Effects of Longitudinal Vortices on Turbulent Junction Flow Heat Transfer

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Turbulent junction flow is a complex vortex system generated upstream of a blockage embedded in a turbulent boundary layer, which leads to augmented heat transfer in the vicinity of the blockage. The vortex legs wrap around the blockage and are carried downstream as longitudinal vortices. In scenarios such as multi-stage axial turbines or multiple row tube heat exchangers, these longitudinal vortices can collide with the next junction flow vortex on a downstream blockage. Furthermore, freestream turbulence is often present in these devices to augment mixing or increase heat transfer. This paper provides a comprehensive study on how a longitudinal vortex affects junction flow and associated heat transfer for a variety of Reynolds numbers, freestream turbulence values, and longitudinal vortex configurations. Longitudinal vortices were generated upstream of a Rood wing airfoil using a single, or pairs, of delta winglet vortex generators. Spatially-resolved endwall heat transfer coefficients upstream and around the Rood wing junction were measured using infrared thermography, and time-averaged flow field measurements of the incoming longitudinal vortex were taken using Stereo Particle Image Velocimetry. Longitudinal vortices provided some augmentation upstream and around the junction, but did not greatly increase heat transfer at the junction or disrupt the time-average horseshoe vortex. At high turbulence, longitudinal vortices were found to be less effective at augmenting heat transfer, with their effectiveness further decreasing at higher Reynolds number values. This was the result of decreased normalized vorticity at these conditions. Because of this, vorticity was determined to be a key parameter in determining quantitative heat transfer augmentation from a longitudinal vortex. Qualitative trends on the other hand are heavily influenced by the velocity vectors, as seen in how peaks in St augmentation were more narrow at higher turbulence levels. This was the result of secondary vorticity cores only present at low turbulence preventing fluid from being able to directly impinge on the endwall.

\textbf{Nomenclature}

\begin{align*}
L & = \text{Vortex generator length, cm} \\
\text{Re}_T & = \text{Body thickness Reynolds number, } \text{Re}_T = \frac{\text{U}_{\text{ref}}}{\nu} \\
\text{St} & = \text{Stanton number} \\
\text{St}_o & = \text{Baseline Stanton number at a low freestream turbulence} \\
\text{St'}_o & = \text{Baseline Stanton number at a high freestream turbulence} \\
T & = \text{Maximum wing thickness, cm} \\
t & = \text{Vortex generator thickness, cm} \\
\text{Tu} & = \text{Freestream turbulence} \\
\text{U}_{\text{ref}} & = \text{Reference velocity, m/s} \\
W & = \text{Vortex generator height, cm} \\
\text{X} & = \text{Streamwise direction} \\
\text{Y} & = \text{Wall-normal direction} \\
\text{Z} & = \text{Spanwise direction} \\
\delta & = \text{Boundary layer height, cm} \\
\nu & = \text{Kinematic viscosity, m}^2/\text{s} \\
\end{align*}

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I. Introduction

Turbulent junction flow occurs when an adverse pressure gradient from a bluff body causes an incoming turbulent boundary layer to separate in front of the body. At the leading edge, a vortex system, referred to as the horseshoe vortex, is formed. The vortex system may consist of several smaller vortices, and the vortices wrap around the leading edge with legs that proceed downstream along the body-wall junction. This vortex system is highly unsteady and is responsible for significant pressure fluctuations and high heat transfer near the leading edge of the bluff body. Praisner and Smith [1] reported up to 300% increase in heat transfer in the junction flow region when compared with the upstream turbulent boundary layer. This rise in surface heat transfer can place additional thermal stresses on gas turbine components and reduce their lifetime by up to half [2]. In heat exchangers, however, this is advantageous because the increase in heat transfer between the fluid and wall increases the heat load of the heat exchanger.

In many devices such as gas turbine engines or multi-row heat exchangers, multiple rows of bluff bodies are present, each generating its own horseshoe vortex system. The legs of the horseshoe vortex become longitudinal vortices downstream of the body and can interact with a downstream horseshoe vortex system, potentially altering that body’s junction flow and its augmented heat transfer field. In addition, high turbulence levels are often present in gas turbines and heat exchangers, such as in a gas turbine combustor to improve mixing, or in a plate-tube heat exchanger to improve tube heat transfer. Freestream turbulence can degrade the strength of longitudinal vortices by increased turbulent dispersion. These complex interactions of longitudinal vortices, freestream turbulence, and junction flow are not well understood despite their common occurrence. Understanding the physics that occur during this interaction could lead to insights about ways to control junction flow. Also, understanding the effects of the interaction could help motivate design decisions for more efficient engines.

