Enhancement of Laminar Boundary Layer Heat Transfer by a Vortex Generator*

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The enhancement of heat transfer caused by the presence of a single vortex generator in a laminar boundary layer was experimentally investigated. The local heat transfer coefficients just downstream of the vortex generator and the mean and fluctuation components of velocity were measured. A substantial increase in the heat transfer was noted, with a maximum improvement of the heat transfer coefficient of 80%, even in regions where the laminar structure was clearly predominant. It was observed that the heat transfer coefficient presented two peaks in the spanwise direction. These peaks were found to be associated with the downward motion of the mean vortex and the corner vortex, which arose in the generator's front corner. The influence of the height, angle of attack and geometry of the vortex generator on heat transfer was also investigated.

Key Words: Boundary Layer, Heat Transfer Enhancement, Longitudinal Vortices, Three-Dimensional Flow, Vortex Generator, Heat Transfer Measurements

1. Introduction

The influence of embedded longitudinal vortices on heat transfer of boundary layers is of great engineering interest. Longitudinal vortices have been found to be a very promising technique for heat transfer enhancement, as seen in some reports^{(1)~(4)} dealing with their application in heat exchangers.

Longitudinal vortices can be generated in various ways: Goertler vortices are formed in flows over concave surfaces, horseshoe vortices appear in boundary layers with protuberances. Longitudinal vortices are expected to increase the local heat transfer over a long streamwise distance, disturbing the entire velocity field and temperature field. However, although a considerable amount of work has been done to examine the fluid-dynamic behavior of the flow dominated

by longitudinal vortices, its heat transfer characteristic is not adequately understood. In the case of turbulent boundary layers, there are some reports^{(5)~(6)} which deal with heat transfer. For laminar flows the research studies are restricted to global analysis only, with little detailed information about the mechanisms of heat transfer enhancement. On the other hand, there is a large amount of work focusing on the velocity field of longitudinal vortices interacting with boundary layers because they are related to turbulent separation prevention, durability of turbine blades and navigation control of ships.

Studies relating longitudinal vortices and heat transfer enhancement are relatively recent. One of the earliest was reported by Edwards and Alker⁽¹⁾, who investigated the effect of counter-rotating and co-rotating longitudinal vortices on heat transfer of boundary layers. They used cubes and vortex generator blades to create the longitudinal vortices and found that cubes produced the highest local improvement while the effect of vortex generators extended further downstream. Russel et al.⁽²⁾ conducted experiments with sensitive paints to determine the spanwise temperature distribution of alternating rows of close-

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ly spaced counter-rotating vortex generators on a simulated plate fin surface. They found that considerable enhancement of heat transfer occurs, with a modest pressure loss penalty. Fiebig et al.⁽³⁾ reported on experimental work in which the local heat transfer and friction coefficients for channels with various kinds of wing-type vortex generators were measured. They concluded that some geometries of vortex generators are more suitable for heat transfer augmentation. Turk and Junkhan⁽⁴⁾ conducted similar research on blade-type vortex generators in flat-plate, with the emphasis being placed on the relationship between the geometry and the augmentation of the overall coefficients.

There are some detailed reports which deal with the interaction of longitudinal vortices and turbulent boundary layers. Eibeck and Eaton⁽⁵⁾ examined the influence on heat transfer of a longitudinal vortex embedded in a turbulent boundary layer. Pauley and Eaton⁽⁶⁾ extended the above work to include the case of a pair of vortices. The reports of Shabaka et al.⁽⁷⁾, Westphal et al.⁽⁸⁾ and Mehta and Bradshaw⁽⁹⁾ focused attention on the velocity field and the characteristics of turbulence.

The present authors reported previously⁽¹⁰⁾ on the isolated influence of longitudinal vortices well downstream from a half-delta wing vortex generator on heat transfer of an otherwise laminar boundary layer. In this case, it was observed that the main reason for the large enhancement in heat transfer in such flows is the transition to the turbulent regime rather than the vortical motion itself.

The objective of the present study is to determine the influence of a single longitudinal vortex on heat transfer of an otherwise laminar boundary layer, near the vortex generator. The local heat transfer coefficient and the streamwise velocity field were measured. The height, angle of attack and geometry of the vortex generator were varied for parametric studies.

2. Nomenclature

- H : Vortex generator height
 St : Stanton number
 St_0 : Experimental two-dimensional value of Stanton number
 u : Streamwise mean velocity
 u' : Fluctuation component of streamwise velocity
 u_s : Free-stream velocity
 x, y, z : Cartesian coordinates
 α : Vortex generator's angle of attack
 δ : Boundary layer thickness at the generator's location

3. Experimental Apparatus and Procedure

The test facility consisted of a low-speed, open-circuit wind tunnel. The air was delivered by a controlled blower and passed through a turbulence management section. A nozzle with a contraction ratio of 7 : 1 connected the wind tunnel to the 300 × 300 -mm-square test section. The nominal free-stream velocity (u_s) was 4 m/s, with the free-stream turbulence intensity around 0.3%.

