HEAT TRANSFER MEASUREMENT OF JUNCTION FLOW WITH VARIABLE REYNOLDS NUMBER AND FREESTREAM TURBULENCE

A Thesis in
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by
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ABSTRACT

The demand for ever increasing performance of gas turbine engines has led to the increase in the inlet temperature for turbines over the years causing durability and structural challenges for turbine vanes and blades. In addition to extremely high temperatures, the incoming flow to the turbine components is known to have high freestream turbulence. Turbulent junction flow or horseshoe vortex is a well-known phenomenon observed on the platforms of turbine vanes and blades and is known for causing thermal degradations over time. The turbulent junction flow occurs when a wall boundary layer encounters an obstacle causing the flow to separate from the wall and reorganize into coherent vortices. Previous studies on the horseshoe vortex have demonstrated significant unsteadiness making the flowfield and associated endwall heat transfer complicated. While the time-averaged and time-resolved flowfield and heat transfer measurements of turbulent junction flow have been well-understood, many of these previous studies were conducted in a single Reynolds number and at a baseline freestream turbulence. In this thesis, the effects of Reynolds number and high freestream turbulence on time-averaged and time-resolved flowfield and surface heat transfer measurements are presented.

The first study in this thesis focuses on the effects of Reynolds number on the unsteady flowfield and time-averaged endwall heat transfer in the turbulent junction flow using high-speed stereo particle image velocimetry and infrared thermography. The measurements are conducted in a large scale optically accessible wind tunnel with an academic airfoil geometry. Time-mean vortex core position upstream of the wing is unchanged with increasing Reynolds number, but turbulent kinetic energy levels are shown to increase underneath the vortex core. Also, the time-resolved vortex core position is found in somewhat distinct positions at low Reynolds number, and is more broadly distributed at high Reynolds number. Furthermore, the time-averaged heat transfer around the junction changes its distribution around the wing body with increasing Reynolds number.

The second study examines the influence of freestream turbulence and Reynolds number on unsteady endwall heat flux measurements using high-speed heat flux micro-sensors. The measurements are taken using the same wind tunnel and airfoil geometry as
the first study. A turbulence grid with cylindrical bars has enhanced the freestream turbulence intensity to around 18%. The effects of freestream turbulence on endwall heat transfer are significant at low Reynolds number but are negligible at higher Reynolds number, with heat transfer augmentation due to turbulence varying from 1.20 to 1.00 as Reynolds number increases. The root mean square of the heat flux fluctuations is increased with freestream turbulence at lower Reynolds number. One of the broader conclusions from this study is in the hot section of the gas turbine engines where Reynolds numbers are relatively high, freestream turbulence does not have an impact on endwall heat transfer. However, in lower Reynolds number applications such as in heat exchangers, endwall heat transfer is augmented with higher freestream turbulence.
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Chapter 1
Introduction

Junction flow commonly occurs when a turbulent boundary layer on a wall encounters an obstacle, which causes the turbulent boundary layer to separate from the wall and reorganize into coherent vortices. These obstacles can range from turbine stators/rotors, aircraft wings, and fin-tube interfaces of heat exchangers to submarine conning towers and bridge piers. Turbulent junction flow, also known as the horseshoe vortex system, is well-known to increase surface heat transfer near the junction. Both the fluid mechanics and surface heat transfer of the turbulent junction flow are complex due to the unsteady nature and flow separation/reattachment that occurs. These flow separations and reattachments are in part triggered by the adverse pressure gradient and in part caused by the dynamic interactions between the leading edge flow and incoming boundary layer flow. Many experimental and computational efforts have been performed in the past to investigate what triggers the flow to form into vortices of different sizes and shapes and the extent to which surface heat transfer is augmented by these vortices. Previous studies also investigated effects of different bluff body shapes, fluid mediums (i.e. water and air), Reynolds number, freestream turbulence, and different inlet boundary conditions on turbulent junction flow.

The primary feature of the junction flow is the semi-coherent circulating structure that persists at the leading edge of the bluff body. This coherent structure is developed by the stagnating boundary layer and the streamwise adverse pressure gradient caused by the bluff body. Other than the primary circulating structure, other distinct circulating structures also often observed are known as secondary and tertiary vortex cores. These vortices wrap around the bluff body and become aligned with the streamwise direction downstream of the leading edge. The flowfield of the turbulent junction flow, though highly unsteady, has some underlying structure. Experimental efforts by Devenport and Simpson [1] and computational investigation by Paik et al. [2] found a bimodal structure in the probability density functions of streamwise fluctuating velocity component in the horseshoe vortex region. Conditionally averaged flowfields indicate two distinct forms of the horseshoe vortex. A large coherent structure with strong backward-directed flow under the vortex is
known as “backflow mode” and a smaller, more chaotic mode closer to the leading edge with reduced backward flow is known as the “zero-flow mode” [1]. Anderson and Lynch [3] observed these two bimodal structures in the horseshoe vortex in front of a circular pin in a fully developed channel flow. A recent study by Apsilidis et al. [5] and Chen et al. [6] on the turbulent junction flow shown a third mode, which they termed as the “intermediate mode” persisting between the backflow and the zero-flow modes.