In this paper, the effects of longitudinal vortices on turbulent junction flow are investigated for various Reynolds numbers and freestream turbulence levels relevant to a variety of applications. Delta winglet vortex generators (VG) are used to generate longitudinal vortices upstream of a research airfoil geometry (Rood wing), and bar grids are used to generate homogeneous freestream turbulence. Spatially resolved measurements of surface heat transfer coefficients are made using infrared thermography to obtain surface temperatures on a constant heat flux wall. Time-averaged flowfield measurements of the incoming vortices are made with a stereo Particle Image Velocimetry system to understand the incoming vortical structures.

II. Previous Studies

The adverse pressure gradient formed by a bluff body causes the approach boundary layer to separate creating a vortex system. A primary vortex, a secondary vortex, and possibly even tertiary vortices are formed, and follow the contours of the obstacle before merging with vortices generated by the trailing edge [3]. Devenport and Simpson [4] found that instantaneous velocity behavior in the leading edge junction produces a bimodal velocity distribution. They proposed a coherent upstream mode with a strong backward-directed wall jet called the “backflow mode” and a more chaotic mode without a strong wall jet near the leading edge, called the “zero-flow mode”. Detached Eddy Simulations by Paik et al. [5] revealed that the presence of the endwall led to the existence of the bimodal behavior. Counter-rotating vortices formed between the primary vortex and endwall were found to lift away from the wall and merge into hairpin vortices. The hairpin vortices push the primary vortex near the wing and break it down forming the “zero-flow mode”, and the reformation of the primary vortex pushes it away from the wall forming the “backflow mode”. Chen et al. [6] found that during the transition from “backflow” to “zero-flow” mode, a third “intermediate mode” can occur if the incoming fluid has low enough momentum. Another study by Apsilidis et al. [7] found the “intermediate mode” may exist as well. Apsilidis et al. [7] also found that at a body thickness Reynolds number of about 25,000 that the “zero-flow mode” was appeared more often and for longer periods of time. This was due to a disintegration of the primary horseshoe vortex.

Other more recent studies [8, 9] have found that the horseshoe vortex can be altered, but not completely destroyed, in the presence of high turbulence. When subjected to high freestream turbulence, Lange et al. [8] found that the turbulent kinetic energy (TKE) of the horseshoe vortex is greatly augmented at low Reynolds numbers with augmentation diminishing as Reynolds number increases. This was due to a decreased potential for turbulent structures to penetrate the junction flow at high Reynolds number and turbulence values. They also observed that the time-resolved vortex core becomes more chaotic. Anderson and Lynch [9] found that the time-mean horseshoe vortex in latter rows of a pin-fin array had its turbulence levels increased to around 40% in the mid-channel. Both studies, however, observed that the time-resolved horseshoe vortex consistently produced “backflow mode” and “zero-flow mode”.
Praisner and Smith [1] found that the vortex system resulted in observable bands of high time-average endwall heat transfer, but Lewis et al. [10] found no corresponding bimodal behavior in the instantaneous surface heat transfer. More recently, spatially-resolved heat transfer measurements for the same airfoil shape were made by Elahi et al. [11] using infrared thermography at various Reynolds numbers and freestream turbulence conditions. They found that close to the wing there are bands of augmented Stanton number that become more tightly attached to the wing as Reynolds number is increased. Later, the same group found that increasing turbulence intensity augmented Stanton number at lower Reynolds numbers, but not at higher Reynolds numbers [12]. This agrees with the behavior Lange et al. [8] noticed with the TKE in the horseshoe vortex.

There have been multiple studies concerning the flowfield generated by a longitudinal vortex embedded in a flat plate boundary layer [13-16]. Yao and Lin [13] reported a connection between the vorticity to both the angle of attack and the vortex generator relative size. When the ratio between vortex generator size and the boundary layer (W/δ) was small, vorticity exhibited a proportional relationship with angle of attack. This became an inversely proportional relationship when W/δ approached unity. Variations in angle of attack have also been reported to have a minimal effect on the core height and size but did increase circulation [14]. The longitudinal vortex modifies the boundary layer by thinning it in the downwash regions and causing it to grow in upwash regions [14-16]. For individual vortices, the boundary layer thickness can grow or shrink by up to a factor of 2. Despite this occurrence, there was a minimal effect on the static pressure near the longitudinal vortex [14]. Regardless of the vortex generator set up, longitudinal vortices were found to be persistent and able to last many boundary layer thicknesses downstream [14, 16].

