques such as vibration, electro field, and acoustic excitation require external power to accomplish enhancement [2]. Due to cost/benefit considerations, passive techniques such as fins (extended surface) and turbulators (perturbed flow) are more widely used. However, the heat transfer enhancement by these techniques typically comes with significant pressure drop, leading to some heat transfer loss associated with flow speed reduction. A specific type of turbulator called the longitudinal vortex generator has been gaining attention since the 1990s. It can generate vortices with an axis parallel to the main flow direction. These vortices are produced via flow separation and viscous friction. This type of strong swirling secondary flow can reduce the boundary layer thickness, increase the temperature gradient near the surface, and directly increase convective heat transfer via cross-stream velocity. This longitudinal vortex generator has the added feature of an extended heat transfer surface. Furthermore, the pressure drop associated with longitudinal vortices is significantly less than that caused by streamwise vortices [2] and hence, less reduction in streamwise velocity results.

The heat transfer enhancement by longitudinal vortex generators has been extensively studied [3–15]. The rectangular and delta wings and winglets are typical objects of studies, as sketched in Fig. 1. These wing-type vortex generators can be either attached on the wall or punched out of the surface. Previous studies [3–15] have found that these longitudinal vortex generators could achieve a significant enhancement of heat transfer with a moderate pressure drop. The influence of longitudinal vortices on energy and momentum transport is long lasting; as far as 60 wing chords downstream behind Eibeck and Eaton's delta winglet [5]. Fiebig compared wings and winglets of different shapes, and found that the rectangular and triangular shapes give similar pressure penalty and heat transfer enhancement, while winglets have better performance than wings [14]. Torii and Yanagihara [15] conducted systematical study on the heat transfer enhancement by a single vortex generated by a winglet. They investigated the influence of the angle of attack, free stream velocity and the winglet height. However, their study is not accompanied with the flow structure measurement.

To better understand the underlying physics of the longitudinal vortex and its interaction with the boundary layer, detailed turbulent flow parameters must be systematically scrutinized. Godard and Stanislas [16] investigated the vortices generated by a pair of counter-rotating winglets using particle image velocimetry (PIV). The winglets were mounted on a bump, which was used to

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http://dx.doi.org/10.1016/j.expthermflusci.2017.05.012
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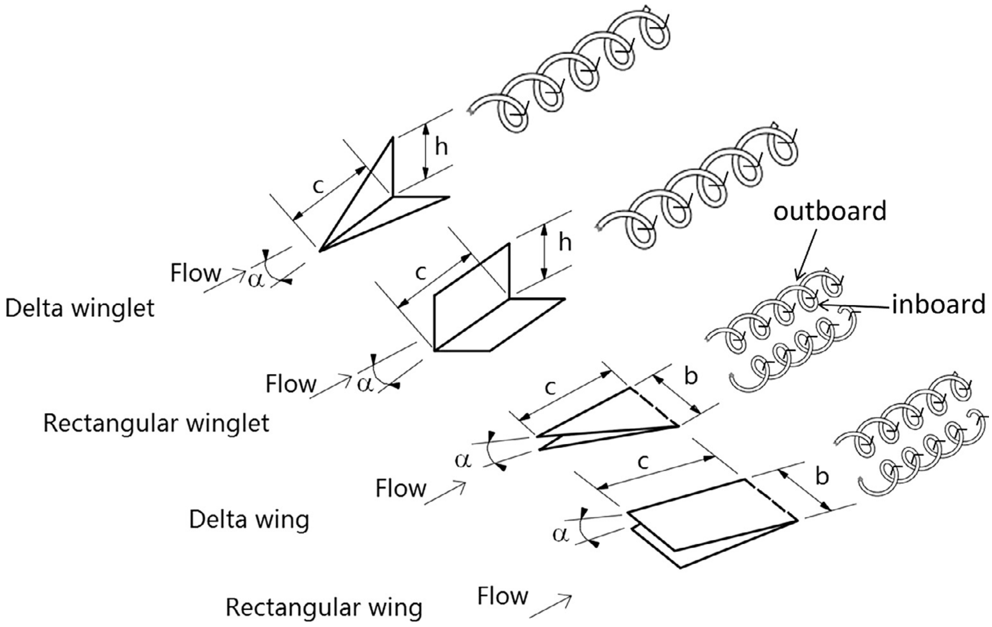