It is well-known in the turbomachinery community that the turbulent junction flow can cause high levels of endwall heat transfer in front of a bluff body. The augmentation in heat transfer can be as much as 200% greater than in the boundary layer upstream [4,7]. This increase in endwall heat transfer can certainly pose a threat to the durability of various hot-section turbomachinery components, where a variation of 25°C in metal temperature can potentially reduce the turbine part life by half [8]. Therefore, it is of interest to understand the conditions under which this augmentation occurs and the possible correlation between vortex breakdown and endwall heat transfer. For instance, Praisner and Smith [4] found two distinct bands of high heat transfer in their instantaneous endwall heat transfer contour plots corresponding to primary and secondary vortices. Attempts were made by researchers to quantify the sources of heat transfer augmentation in time-mean and time-resolved sense [4,9]. Lewis et al. [9] investigated the spatially and time-resolved heat flux with a single Reynolds number and baseline freestream turbulence and found that the probability distribution functions of the fluctuating components of the heat flux did not show a bimodal behavior although Devenport and Simpson [1] did show a bimodal structure in the probability density functions of their streamwise fluctuating velocity component in the turbulent junction flow region.

Ames et al. [10] on the other hand were interested in understanding effects of high freestream turbulence on endwall heat transfer both upstream and around a turbine vane cascade. They reported turbulence levels ranging from 0.7% to 14% and inlet Reynolds number based on true chord length and exit conditions was as high as 2,000,000. One of the conclusions was as Reynolds number increased, the effect of freestream turbulence on endwall heat transfer became negligible in the turbulent junction flow region. Radomsky and Thole [11] investigated how endwall heat transfer was augmented at a freestream turbulence of 20% and found a 15% increase in endwall heat transfer underneath the
horseshoe vortex core. Although spatially and time-resolved flowfield and time-averaged endwall heat transfer for turbulent junction were investigated extensively, these studies were mostly done using wide range of Reynolds number and mainly at a baseline freestream turbulence of 0.5-1%. Time-resolved endwall heat transfer for turbulent junction flow region with high freestream turbulence (>15%) is not yet well-understood. Therefore, the current studies have attempted to explore not only the time-resolved flowfield measurements at different Reynolds number, but most importantly the effects of freestream turbulence on time-resolved heat transfer measurements both in front of and around a bluff body.

Chapter 2 focuses on the experimental flowfield and heat transfer measurements of the turbulent horseshoe vortex region through high speed stereo particle image velocimetry and infrared camera imaging of the endwall at various body thickness Reynolds numbers and at low turbulence. A detailed description of the test facility, research geometry, flow diagnostic tools, and data validation and experimental uncertainties has been presented. Inlet approach boundary layer profiles for various body thickness Reynolds numbers are also reported using Laser Doppler Velocimetry so that this dataset can be used in benchmarking advanced numerical studies of horseshoe vortex.

Chapter 3 focuses on the effects of Reynolds number and freestream turbulence on the unsteady heat flux measurements of turbulent junction flow. Two high speed heat flux gauges are used to capture the time-resolved heat flux from the horseshoe vortex dominated region on the plane of symmetry as well as around the airfoil body. A detailed description of the test facility, turbulence grid system, test conditions, approach boundary layer and heat transfer parameters, and measurement validation and uncertainties is presented. Three body thickness Reynolds numbers are used to highlight the effects of variable Reynolds number on the endwall heat flux. Also, a baseline turbulence and high turbulence (representative of turbomachinery applications) are used to demonstrate the effects of turbulence on the endwall heat flux.
References


Chapter 2

Experimental Measurements of Turbulent Junction Flow Using High Speed Stereo PIV and IR Thermography*

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Abstract

Turbulent junction flow is commonly seen in various turbomachinery components, heat exchangers, submarine appendages, and wing-fuselage attachments, where the approach boundary layer separates and rolls up into a coherent system of vortices upstream of a bluff body. The highly unsteady behavior of this flow causes high pressure fluctuations on the wall, and if the fluid temperature is different than the wall temperature, also causes high heat transfer. One of the signature features of these flows is a bimodal distribution of velocity around the vortex system. In this paper, the flow physics as well as heat transfer of the turbulent junction flow are investigated using PIV and IR measurements respectively. Among the three objectives of this paper, the first one is to demonstrate the unique experimental setup that captures temporally resolved turbulent flow-field measurements. The second objective is to analyze the dynamics of primary vortex for various Reynolds numbers. The final objective is to investigate the effect of the unsteady junction flow on the endwall heat transfer.