Vortex generator pairs have a different influence on the flowfield depending on their configuration. Pairs can either be counter-rotating or co-rotating. Counter-rotating pairs come in two different types and consist of vortices producing opposing signs of vorticity. These adjacent vortices can be in either “common upflow” or “common downflow” configurations. Common upflow occurs when the fluid between the pair of vortices is directed away from the wall, while common downflow results in fluid being pushed down to the wall. Vortex generator pairs in the common downflow configuration thin the boundary layer, but the amount by which it the boundary layer is thinned decreases as the gap between the vortices increases. For the common upflow configuration, the vortices eventually merge and cancel each other out. As with individual vortices, circulation increases with angle of attack. One interesting feature is that the boundary layer thinning at the centerline is independent of angle of attack [15].

How longitudinal vortices impact endwall heat transfer over flat plates has been well documented [14-17]. Fiebig [16] noted that longitudinal vortices were the most effective vortex type at augmenting endwall heat transfer as they both destabilized the flow and increased interactions between the freestream and endwall. Peak values of heat transfer augmentation occurred in the vortex downwash region while strong upwash regions were found to have slightly decrease heat transfer [14, 16]. The delta winglet has been shown to be the most effective vortex generator geometry at augmenting surface heat transfer [16, 17]. Heat transfer augmentation was also reported to be dependent upon the W/δ ratio. As the W/δ increases, so does heat transfer augmentation. This relationship however, is asymptotic. Angle of attack, like vortex generator height, has an asymptotic relationship with heat transfer augmentation with angles beyond approximately 20° providing minimal additional heat transfer augmentation. At these steep angles, vortices only move laterally away from the generator at a faster rate [14]. Peak augmentation occurred with an angle of attack of 45° [16]. Minimal variation with distance downstream was observed, other than the vortex’s lateral motion [14].

For counter-rotating vortex generator pairs, both the common upflow and common downflow configurations augmented heat transfer [15, 16, 18]. However, the distance between the generators seemed to have a limited effect on heat transfer augmentation [15]. The common downflow configuration was found to have strong interactions with the boundary layer while the common upflow had the vortices strongly interacting with each other as a result of them approaching one another. This led to the common downflow configuration exhibiting two Stanton number peaks in the transverse direction and providing more heat transfer augmentation than the common upflow configuration [18]. Common downflow pairs were found to have better heat transfer performance in other studies as well [15, 16].

Only a few studies have researched how a longitudinal vortex interacts with the junction flow system. Introducing vortices upstream of the junction flow has been considered as a method to delay flow separation and therefore as a means to possibly delay or circumvent the creation of junction flow [15]. The incoming vortices have also been reported to merge into larger structures [19] and increase aerodynamic losses [20]. Hussain et al. [21] measured Nusselt numbers near a cylinder at multiple Reynolds numbers when a common downflow vortex generator pair was placed upstream. They reported the centerline heat transfer was hardly affected, but that heat transfer augmentation was more prevalent when the vortex legs were shifted off of the centerline. Vortices were observed to persist after the leading edge, impacting the flow in the wake. One limitation was that their study was done at a single freestream turbulence condition and with a single vortex generator configuration.

The previously discussed research shows that junction heat transfer is impacted by flow Reynolds number and freestream turbulence, and possibly by upstream longitudinal vorticity. However, no studies have considered the
combined impact of upstream longitudinal vorticity, turbulence, and Reynolds number and how these effects vary with different vortex generator configurations. This work aims to fill in this gap in knowledge by measuring surface heat transfer in a junction flow with various longitudinal vortex configurations, freestream turbulence conditions, and Reynolds numbers.

III. Experimental Description

A. Facility

All experiments were conducted using a large, recirculating low speed wind tunnel, see Fig. 1. A variable frequency fan is used to set air velocities up to 12 m/s to achieve the desired Reynolds number. The airfoil shown in Fig. 1, known as a Rood wing, has been previously studied in junction flow experiments [1, 8, 11, 12]. The Rood wing is a symmetric airfoil that was aligned in the tunnel with an angle of attack of 0°. Dimensions of the Rood wing match those used by Elahi et al. [11]. Also shown in Fig. 1, the streamwise direction is chosen as the positive x-direction, y-direction is chosen to be the normal to the endwall, and right hand rule is applied to designate the z-direction. The nominal freestream turbulence value was previously measured to be about 1% using 2-component Laser Doppler Velocimetry (LDV) [11]. A passive bar grid was used in this study to generate freestream turbulence, due to its ability to generate homogenous freestream turbulence [22]. Parallel pipes, seen in Fig. 1, each had a diameter of 10.16 cm, which also equals the spacing between them. This configuration, used in this tunnel in prior studies [8, 12], results in a turbulence intensity of 15-20% depending on the Reynolds number [8]. Experiments were run with and without the grid to observe the effect of freestream turbulence on the longitudinal vortices.