Fig. 1. Typical vortex generators. α is the angle of attack, c is the chord length, h is the winglet height, and b is the span or width.

generate an adverse pressure gradient. The winglets height was less than half of the boundary layer thickness. They studied at three locations, from 22 to 57 winglet heights downstream of the winglets. The vortices decreased in intensity and increased in size with distance, and when reaching 57 winglet heights downstream, the vortices were hardly detectable, although the downwash was still visible. Velte et al. [17] furthered this study by performing stereoscopic PIV measurement at four locations close to the winglets, from 1 to 8 winglet heights downstream of the winglets on a bump. In this study the winglets height was the same as the boundary layer thickness. Henze et al. [18] studied the vortices generated by a full-body tetrahedral element, mounted on the bottom wall of a wind tunnel test section. They used a three-component PIV system to capture flow velocities in all directions. The PIV measurements were conducted in cross-stream plane and streamwise plane.

The PIV technique is suitable for obtaining the velocity profile and velocity vector of vortices. On the other hand, the hot wire, with its ability to measure at much higher frequencies, can give a deeper view of the underlying turbulent parameters. Cutler and Bradshaw [19,20] conducted detailed measurements of the common wake of delta wings using hot-wire and pressure probes. In their studies, the vortices were generated at two different heights, one over the boundary layer and the other merged into the boundary layer. For the first case, the boundary layer beneath the vortices is thinned by lateral divergence, and at the outboard of the vortices, it is thickened by lateral convergence. As the vortices merge into the boundary, the boundary layer between the vortices is kept thin by lateral divergence.

Shabaka et al. [21] studied a single vortex generated by a half-delta wing penetrating into the turbulent boundary layer using hot wire anemometers. The circulation around the vortex penetrating into the boundary layer was almost conserved, that is, it decayed very slowly. Mehta and Bradshaw [22] furthered this study by using two half-delta wings to generate vortices that rotate in opposite directions and the common flow between them was away from the surface. The mean velocity and turbulence downstream were quantified. The cancellation of circulation by fluid mixing from the two vortices was found to be slow.

Lau [23] investigated the channel flow with pairs of rectangular winglets arranged periodically in both spanwise and streamwise directions. The three components of the flow velocity were measured using an X-wire and a quadruple hot-wire probe. The mean velocity vector, long-time averaged Reynolds stresses and the turbulent kinetic energy are presented. Biswas et al. [13] investigated the flow structure of a vortex generated by a delta winglet in a channel flow by a rotation probe, and compared their measurements with simulation results. They found that the vortices undergo elliptical deformation due to the channel walls. Also observed was a corner vortex with two induced vortices.

Since a winglet can enhance heat transfer with little pressure penalty, and the generated vortices are more maneuverable than those from wings, the study on the flow structure of the wake of winglets is imperative. Most of the above-mentioned studies on winglets were conducted in a confined channel where the influence of the walls is significant. A more elementary condition, an unconfined flow, may give a clearer and more fundamental view of the vortex flow generated without the interference of confining walls. Though the turbulent flow behind wings on a flat plate has been relatively well studied, the research on winglets is scarce. The objective of this study is to investigate the turbulent structures and parameters of the vortex generated by a winglet on a flat plate in the unconfined condition using a triple sensor hot-wire anemometer. The detailed flow characteristics are related to heat transfer based on existing knowledge in the literature and physical reasoning.

2. Experimentation

Fig. 2 shows the experimental setup. The studied delta winglet was made from a 0.1 mm thick aluminum sheet. The height of the delta winglet, h, was 10 mm and the length, c, was 20 mm, giving an aspect ratio of 4 h/c = 2. The size of the winglet was chosen to be of the same magnitude as the boundary layer thickness to ensure the generated vortex interacted well with the boundary layer. The experiment was conducted in a wind tunnel with a 76 cm high and 76 cm wide cross section. The delta winglet was attached to a flat plate via one of its folds with an angle of attack, α, of 30°. The winglet was placed one chord length away from the leading edge to avoid the possible influence by the flow separation from the plate's leading edge. The flat aluminum plate was 33.5 cm wide,