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Nomenclature

$Re_T$  Body thickness Reynolds number, $(\frac{U_{ref} T}{\nu})$

$C$  Chord length

DES  Detached Eddy Simulation

$Y$  Direction normal to the endwall

$Z$  Direction across the tunnel

$U_{ref}$  Freestream velocity

HS  Horseshoe

IR  Infrared

$u^*$  Inner coordinate velocity $(\frac{u_{wall}}{\rho})$

$y^+$  Inner coordinate $(\frac{y^+ u^*}{\nu})$

LDV  Laser Doppler velocimetry

$St_x$  Local Stanton number $(\frac{h}{\rho c_p u_{ref}})$

$Re_\theta$  Momentum thickness Reynolds number, $(\frac{U_{ref} \theta}{\nu})$

MDF  Momentum Deficit Factor $(Re_T)^2 (\frac{\theta}{T})$

$T$  Maximum Rood wing body thickness

$\frac{\delta}{T}$  Nondimensional boundary layer thickness

$\frac{\delta^*}{T}$  Nondimensional displacement thickness

$\frac{\theta}{T}$  Nondimensional momentum thickness

$f_{nd}$  Nondimensional sampling frequency

RANS  Reynolds-Averaged Navier Stokes

$C_p$  Pressure coefficient

$C_f$  Skin friction coefficient

$S$  Span

$X$  Streamwise direction

$Tu$  Turbulence intensity
Introduction

Turbulent junction flow is a phenomenon that is often observed in turbomachinery components, wing-fuselage attachments on aircrafts, fin-tube interfaces of heat exchangers, bridge piers, and submarine appendages. It is generally well-understood that turbulent junction flow causes high surface heat transfer near the junction. This rise in surface or endwall heat transfer severely affects the performance of hot-section turbomachinery components such as first-stage turbine vanes and blades. Han et al. [1] reported that a variation of 25°C in the incoming flow (where nominal gas temperature is 1800°C) for hot-section turbine parts can reduce the part life by half.

A turbulent junction flow or horseshoe (HS) vortex system occurs when a turbulent boundary layer on a wall encounters a bluff body, which causes the turbulent boundary layer to separate from the wall and reorganize into coherent vortex. The size and dynamics of the HS vortex system is dependent upon the angle of attack of a wing, Reynolds number, the size of the body, and inlet boundary conditions. This flow is well-known to be highly unsteady, which leads to high pressure fluctuations around the vortex location. In addition, convective heat transfer near the junction due to the HS vortex can be up to 200% greater than in the boundary layer upstream [2]. The turbulence intensities are also reported to be high in this type of flow [3].

In this paper, an experimental setup is presented which is designed to capture the time-resolved junction flow in front of a common research wing geometry, also known as the Rood wing [4]. Experimental measurements of the junction flow are captured with a high speed stereo particle image velocimetry (SPIV) system, which provides three components of velocity in a plane at kHz sampling rates. Time-averaged data are compared to previous measurements [4] of junction flow, and the temporally resolved dataset are analyzed for dynamic behaviors over a wide range of Reynolds numbers. Finally, convective heat transfer around the junction is presented and explained using the flowfield measurements.

Previous Studies

Junction flow is a frequently studied topic in fluid mechanics and heat transfer due to its relevance in many engineering applications. Devenport and Simpson [4] studied the endwall flow behavior of the HS vortex in front of a Rood wing (3:2 semi-elliptical leading
edge connected at the maximum thickness with NACA0020 trailing edge). Time mean measurements of the HS vortex identified two regions of distinct behavior; an upstream region of moderate turbulence stresses and a more intense region of turbulence stresses near the endwall junction. These increases in turbulence stresses were determined to be the product of bi-stable velocity fluctuations, suggesting that the HS vortex exists in two quasi-steady modes, the coherent “backflow mode” near the junction and the more chaotic “zero-flow mode”. Time mean measurements of the heat transfer augmentation effect caused by the HS vortex were undertaken by Lewis et al. [5] and by Praisner and Smith in a water tunnel [2,6]. Lewis et al. [5] measured mean heat flux on heated wing/endwall junctions for several wing shapes, finding that the presence of the HS vortex enhanced heat transfer due to the high levels of turbulent stresses found between the separation line and the region upstream of the time mean vortex center, with the maximum heat transfer augmentation right at the junction. Lewis et al. [5] did not find any bimodal behavior in PDF’s of heat flux in the junction flow region of the Rood wing, and thus he was unable to complement the bimodal flow behavior seen by Devenport and Simpson [4]. Praisner and Smith [6] produced contours of time-mean Stanton number on the endwall in front of a Rood wing that showed two distinct bands of high heat transfer associated with the two quasi-steady modes observed by Devenport and Simpson [4]. Time-mean vorticity contours provided a direct correlation between mean heat transfer augmentation and quasi-steady behavior of the HS vortex. Computational studies, such as those by Paik et al. [7] and Yakhot et al. [8] had further supported the existence of quasi-steady modes in the vortex behavior in front of bluff bodies; however, most numerical studies were unable to correctly predict the time-mean vortex core location. Very recent studies on junction flow with cylindrical bodies by Apsilidis et al. [9] and Chen et al. [10] reported a third mode called “intermediate mode” which persisted between the “backflow mode” and “zero-flow mode.”