The addition of vortex generators was implemented to simulate upstream vortices impinging on the junction of an airfoil. Delta winglets were the chosen generator shape due to their superior ability to augment heat transfer compared to other geometries [16, 17]. In this study, a small and large generator geometry were used both individually and in a common downflow pair. The large generator, depicted in Fig. 2, was 13 cm tall while the small generator was 7 cm tall. These sizes were determined from boundary layer thickness measurements previously taken in the same wind tunnel. At ReT of 7,000; 25,000; and 50,000, δ was 10.7 cm, 8.5 cm, and 7.3 cm respectively at low turbulence. At high turbulence, δ was 9.9 cm, 9.3 cm, and 7.1 cm respectively [8]. This gave winglet height to boundary layer thickness ratio (W/δ) ranges from 0.65 to 0.99 for the small generator. For the large generator, the W/δ ranges from 1.21 to 1.84. An aspect ratio of 1:1 for the horizontal and vertical sides was used and the thickness, t, was 1 cm. The vortex generators were placed one chord length (40 cm) upstream of the Rood wing. This location was chosen because...
the previously determined boundary layer profiles were measured at this point. When placed individually, the vortex generators were oriented so the trailing vortex would have negative $x$-vorticity with respect to the previously described coordinate system. Horseshoe vortices from upstream bluff bodies form common downflow pairs; therefore, generator pairs were set in a common downflow configuration in this study. All vortex generators were placed at an angle of attack of 45° with respect to the streamwise direction.

Spatially-resolved endwall heat transfer coefficient measurements were obtained using infrared (IR) thermography to measure surface temperatures on a constant heat flux surface. Tunnel freestream temperature was set through the use of different stages of pre-conditioning, while multiple identical thin surface heaters attached to insulating surfaces were used to maintain the constant heat flux condition upstream the Rood wing. Details on the surface heater set up and validation can be found in Elahi et al. [11]. Heat flux level varied with Reynolds number to maintain a difference between freestream to average endwall temperature of about 20°C. This was done to ensure sufficient resolution for the camera, without changing local fluid properties significantly. Surface temperatures from the IR camera were calibrated against thermocouples attached to the underside of the heater, with average agreement generally better than 1°C.

Flowfield measurements were taken using the Stereo Particle Image Velocimetry (SPIV) system described by Elahi et al. [11]. The laser sheet was aligned parallel to the $z$-direction with measurements being taken 29 cm upstream of the leading edge, $X/T = -3.08$. This location is immediately upstream of the IR measurements and was selected so an inlet flow profile could be determined. Figure 3 shows a close up of the test section along with more exact locations of the vortex generators and laser sheet. Images were taken using two Photron FASTCAM Mini UX100 high speed cameras with 62 mm focal length lenses and Scheimpflug adapters. This produced a magnification of 0.1 mm/px. Cameras were placed 45° off of the laser sheet and received forward scatter of the reflected light. Double frame images were taken at a 500 Hz sampling rate. Initial calibration was performed using a LaVision calibration plate. Self-calibration was then performed after data collection to ensure data accuracy. A multi-pass processing operation was performed where the first two passes had a 96 x 96 window size with 50% overlap. The final three passes had a window size of 32 x 32 with a 75% overlap.

Table 1 shows the airflow conditions and the type of data obtained for each case. Surface heat transfer measurements were taken at three Reynolds numbers and two turbulence intensities for four vortex generator configurations. Body thickness Reynolds number ($Re_T$) was used where the length scale is the airfoil maximum thickness, $T$ (9.42 cm). $Re_T$ values of 7,000; 25,000; and 50,000 were used. Data was taken without and with the turbulence grid, generating what will be referred to as the low and high freestream turbulence conditions, respectively. Small and large vortex generators were used both individually (single) and as a common downflow pair. Flowfield measurements were taken for the small generators only. Data was acquired at $Re_T$ values of 7,000 and 25,000 across both turbulence conditions. All properties were normalized using the reference $U_{ref}$ as a velocity scale and $T$ as a length scale.