The longitudinal vortex was generated in the centerline of the laminar boundary layer by means of a half-delta wing and then passed over a constant heat-flux heat transfer surface with an unheated starting length of 0.2 m (Fig. 1). A stainless-steel heated surface (903 × 260 × 0.03 mm³) was set up at the upper side of the test section to eliminate the influence of natural convection. The back face of the heater was insulated by a bakelite plate covered with styrene-foam insulation. The distributions of heat transfer coefficients in both spanwise and streamwise directions were based on temperature measurements by fine thermocouples attached to the back of the heat transfer surface. One-hundred and thirty Cooper-Constantan thermocouples (0.06 mm diameter) were arranged along the surface in five spanwise rows of twenty or thirty thermocouples each.

The uncertainty of the Stanton number was estimated by combining uncertainties in the measurements of the local temperature and the power supplied, and in the correction applied for radiation and conduction losses. The resulting uncertainty of the Stanton number was 10%. Because the heat transfer results are presented in nondimensional form, normalized by the two-dimensional experimental data, the bias errors were taken into consideration. Therefore, the uncertainty of the normalized Stanton number should be lower than 10%.

The mean and fluctuating components of the velocity were measured by a single, constant-temperature hot-wire anemometer which was traversed in the normal (y) and spanwise (z) directions for each

Fig. 1 Schematic view of the heat transfer surface

streamwise (x) station. The contour plots in this paper represent the results for the streamwise component of velocity taken by a single probe.

The longitudinal vortices were generated by half-delta wings of various heights ($H=6/10/15/25$ mm) and angles of attack ($\alpha=5^\circ/10^\circ/15^\circ/20^\circ/25^\circ$). The geometry of the generator was also changed to verify its influence on heat transfer. The generators were positioned just upstream of the heating starting point. The velocity boundary layer thickness at the generator's location (δ) was 4.8 mm.

4. Results and Discussion

4.1 Development of the vortex

The behavior of the longitudinal vortices generated by a single generator is discussed in this section. The following vortices were found to significantly affect the flow field: (1) the main vortex that is formed as a result of the flow separating at the tip of the half-delta wing and rolling up due to the lower pressure in the back side of the vortex generator, (2) the corner vortices that are horseshoe-like vortices formed in the corner between the front side of the wing and the duct plate and (3) the induced secondary vortex which is formed in the corner between the back side of the wing and the duct plate as a result of the redirectioning of the near-wall flow caused by the lower pressure behind the generator. Figure 2 shows the streamwise development of a longitudinal vortex generated by a single vortex generator whose height (H) is 15 mm and angle of attack (α) is 15° . Each contour plot represents the streamwise velocity map for one streamwise station. Although the signal from a single-wire probe can also include the normal component of the velocity, comparison with three-dimensional measurements showed that the streamwise

Fig. 2 Streamwise velocity contour for a vortex generator ($H=15$ mm and $\alpha=15^\circ$)

component is predominant. It is important to note in this figure that the longitudinal vortex, although suffering from the influence of viscous dissipation, persists well downstream, modifying the entire velocity field. Because of the interaction between the vortex and the wall, the vortex shifts its position to the upwash region. In the first streamwise station ($x=0.08$ m), there are indications of three vortices (the main, corner and induced secondary vortices) that were captured in the velocity measurement. These vortices modify the flow structure near the wall, which can influence the heat transfer results. The corner and the induced secondary vortices decay more rapidly because they are located near the wall.

4.2 Relationship between the velocity field and the heat transfer

Downstream from the vortex generator, the heat transfer coefficient is expected to be high. In this case, the heat transfer enhancement can be attributed to the boundary layer thinning due to the vortical motion, or to the local growth of turbulence intensity. The relative influence of these two factors on heat transfer downstream of a vortex generator with a relatively small angle of attack is shown in Fig. 3. This figure shows the heat transfer results and the velocity contour plots for a single vortex generator with $H=15$ mm and $\alpha=15^\circ$ in a streamwise station which corresponds to the second thermocouples row. The top contour shows the mean streamwise velocity contour

Fig. 3 Heat transfer results and velocity contours for a vortex generator ($H=15$ mm and $\alpha=15^\circ$) at $x=0.1$ m

plot and the bottom, the fluctuating component. The heat transfer results corresponding to this streamwise station show that there are two peaks for the heat transfer coefficient which are associated with the regions where the boundary layer is thinned by the downward vortical motion of the main and corner vortices. On the other hand, these peaks are not necessarily related to the regions which have high turbulence intensity. The velocity profiles for this streamwise station (Fig. 4) also show how the boundary layer is thinned by the action of the main and corner vortices. The velocity gradients near the wall as affected by the vortices are steeper than the veloc-

Fig. 4 Mean velocity profiles for a vortex generator ($H=15$ mm and $\alpha=15^\circ$) at $x=0.4$ m.