Time-resolved measurements and simulations of the HS vortex have been the focus of many recent studies in turbulent junction flow and have attempted to gain a greater understanding of the transition between the quasi-steady modes of the HS vortex. Hydrogen-bubble flow visualization and laser velocimetry were used by Kim et al. [11] in a water tunnel to analyze the unsteady vortex behavior in front of a cylinder. Kim et al. [11] identified the formation of strong primary and secondary vortices rotating in the same
direction, with a weaker tertiary counter rotating vortex between them. Disturbances caused by separation upstream of the vortices led to acceleration of flow and instability around the primary and secondary vortices. Further details of the transition between quasi-stable states were provided in a numerical study by Paik et al. [7] in which the conditions of Devenport and Simpson’s [4] experiment were closely matched. While there was discrepancy between RANS and DES predictions of the location of the mean HS vortex core, Paik et al. [7] showed that DES predicted the cyclical transition between backflow and zero-flow modes, which occurred due to the generation of hairpin vortices in front of the HS vortex. These hairpin vortices deconstructed the HS vortex in its coherent backflow mode to form its more chaotic zero-flow mode. Escauriaza and Sotiropoulos [12] also simulated the HS vortex using DES analysis on HS vortex at an order of magnitude lower Reynolds number (2.0 \times 10^4) than in the experiment of Devenport and Simpson [4]. At this lower Reynolds number, mean flow and coherent dynamics of turbulent HS vortex varied significantly from Devenport and Simpson [4]. Previous research by Fleming et al. [13] and Ballio et al. [14] aimed to find the consequences of changing bluff body thickness. Both of these efforts concluded that in the turbulent regime, the dynamics of HS vortex mainly depended on the maximum bluff body thickness and the adverse pressure gradient caused by it.

Other studies attempted to link the unsteady velocity behavior of the HS vortex with time-resolved heat transfer observation on junction surfaces. These studies are particularly relevant to components in a gas turbine, where minimizing thermal loading can be critical to part life. Of particular relevance is a study by Praisner and Smith [2] which presented time-resolved PIV measurements of vorticity in a plane bisecting the nose of a faired cylinder, correlated with time-resolved contours of surface Stanton number. This study found that two bands of high heat transfer were produced by the unsteady junction flow. The first band was near the leading edge which is caused by fluid flowing down the face of the bluff body leading edge and impinging on the endwall. Another secondary band was upstream of the first band, caused by unsteady eruptive events in which the secondary vortex separated from the endwall, allowing outer region fluid to penetrate to the endwall. While Praisner and Smith [2] provided a good understanding of the effect of unsteady HS vortex behavior on surface heat transfer, the study was done at a freestream Reynolds
number based on cylinder diameter of only approximately $2 \times 10^4$, an order of magnitude below that of Devenport and Simpson [4] and below the typical range for gas turbine applications. Unsteady heat flux measurements upstream of the Rood wing by Lewis et al. [5] did not exhibit any bimodal behavior in PDF’s in the junction flow region, despite the bimodal flow behavior seen by Devenport and Simpson [4]. Hada et al. [15] replicated the “double-band” heat transfer phenomenon in their study of a wide range of inlet velocities, boundary layer thicknesses, and body thicknesses. They also reported that as the body thickness decreased, the endwall heat transfer increased proportionally. Finally, they also found negligible changes in endwall heat transfer as boundary layer thickness changed.

While much research has already been done on HS vortex dynamics, only a few studies have examined both the HS vortex breakdown dynamics and the associated heat transfer at a range of Reynolds numbers. The study presented in this paper attempts to provide correlated velocity field and endwall heat transfer measurements over a wide range of Reynolds numbers using a symmetric airfoil as a bluff body. The time-averaged vortex core locations are tracked as Reynolds number increased. The time-averaged endwall high heat transfer bands are also investigated for various Reynolds number. In addition, the study presents detailed boundary condition information in order to allow for its use in benchmarking advanced numerical studies of the HS vortex. This study also presents a two-dimensional histogram of instantaneous vortex core positions at various Reynolds number.

**Experimental Setup**

1. **The Facility**

   All the experiments for this paper are conducted in a large closed-loop low speed wind tunnel. As shown in Figure 2.1, the air circulates around the tunnel via a fan, and the flow can be preconditioned by heat exchangers at different stages in the wind tunnel. Also shown in Figure 2.1 is a newly constructed test section with significant optical access for flow diagnostics. The test section sidewalls as well as the top wall are made of polycarbonate (Lexan), and these walls also have sections where glass is used for optical accessibility. A flow trip as shown in Figure 2.1 is applied at the start of the boundary layer to ensure a turbulent boundary layer throughout the boundary layer development region. For the current studies, the test section has a boundary layer development length of 2.58
m. The width and height of the test section are 1.12m and 0.55m respectively. Two quarter round shaped geometries ensure a smooth transition into the boundary layer development region.

![Diagram of wind tunnel](image)

**Figure 2.1.** A recirculating low-speed wind tunnel with a new test section to capture junction flow using LDV and SPIV laser diagnostics as well as an IR camera to capture surface heat transfer.

The test section in Figure 2.1 houses a single airfoil (Rood wing) at 0° angle of attack. The Rood wing is a research airfoil [4,7] consisting of a 3:2 ellipse nose joined to a NACA 0020 at the maximum thickness point. In Figure 2.2(a), a symmetric hollow Rood wing with removable nose piece and embedded pressure taps is shown. The dimensions of this geometry are a chord (C) of 40.00 cm, a span (S) of 54.50 cm, and a maximum thickness (T) of 9.42 cm. The coordinate system origin for this study is at the intersection of the leading edge and endwall, where X is the streamwise direction, Y is the direction normal to the endwall (also parallel to the wing height), and Z is across the tunnel. The Rood wing body is transparent for experimental ease and so that the pressure taps remain
visible. The wing is manufactured using a stereolithographic process. The removable nose piece highlighted in Figure 2.2(a) is made out of polished acrylic so that a laser sheet can be sent through it.