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B. Experimental Uncertainty

Uncertainty in the heat transfer measurements vary depending on the body thickness Reynolds number. For the $Re_T$ values 7,000; 25,000; and 50,000, the uncertainty is approximately 14%, 9.5%, and 8% respectively. The primary contributions to uncertainty are measurements of the freestream temperature, surface temperature, and surface heat flux. More details on uncertainty for this set up are presented in Elahi et al. [11]. SPIV uncertainty was determined using the method presented by Wieneke [23]. At a $Re_T$ of 7,000, uncertainty in the time-averaged velocity magnitude in the freestream, vortex edge, and vortex core were 4.5%, 5.0%, and 6.6% respectively. At a $Re_T$ of 25,000, uncertainty for the freestream, vortex edge, and vortex core changed to 5.5%, 5.8%, and 7.6% respectively.

IV. Results

A. Baseline Stanton Numbers

Baseline Stanton number contours at low freestream turbulence, denoted as $St_o$, are presented in Fig. 4 with $Re_T$ increasing from (a) – (c). In Fig. 4, Stanton numbers far upstream the airfoil decrease as the junction is approached. Near the airfoil, the junction region is indicated by bands of high heat transfer. As $Re_T$ increases, these bands move closer to the airfoil, a pattern also reported by Elahi et al. [11], and $St$ magnitudes at any given location decrease. The baseline cases are further validated in Fig. 5 which compares results from $Re_T=25,000$ between the current study and Elahi’s results, but there is overall good agreement in both magnitude and trend of junction heat transfer.

Endwall Stanton number at a high freestream turbulence in Fig. 6, denoted as $St'_o$, exhibits the same patterns found at low turbulence. The high heat transfer bands near the junction shrink with increasing Reynolds number. When comparing the contours of low and high freestream turbulence at the same $Re_T$, (Fig. 4 and 6), $St$ values everywhere upstream of the junction increase as a result of increased turbulent mixing between the flow and endwall. The bands of augmented heat transfer near the junction move closer to the airfoil at higher freestream turbulence, as well. This
follows with results from Lange et al. [8], who reported that the time-averaged horseshoe vortex moves closer to the junction as freestream turbulence increases.

Baseline data was quantitatively compared using surface averaged Stanton numbers, plotted in Fig. 7. The averaging area encompassed the IR image area shown in Fig. 3 which was approximately 0.12 m². Surface averaged St values were obtained from Elahi et al. [11] over the same averaging area. The local Stanton number correlation for turbulent flow over a flat plate with a constant wall heat flux, Eq. (1) [24], was averaged over length to obtain Eq. (2), which is also plotted in Fig. 7.

\[
StPr^{-0.4} = 0.03Re_x^{-0.2}
\]  

\[
\overline{St_L} = 0.0375Re_L^{-0.2}Pr^{-0.4}
\]  

In Fig. 7, low freestream turbulence results from the present study fall within the uncertainty of the data from Elahi et al. [11] and Eq. (2). The high heat transfer around the wing junction may not have the same Reynolds dependency as a flat plate turbulent boundary layer. However, over the averaging area considered, it appears that generally these results follow a turbulent boundary layer trend.

Surface averaged St at high freestream turbulence is also plotted on Fig. 7. Comparing the low and high freestream turbulence results shows an increase in St of about 25-30% at the higher turbulence level. One interesting observation
about the high turbulence cases is that the Reynolds dependence of the Stanton number still seems to follow $Re^{0.2}$. The impact of high freestream turbulence, therefore, is to increase the level of endwall heat transfer but not change the Reynolds dependence.

B. Effects of Vortex Generators in Low Freestream Turbulence

Endwall heat transfer results acquired with vortex generators present was normalized by $St_o$ (low-turbulence result, for a given Re number) to acquire Stanton number augmentation. Contours of Stanton number augmentation for each vortex generator configuration at a $Re_T$ of 7,000 are presented in Fig. 8. For all vortex generator configurations, Stanton number is augmented in the vortex path. Increasing the vortex generator size in Fig. 8(a) vs. (b) and (c) vs. (d), yields higher Stanton number values along the vortex path due to the existence of a stronger vortex further disturbing the flowfield. Comparing individual generators relative to a pair with the same size, Fig. 8(a) vs. (c) and (b) vs. (d), also shows an increase in Stanton number in the streamwise direction for the pairs. The Stanton number augmentation in this case is a consequence of two sources. First is the increased lateral coverage from the presence of two vortices as opposed to one. Second is from the pairs in a common downflow configuration which further thins the local boundary layer under the downflow.