Fig. 5 Heat transfer results and velocity contours for a vortex generator ($H=15$ mm and $\alpha=15^\circ$) at $x=0.4$ m

ity gradient for the two-dimensional case. The conclusion is that the boundary layer thinning plays a major role in heat transfer enhancement in the region near the generator. The situation in the region well downstream ($x=0.4$ m) for the same generator is shown in Fig. 5. In the downwash region, the area with heat transfer enhancement corresponds closely to the region in which the boundary layer is thinned by the main vortex. In the upwash region, the heat transfer is augmented over a broader area and the peak shifts its spanwise position. The spanwise shift is related to the shift of the longitudinal vortex system. From the contour plot of the fluctuating component of velocity, it is possible to associate the broader region with heat transfer enhancement to the local growth of the turbulence intensity in the upwash region. The upwash vortical motion and the presence of the corner and induced secondary vortices produce additional instabilities which produce the local growth of the turbulence intensity. In fact, the region around $z=-20$ mm shows a valley of the heat transfer coefficient while the mean velocity contour plot shows a thinned boundary layer in the same location, probably due to the remnant corner vortex. Because the velocity and heat transfer measurements were conducted in opposite walls of the same test section, it is possible that the spanwise shift of the vortex was not identical on both sides of the duct, especially considering the fact that this particular measurement was conducted 0.6 m downstream of the nozzle exit. Nevertheless, it is possible to conclude that well downstream the local growth of the turbulence intensity plays an important role in enhancing heat transfer together, with the local boundary layer thinning by the longitudinal vortices.

4.3 Influence of the vortex generator's height

The influence of variations in the height (H) of the vortex generator on heat transfer is shown in Fig. 6. In this case, the size of the vortices is varied by modifying the generator's height. It is worth noting that the heat transfer enhancement persists well downstream. This heat transfer effect is a natural consequence of the persistence of the longitudinal vortices, as seen in the velocity contours. The two peaks of the heat transfer coefficient caused by the main and corner vortices appear clearly for $H \geq 10$ mm. For $H=25$ mm, there is a third peak which appears in the upwash region. This peak is related to the second corner vortex which appears in vortex generator configurations with large frontal areas. For $H=6$ mm, the corner vortex is apparently weak with slight influence on the heat transfer results. The heat transfer coefficient well downstream ($x=0.4$ m) is not as dependent on H , for $H \geq 10$ mm. The heat transfer enhancement level is around 50% in the region near

the generator and 80% well downstream.

4.4 Influence of the vortex generator's angle of attack

The influence of variations in the angle of attack (α) of the vortex generator on heat transfer is shown in Fig. 7. These results are for vortex generators with $H=15$ mm and $\alpha=5^\circ/10^\circ/15^\circ/20^\circ/25^\circ$. It has been established that the strength of the vortices generated

Fig. 6 Streamwise development of local Stanton number ratios (parameter: height)

Fig. 7 Streamwise development of local Stanton number ratios (parameter: angle of attack)

by half-delta wings is proportional to the angle of attack. The heat transfer results show that the heat transfer enhancement for both the downwash region (heat transfer dominated by the main vortex) and the upwash region (heat transfer dominated by the corner vortex) becomes larger for larger angles of attack. The heat transfer peaks and valleys shift their positions to the upwash side, as the angle of attack becomes larger. This shift occurs as a result of the larger flow redirectioning caused by the vortex generators with larger angles of attack. Well downstream, the region of heat transfer enhancement becomes broader for generators with larger angles of attack. Another interesting feature is the third small heat transfer peak which appears in the upwash side for larger angles of attack. This third peak is related to a small corner vortex which appears more clearly for generators with larger frontal areas. In conclusion, larger angles of attack produce greater heat transfer enhancement in terms of magnitude and area coverage.

4.5 Influence of the vortex generator's geometry

The influence of variations in the geometry of the vortex generator on heat transfer was also investigated. Figure 8 shows the various alternative vortex generator geometries which were used in the experiments. The heat transfer results shown in Fig. 9 correspond to the generators with $H=10$ mm and $\alpha=15^\circ$. The K-type vortex generator shows modest heat transfer enhancement because of the weak main and corner vortices it produces. The S-type vortex generator shows the best heat transfer performance. The heat transfer enhancement is greater for geometries with larger frontal areas because the main and corner vortices in such cases are expected to be stronger.

5. Conclusions

The influence of longitudinal vortices just downstream of half-delta wing vortex generators on heat transfer of laminar boundary layers was experimentally investigated. The longitudinal vortices generated by a half-delta wing produced two peaks in the heat

Fig. 8 Geometries of the vortex generator

Fig. 9 Streamwise development of local Stanton number ratios (parameter: geometry)

transfer coefficient across the span. The boundary layer thinning caused by the downward motion of the main and corner vortices was the primary reason for the local heat transfer enhancement. An expressive value of the heat transfer coefficient, 80% above the two-dimensional result, was found in a region clearly dominated by a laminar structure. Well downstream, the local growth of the turbulence intensity was also an important factor for the high heat transfer coefficients. Experiments with wings having different heights, angles of attack and geometries showed that configurations which produce stronger main and corner vortices are more effective for heat transfer enhancement.

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