Figure 2.2. (a) The Rood wing with the leading edge nose piece and built-in pressure taps is shown; (b) the pressure loading around the wing body at 50% span is compared with time-averaged RANS model.

Static pressure taps are located at 50% of the span to check flow symmetry and agreement of the wing pressure distribution with expected behavior in the tunnel. The leading and trailing edges of the Rood wing are intentionally clustered with pressure taps so that flow symmetry and pressure coefficient (\(C_p\)) can be determined with higher precision. Figure 2.2(b) compares measured \(C_p\) with time-averaged RANS predictions at 50% span. The x-coordinate is non-dimensionalized by the chord length (C). The \(C_p\) measured from the right and left sides of the Rood wing aligns well with time-averaged RANS, confirming flow symmetry around the wing and expected behavior.

The wing and test section are carefully designed to minimize endwall glare from the laser-based flow diagnostics described later. As shown in Figure 2.1, the laser output is directed to a 45° mirror under the test section, and then to a series of cylindrical lenses to create a laser sheet, (lenses are not shown in Figure 2.1 for simplicity), and finally to a second 45° mirror inside the Rood wing. This optical path directs a laser sheet through the leading edge of the wing body along the symmetry plane of the wing, which illuminates the junction flow region for stereo particle image velocimetry (SPIV) measurements. The intensity of the laser sheet near the wall can be controlled to minimize wall reflection.
To capture the flow physics in the junction flow region, two sets of flow diagnostics are available: a three-component laser Doppler velocimeter (LDV) and a stereo particle image velocimetry (SPIV) system. For the current study, only the SPIV is used for the junction flow measurements. Two components of the LDV are used to measure incoming boundary layer velocity profiles. The LDV system consists of a Coherent Innova 70C series argon-ion laser outputting three wavelengths of light into a TSI Fiberlight beam splitter. The beam splitter output is coupled to fiber optic cables to a two-component transceiver probe equipped with a 2.6X beam expander attachment. A TSI PDM 1000 photo detector module along with a TSI FSA 3500 signal processor, all controlled by Flowsizer software are used to acquire measurements. Di-Ethyl-Hexyl Sebecat (DEHS) is used as a tracer particle in the flow. The probe volume is approximately 70 µm in diameter at a standoff distance of 750 mm using the beam expander. Coincident measurements of streamwise and wall-normal velocity are obtained for most of the boundary layer profiles, at sampling rates ranging from 100 Hz very near the wall to 3500 Hz in the freestream. 20,000 data points are obtained for each measurement location to ensure statistical convergence.

The Stereo PIV system includes two Photron FASTCAM Mini UX100 high speed cameras, a Photonics DM20-527 Nd:YLF dual-head laser, and a LaVision timing unit and software control. Images collected are processed using DaVis 8 software. For all cases, the high speed cameras are run at their maximum resolution of 1280x1024 pixels and at a frame rate of 4000 frames per second, or 2000 image pairs (flow samples) per second. For each case, two sets of 4370 image pairs are acquired, (8740 total image pairs, camera memory limited to total of 4370 image pairs at full resolution) taken within 10 minutes of each other at steady state conditions. Because sampling is done with the same sampling rate and image count for all Reynolds numbers, a differing number of flow-through times is captured for each Reynolds number, as can be seen in Table 2.1. A nondimensional sampling frequency ($f_{nd}$) is calculated to represent the number of samples per flow-through time, where the flow-through time is determined by the freestream velocity and the size of the measurement window. During data collection, both cameras are fitted with 200 mm focal length lenses and Scheimpflug adapters, for a magnification of 0.04 mm/pixel. Initial calibration of the cameras is done using a LaVision supplied calibration.
plate, and stereo self-calibration is performed in DaVis after data collection prior to processing to increase stereo reconstruction accuracy. The laser source outputs light at a wavelength of 527 nm with maximum repetition rate of 10 kHz per head, and a maximum output pulse energy of 20 mJ per head. Tracer particles of Di-Ethyl-Hexyl Sebecat (DEHS), with a diameter of approximately 1 micron, are introduced to the flow upstream of the fan so that they are fully mixed in the flow by the time they reach the test section.

Table 2.1. Summary of flow-through times and non-dimensional sampling frequencies

<table>
<thead>
<tr>
<th>Re&lt;sub&gt;f&lt;/sub&gt;</th>
<th>6,920</th>
<th>12,600</th>
<th>25,400</th>
<th>47,000</th>
<th>75,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow-through time (sec)</td>
<td>0.128</td>
<td>0.0545</td>
<td>0.0265</td>
<td>0.0140</td>
<td>0.0115</td>
</tr>
<tr>
<td>Flow-through Times Captured</td>
<td>34.1</td>
<td>80.1</td>
<td>165</td>
<td>312</td>
<td>316</td>
</tr>
<tr>
<td>Nondimensional Sampling Frequency (f&lt;sub&gt;rad&lt;/sub&gt;)</td>
<td>256</td>
<td>109</td>
<td>52.9</td>
<td>28.0</td>
<td>23.0</td>
</tr>
</tbody>
</table>