The longitudinal vortices in the current study almost immediately begin to weaken as indicated by the decrease in Stanton number augmentation along the vortex path toward the wing, contradicting prior flat plate research [14, 16]. In those studies, longitudinal vortices were observed to last at least 100 boundary layer thicknesses downstream, and Stanton number stayed constant along the vortex path. This difference in behavior can be attributed to the adverse pressure gradient created by the wing leading edge, as well as the dominance of the junction flow vortex over the longitudinal vortex on the local heat transfer around the wing leading edge. Heat transfer augmentation, and therefore the longitudinal vortex, are weakening as the vortex approaches the leading edge with minimum augmentation values occurring close to the junction. Augmentation values are slightly above 1.0 in the region close to the wing, indicating that the longitudinal vortex does have some degree of influence in the junction area. Augmentation values near the junction across all cases were never found to exceed about 30%, however. Hussain et al. [21] also found that vortex generator pairs cause relatively little effect near the junction for a cylinder, with augmentation also less than 30%.

Stanton number augmentation wraps around the sides of the airfoil for all vortex generator configurations in Fig. 8, sometimes forming bands of high $St$ around the sides of the airfoil. These bands are best seen in Fig. 8(d) where the vortex system has a large amount of lateral coverage. The existence of augmentation around the sides of the wing implies the longitudinal vortex is not completely broken up and is progressing separately from the horseshoe vortex legs generated at the wing junction. For individual longitudinal vortices, the vortex seems to gradually widen and split, supported by how the $St$ augmentation spread laterally close to the junction. When in the pair configuration, however, the longitudinal vortex cores are offset from the centerline. Therefore, lateral augmentation spreading and the vortex’s ability to persist beyond the wing leading edge is more likely due to the fact that vortices in the common downflow

![Fig. 8 Stanton number augmentation at a low freestream turbulence and $Re_T$ of 7,000 with a (a) small single, (b) large single, (c) small pair, and (d) large pair](image-url)
configuration tend to separate downstream [18]. The vortex pair’s ability to persist downstream of the junction was also reported by Hussain et al. [21].

Behaviors observed at $Re_T$ of 7,000 were similar to those observed at higher $Re_T$. This agrees with results obtained by Hussain et al. [21], who found little to no variation in heat transfer augmentation from Reynolds numbers of 20,000 to 50,000. In this study, the primary difference between Reynolds number cases for a constant vortex generator configuration is that augmentation values near the leading edge are higher. The likely cause of this behavior is that the horseshoe vortex moves closer to the leading edge at higher Reynolds numbers.

Surface averaged $St$ augmentation values for each case were obtained using the same averaging area as described above, and are shown in Fig. 9. Reynolds number appears to have an insignificant effect on augmentation regardless of the vortex configuration. As expected, larger vortices in pairs produce the highest augmentation in the averaging area. Two interesting features are observed in Fig. 9. First is the similarity between the surface averaged values of the large single VG and small pair VG configurations. Though the small pair has more lateral coverage and high heat transfer from the common downflow arrangement, the strength of the larger vortex is higher than the small pair. The second observation is the difference between the augmentations from an individual generator versus a pair, for different generator sizes. For the small generator, Stanton number augmentation increases on average by about 12% between the single generator and the pair. For the large generator, the increase is about 25% from single vortex to pair. This is due to the larger vortex generator producing a strong longitudinal vortex with additional lateral coverage.

C. Effect of Vortex Generators in High Freestream Turbulence

Stanton numbers acquired at high freestream turbulence were normalized by $St_a$ to present augmentation relative to a common baseline for a given $Re_T$. $St$ augmentation values for a $Re_T$ of 7,000 are shown in Fig. 10 and are higher than their low freestream turbulence counterparts in Fig. 8, due to the additional effect of freestream turbulence. Large generators, Fig. 10(b) and (d), once again result in more augmentation than smaller ones, (a) and (c). Generator pairs, Fig. 10(c) and (d), show an increase in augmentation and lateral coverage when compared to individual generators (a) and (b). How vortex generators impact heat transfer near the junction did not change at high $Tu$. The incoming longitudinal vortices break up, wrap around the sides of the airfoil, and form augmentation bands. In Fig. 10, the maximum augmentation near the airfoil-endwall junction occurs for the large pair configuration, Fig. 10(d), and was about 40%. This is 10% greater than the peak augmentation found near the junction at low freestream turbulence, so the largest vortex generators can have some effect but it is small compared to the impact far upstream of the junction.

Area-averaged heat transfer at high turbulence, plotted in Fig. 11, generally increased with freestream turbulence at a given $Re_T$, but a dependency on $Re_T$ not present at low turbulence conditions appears. Surface averaged Stanton number augmentation for all high turbulence cases is plotted in Fig. 11(a), and Figure 11(b) compares surface averaged heat transfer augmentation for both large generator configurations at varying turbulence levels. Figure 11(a) shows that an increase in $Re_T$ yields a decreasing Stanton number augmentation. This results in overall augmentation between low and high turbulence cases converging as $Re_T$ increases, as seen in Fig. 11(b). In the instance of the large vortex generator pair at a $Re_T$ of 50,000, the area-average $St$ from low freestream turbulence is nearly the same as for high freestream turbulence. This behavior is likely due to the combined effect of the vortex strength being weakened by an

![Fig. 9 Surface averaged Stanton number versus $Re_T$ at low turbulence](image-url)
increase in freestream turbulence, as well as the high unsteadiness of the turbulent boundary layer in which the vortex is embedded at high Reynolds number.

It appears that longitudinal vortices less effectively augment heat transfer in high turbulence conditions, relative to low turbulence. To isolate the effects of the vortex generators, surface averaged Stanton number was normalized by $St'_o$, as shown in Figure 12. Vortex generator contribution in Fig. 12 exhibits the same inverse relationship between Stanton number augmentation and $Re_T$ seen in Fig. 11(a). Surprisingly, vortex generator contribution in most cases was under 20%. Comparing $St$ augmentation values at low turbulence (filled in points on the left axis) to the vortex generator contributions at high turbulence (hollow points on the right axis) in Fig. 13 reveals that the vortex generators result in less augmentation at high turbulence than low turbulence. Across all cases, vortex generators at high turbulence contribute 2-7% less to heat transfer augmentation at low $Re_T$ and 9-16% less at high $Re_T$, relative to their behavior in low-turbulence flow. Decrements in heat transfer augmentation efficacy induced by longitudinal vortex pairs in high freestream turbulence has also been previously observed for film cooling configurations (which generate similar horseshoe vortex systems, but also shear-layer rollup vortices). Bolchoz et al. [25] found that the heat transfer from vortices created by the injection of film cooling was reduced at high turbulence, and conjectured this behavior was the result of the freestream turbulence breaking up the vortices.

Fig. 10 Stanton number augmentation at high freestream turbulence and $Re_T$ of 7,000 with a (a) small single, (b) large single, (c) small pair, and (d) large pair

Fig. 11 Stanton number augmentation for (a) high $Tu$ across all vortex generator configurations and (b) the large vortex generator across all turbulence values
The y-direction (wall-normal) component of velocity downstream of the vortex generators (X/T=3.08) is presented in Fig. 14. The magnitude of the y-component is altered when changing turbulence levels, as visible in Fig. 13(a)-(c) and (b)-(d). Pockets of weaker velocity are present toward the centerline, Z/T = 0, at lower turbulence, but disappear at higher turbulence. This is best seen for the vortex pair, Fig. 13(b) and (d). Velocity vectors in (b) noticeably divert around the pocket causing weaker velocities near the endwall when compared to the high turbulence case. Two strong cores of negative velocity are also present in (b). The lack of the low velocity pocket in (d) allows for flow to have a perpendicular approach to the endwall and merges the strong, negative cores into one. These behaviors were also observed at a Re_T of 25,000.

Heat transfer peaks are greatly dependent on how fluid impinges on the endwall. Figure 15 shows the heat transfer contours and velocity field for small, single longitudinal vortex in subplot (a) and a small, longitudinal vortex pair in subplot (b). Both subplots are at the high turbulence condition and a Re_T of 7,000. The flowfield contours are of normalized streamwise velocity, with in-plane vectors. Maximum values in heat transfer line up with where the fluid impinges on the endwall. This agrees with observations made in prior studies [14, 16, 18], and was present across all cases. When comparing (a) to (b), the effect of having a generator pair is evident as well. Heat transfer contours in subplot (b) are more laterally spread out when compared to the contours in (a). Velocity vectors between the longitudinal vortex pair in (b) directly impinge on the wall and are larger than the vectors approaching the endwall in (a). This provides evidence as to why peak St augmentation values far upstream of the wing are greater for generator pairs than individual generators.

D. Flowfield Measurements

Fig. 12 Vortex generator contribution (St normalized by St') for high Tu across all VG configurations

Fig. 13 Vortex generator contributions for the large vortex generator across all turbulence values

Fig. 14 Normalized y-component velocity for at Re_T=7,000 for a(a) small single at low Tu, (b) small pair at low Tu, (c) small single at high Tu, and (d) small pair at high Tu
The lateral distribution of heat transfer augmentation for longitudinal vortex pairs at X/T = -1.0 for a ReT of 7,000 and 25,000 is shown in Fig. 16. When increasing freestream turbulence, lateral heat transfer is modified in one of two ways. First is by narrowing a broad peak, seen in the small generator case in (a). The other is by reducing two peaks into one, seen in the large generator case in (a). This is a result of the flow having more direct endwall impingement at high turbulence when the low velocity pocket is not present.