To capture time-averaged convective heat transfer coefficients near the junction flow region, a constant heat flux boundary condition (indicated in Figure 2.1) is applied using a specially designed serpentine Inconel electric circuit encapsulated in Kapton. A thin copper layer is adhered to the top surface of the encapsulated Inconel circuit to increase heat flux uniformity, and insulation is placed underneath the circuit to minimize the conduction loss. The heaters are coated with a thin layer of black spray paint to increase surface emissivity with a value of \( \varepsilon = 0.95 \). The temperature difference between surface and freestream is maintained close to 30°C by the heaters. A FLIR A655sc IR camera with 640x480 pixel resolution is mounted above the wing, looking through portholes in the top endwall toward the bottom endwall to capture time-averaged endwall temperatures. Five images are obtained and averaged for each of the seven separate measurement locations around the wing. The images are then calibrated to embedded thermocouples underneath the heater wall using FLIR software and transformed to airfoil coordinates using an in-house Matlab code.

To calculate surface heat transfer coefficients, the electric power supplied to the circuit is converted to heat flux by dividing by the circuit active area. Conduction (<2%) and radiation losses (~15%) are subtracted to determine convective heat flux. The calibrated surface temperatures from the IR camera, the measured freestream temperature in the tunnel, and the convective heat flux are then used to determine convective heat transfer coefficients.
2. Approach Boundary Layer Parameters

Flowfield and heat transfer measurements are taken with the baseline freestream turbulence level in the tunnel (~1.8%), at five flow speeds corresponding to Reynolds numbers based on wing maximum thickness (T) ranging from approximately 7,000 to 75,000. Table 2.2 indicates the range of conditions studied along with the measured inlet boundary layer parameters.

Table 2.2. Summary of experimental cases

<table>
<thead>
<tr>
<th>$U_{ref}$ (m/s)</th>
<th>1.10</th>
<th>2.01</th>
<th>3.88</th>
<th>7.52</th>
<th>11.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (cm)</td>
<td>9.42</td>
<td>9.42</td>
<td>9.42</td>
<td>9.42</td>
<td>9.42</td>
</tr>
<tr>
<td>$Re_f = U_{ref}T/\nu$</td>
<td>6,920</td>
<td>12,600</td>
<td>25,400</td>
<td>47,000</td>
<td>75,000</td>
</tr>
<tr>
<td>$Re_{\theta} = U_{ref}\theta/\nu$</td>
<td>550</td>
<td>730</td>
<td>1650</td>
<td>3230</td>
<td>5740</td>
</tr>
<tr>
<td>$\delta/T$</td>
<td>0.732</td>
<td>0.541</td>
<td>0.605</td>
<td>0.626</td>
<td>0.700</td>
</tr>
<tr>
<td>$\delta^*/T$</td>
<td>0.118</td>
<td>0.082</td>
<td>0.094</td>
<td>0.093</td>
<td>0.104</td>
</tr>
<tr>
<td>$\theta/T$</td>
<td>0.079</td>
<td>0.057</td>
<td>0.067</td>
<td>0.069</td>
<td>0.076</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.00583</td>
<td>0.00513</td>
<td>0.00434</td>
<td>0.00337</td>
<td>0.00300</td>
</tr>
<tr>
<td>$Tu$</td>
<td>2.1%</td>
<td>1.4%</td>
<td>1.7%</td>
<td>1.6%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

Table 2.3. Lowest and highest Reynolds number cases from current study are compared with approach boundary layer parameters from previous studies on junction flow

<table>
<thead>
<tr>
<th>Data set</th>
<th>JLF, WJD1</th>
<th>SCD</th>
<th>HMM</th>
<th>JS</th>
<th>Hada</th>
<th>PS</th>
<th>Current study ($Re_f = 6,920$)</th>
<th>Current study ($Re_f = 75,000$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Rood wing</td>
<td>Rood wing</td>
<td>Rood wing</td>
<td>Rood wing</td>
<td>Cylinder Nose</td>
<td>Fair ed cylinder</td>
<td>Rood wing</td>
<td>Rood wing</td>
</tr>
<tr>
<td>$T$ (cm)</td>
<td>7.17</td>
<td>6.4</td>
<td>7.1</td>
<td>7.1</td>
<td>5.0</td>
<td>15.08</td>
<td>9.42</td>
<td>9.42</td>
</tr>
<tr>
<td>$U_{ref}$ (m/s)</td>
<td>26.75</td>
<td>30.5</td>
<td>15.24</td>
<td>20.9</td>
<td>30.0</td>
<td>0.147</td>
<td>1.10</td>
<td>11.95</td>
</tr>
<tr>
<td>$\delta/T$</td>
<td>0.513</td>
<td>1.197</td>
<td>0.947</td>
<td>1.15</td>
<td>0.400</td>
<td>0.345</td>
<td>0.732</td>
<td>0.700</td>
</tr>
<tr>
<td>$\delta^*/T$</td>
<td>0.0779</td>
<td>0.1345</td>
<td>0.1467</td>
<td>0.148</td>
<td>0.050*</td>
<td>0.047</td>
<td>0.118</td>
<td>0.104</td>
</tr>
<tr>
<td>$\theta/T$</td>
<td>0.0548</td>
<td>0.1014</td>
<td>0.1003</td>
<td>0.1227</td>
<td>0.039*</td>
<td>0.037</td>
<td>0.079</td>
<td>0.076</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.0025</td>
<td>0.0025</td>
<td>0.0023</td>
<td>0.0026</td>
<td>0.0033*</td>
<td>0.0047*</td>
<td>0.00583</td>
<td>0.0030</td>
</tr>
<tr>
<td>$Re_{\theta}$</td>
<td>6,300</td>
<td>11,600</td>
<td>6,800</td>
<td>11,700</td>
<td>3716*</td>
<td>814</td>
<td>550</td>
<td>5740</td>
</tr>
<tr>
<td>$MDF$ *10^-8</td>
<td>7.24</td>
<td>13.3</td>
<td>4.61</td>
<td>11.2</td>
<td>3.56*</td>
<td>0.220</td>
<td>0.037</td>
<td>4.28</td>
</tr>
</tbody>
</table>