Further connections between the heat transfer and flowfield are evident when studying vorticity contours in Fig. 17. Increasing freestream turbulence, Fig. 17 (a) vs. (c) and (b) vs. (d), decreases normalized vorticity. Decrements of 4% and 9% at a ReT of 7,000 were observed for the single generator and generator pair respectively. The presence of these weaker vortices at high turbulence is likely the source of decreased longitudinal vortex contribution to heat transfer augmentation. At a ReT of 25,000, the amount by which vorticity decreases from low to high turbulence increases approximately by a factor of 4 for both the single generator and the generator pair. This likely produces the inverse trend between Stanton number augmentation and ReT observed at high turbulence. Vortices in the low turbulence cases are accompanied by a secondary vorticity core of opposite sign located on its side closer to the tunnel centerline. At high turbulence, the secondary cores are no longer present. This behavior is identical to what was observed with the low velocity pockets in y-component velocity.

Patterns observed in turbulent kinetic energy of the vortex flowfields are shown in Fig. 18. At a high turbulence condition, (b) and (d), TKE was over 100% higher in the vortex core than in the low turbulence condition, (a) and (c). The increase in fluctuations within the vortex is representative of increased unsteadiness and a likely increase in the vortex’s tendency to wander. This likely led the secondary vorticity core to collide and merge with the main core, causing its disappearance at high turbulence. An increase in TKE is also representative of increased flow disturbances and should help promote heat transfer. Despite this, vortex contribution to heat transfer augmentation decreased when
freestream turbulence, and therefore TKE, was higher. This is likely due to the decrease in normalized vorticity at high turbulence conditions. This would then imply that vorticity is a more predominant factor than TKE in determining heat transfer augmentation near the longitudinal vortex.

V. Conclusions

The effects of longitudinal vortices on turbulent junction flow heat transfer was experimentally investigated across a range of body thickness Reynolds numbers, freestream turbulence values, and vortex generator configurations. Three Reynolds number and two turbulence conditions were tested. Vortex generators of two sizes were used with each size being placed individually and in a downflow, counter-rotating pair. Spatially resolved heat transfer measurements of the test section endwall were obtained using infrared thermography. Time averaged stereo-PIV was used to obtain inlet profiles for the longitudinal vortices. SPIV data was only acquired at some of the test conditions.

Heat transfer augmentation from the longitudinal vortices was highly dependent upon how much of a flow disturbance it produced. Larger vortices augmented heat transfer more than smaller ones and the increased lateral coverage from pairs allowed for more augmentation than individual vortices. Despite this, the horseshoe vortex system was resistant but not immune to the incoming longitudinal vortices across all conditions. Though the adverse pressure gradient weakened the longitudinal vortices as they progressed downstream, they still existed and augmented heat transfer beyond the leading edge of the junction.

At high turbulence levels, overall heat transfer was greater at high turbulence than low turbulence because of the increase in turbulent interactions across the entire endwall. The vortex generators contributed less to heat transfer augmentation.
augmentation at the high turbulence conditions, however, due to large decreases in coherent time-average vorticity. The decreases in vorticity became larger at higher Reynolds number which led to an inverse relationship between \( \text{Re}_T \) and heat transfer augmentation not present at low turbulence conditions. This shows that vorticity is the dominant mechanism for heat transfer augmentation near the longitudinal vortex.

Secondary vorticity cores near the centerline were present at low turbulence conditions and influenced the velocity vectors in the region. At high turbulence conditions, the increase in TKE led to the dissipation of these secondary cores and therefore altered the flowfield. Flow was able to more directly impinge on the endwall and generate single peaks in Stanton number augmentation that were narrow when compared to the peaks at the low turbulence conditions. This behavior highlights that the velocity fields are important in determining qualitative heat transfer trends.

In gas turbine applications, where Reynolds number and freestream turbulence are high, the presence of longitudinal vortices from upstream secondary flows likely provide little heat transfer augmentation to a downstream turbine component. Artificially introducing larger vortices to disrupt junction flow (so as to possibly control generation of new secondary flows) is not recommended, since the longitudinal vorticity does not disrupt the junction flow in a meaningful way. For heat exchanger applications, however, where Reynolds number and turbulence might be lower, the longitudinal vortices can be beneficial. Since the vortex generators most effectively augment heat transfer at these conditions, integrating them would provide a significant increase in endwall heat transfer upstream of any junction. This would be done without disrupting the benefits provided by the horseshoe vortex.

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VII. References