(* denotes values that are obtained assuming turbulent boundary layer and associated turbulent correlations.)

Table 2.3 compares the range of cases in this study to similar studies from previous work. In Table 2.3, all the datasets except Praisner and Smith as well as Hada et al. used the Rood wing [4,7]. In Table 2.3, JFL dataset came from Fleming et al., 1991 [16]; SCD dataset came from Dickinson, 1986 a,b [17&18]; HMM was obtained McMahon et al., 1987 [19]; JS was from Shin, 1989 [20]; WJD1 was received from Devenport and Simpson,
1990b and Devenport et al., 1990 [4]; PS is from Praisner and Smith, 2006 [2]; and Hada is from Hada et al., [15]. As seen in Table 2.3, the current study encompasses a wide range of momentum thickness Reynolds numbers found in other studies, while keeping the ratio of momentum thickness to body relatively constant and in the middle of the range of prior studies.

**Data Validation and Uncertainty Analysis**

1. **Flowfield Validation**

Velocity field measurements obtained using Stereo PIV were compared against the LDV measurements of Devenport and Simpson [4] for the highest Reynolds number

![Figure 2.3](image)

Figure 2.3. (a) Comparison of two component (u-v) turbulent kinetic energy and mean velocity magnitude contours, and (b) vertical profiles at the time-mean vortex core of two component turbulent kinetic energy and x-direction velocity for $Re_T = 75,000$ at $X/T = -0.16$ compared against Devenport and Simpson at $X/T = -0.20$ [4].
case tested, $Re_T = 75,000$. This Reynolds number provides a similar magnitude to that of Devenport and Simpson’s study on an identical Rood wing geometry (see Table 2.3 for a comparison of the inlet boundary layer parameters). A comparison of two component (streamwise and wall-normal) turbulent kinetic energy and mean velocity between these two cases is presented in Figure 2.3. A significant offset in the x-location of the vortex core is visible in Figure 2.3a between the PIV measurements and Devenport and Simpson’s data, with the PIV measurements predicting the vortex core to be approximately 0.04 $X/T$ closer to the Rood wing leading edge. A comparison of two-component (streamwise & wall-normal) turbulent kinetic energy is shown in Figure 2.3a, which demonstrates similar magnitudes of turbulent kinetic energy in the vortex core and a similar shape of the turbulent kinetic energy distribution between the two datasets. In Figure 2.3b, profiles of the turbulent kinetic energy in a vertical line through the vortex core are compared and show some agreement in the peak turbulent kinetic energy in the vortex core. Near the wall below the vortex core, however, the PIV measurements do not indicate the high values of turbulent kinetic energy shown in Devenport and Simpson’s data. This is likely due to the limitations of the PIV system in capturing the very high velocity gradient right at the wall.

2. **Inlet Flow and Heat Transfer Characterization**

Two components of the LDV are used to take inlet mean velocity profiles in all five $Re_T$ cases. The measurements are taken 40.64 cm ($X/C=-1.0$) upstream of the Rood wing.

![Figure 2.4.](image)

**Figure 2.4.** (a) Inlet mean velocity profiles at different $Re_T$ (fixed boundary layer development length); (b) local Stanton numbers ($St_x$) along the heater upstream of the wing.
leading edge. As seen in Figure 2.4(a), the inlet mean velocity profiles compare well with the Spalding law of the wall in the log region as expected. Thermocouples are located underneath the endwall heaters from the start of the heating zone to the wing, to capture the development of the endwall heat transfer. Figure 2.4(b) shows the measured $St_x$ compared with the turbulent Stanton number correlation for a constant heat flux surface. In Figure 2.4(a&b), $Re_T$ is measured with a fixed body thickness ($T=9.42$ cm) and with changing freestream velocities, and the kinematic viscosity is calculated via measured air density.

3. LDV and PIV Uncertainty

Uncertainty analysis is performed on the Stereo PIV and LDV measurements in this study, showing estimated uncertainty for PIV measurements ranging from approximately 1% near the freestream to 11% in the vortex core, and showing an uncertainty of approximately 5% for LDV measurements. Precision uncertainty is estimated for PIV measurements using four data points sampled from five sets of 4000 images taken under identical conditions using the method described by Moffat [21]. RMS uncertainty in velocity measurements for each of these four locations is reported in Table 2.4 below. The high degree of uncertainty in the inner core of the vortex and near the bottom wall are likely due to the large gradients in velocity in this region, which is known to be difficult for PIV to accurately capture. LDV precision uncertainty was similarly done by taking multiple points from two separate boundary layer profile measurements (outside the laminar sublayer) to estimate overall uncertainty.

Table 2.4. Uncertainty in PIV measurements at various locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Non-dimensional Coordinates (X/T, Y/T)</th>
<th>RMS Uncertainty (% with respect to local velocity)</th>
<th>RMS Uncertainty (m/s)</th>
<th>Magnitude of Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS Vortex Center</td>
<td>(-0.145, 0.06)</td>
<td>10.9</td>
<td>0.102</td>
<td>0.940</td>
</tr>
<tr>
<td>Outer HS Vortex</td>
<td>(-0.145, 0.08)</td>
<td>5.0</td>
<td>0.0652</td>
<td>1.292</td>
</tr>
<tr>
<td>Near Bottom Surface</td>
<td>(-0.15, 0.015)</td>
<td>10.0</td>
<td>0.109</td>
<td>1.088</td>
</tr>
<tr>
<td>Near Freestream</td>
<td>(-0.54, 0.34)</td>
<td>0.82</td>
<td>0.0240</td>
<td>2.920</td>
</tr>
</tbody>
</table>

4. Heat Transfer Coefficient Uncertainty

The surface temperatures are measured with thermocouples that have 0.5°C biased and 0.26°C precision uncertainties. The freestream velocity is measured with 5% uncertainty. The conduction and radiation errors are 2% and 15% respectively and are
taken into account when calculating for the local convective heat transfer coefficients (h). The emissivity (ε) from the surface is assumed to be 0.95. Heat transfer coefficient (h) is calculated by first measuring the surface temperature at 0.25 m upstream of the Rood wing leading edge. Then, this calculated h is used to find the uncertainty in the local convective heat transfer measurements shown in Figure 2.5 for the cases studied. The main contribution to the Stanton number uncertainty comes from the uncertainties associated with the measurements of freestream temperature, surface temperature, and surface heat flux.

![Graph](image)

**Figure 2.5.** Percent uncertainty in Stanton number shows downward trend with increasing $Re_T$.

### Results and Discussion

1. **Time Mean Velocity Measurements**

   An analysis of the time-mean flowfields measured using high speed PIV at varying Reynolds numbers has revealed several key trends in the behavior of the horseshoe vortex with varying Reynolds number. Contours of the three component normalized mean velocity magnitude, turbulent kinetic energy, and the RMS of the fluctuating u-component velocity are provided in Figure 2.6. The time-mean velocity is typical of other studies, with a large primary vortex that is elliptical-shaped. These results do not indicate strong secondary or tertiary vortices upstream of the primary vortex, as found by some researchers [2,15], although those vortices are also not apparent in the Rood wing results of Devenport...
and Simpson [4]. The time-mean turbulent kinetic energy is also typical of other studies, with high turbulence in the core of the vortex. A significant contribution to the turbulent kinetic energy is the u-component fluctuations, which are highest right below the time-mean vortex core. This is the region where the intermittent breakdown of the vortex between the backflow and zero-flow modes is occurring most strongly.

Based on the contours of mean velocity magnitude and turbulent kinetic energy in Figure 2.6, there is no strong trend between the position of the time-mean vortex in the x-direction and the Reynolds number. This conclusion is supported by the earlier findings of Ballio, et al. [14] which also found little effect of Reynolds number on mean core location for a similar range of Reynolds numbers.

Figure 2.6 indicates some noticeable changes in structure of the mean turbulent kinetic energy within the HS vortex with varying Reynolds number. Underneath the time mean vortex core, turbulent kinetic energy increases near the wall as Reynolds number increases, an effect that is primarily due to an increase in fluctuating velocity in the x-direction near the wall. High turbulent kinetic energy near the wall was also observed at high Reynolds number by Devenport and Simpson [4] and by Escauriaza and Sotiropoulos [12]. Escauriaza and Sotiropoulos [12] also found some evidence of changes to the turbulent kinetic energy underneath the vortex core with Reynolds number; however, they only investigated a small range of Reynolds numbers. The results presented here indicate significant evolution of the high u-rms structure found beneath the vortex as Reynolds number is increased.
Figure 2.6. Contours of non-dimensional velocity magnitude (left), turbulent kinetic energy (center), and RMS of streamwise fluctuating velocity (right) are given for all Reynolds number cases.
2. Vortex Tracking Analysis

An analysis tool was developed in Matlab to track the instantaneous vortex core to provide additional insight on its movement with varying Reynolds number. The analysis tool computes the instantaneous q-criterion (second invariant of the velocity gradient tensor [22]; q>0 is associated with the swirling component of flow) for each time step and normalizes it so that the maximum in the flowfield is equal to one. It then searches through a specified region in the flow where the HS vortex is known to exist, and extracts the (x,y) coordinates that correspond to a value of normalized q-criterion larger than 0.75. This cutoff is necessary, since in some instances there is no clear vortex feature in the flow during the breakdown events. A search window with dimensions of -0.3 ≤ X/T ≤ 0.02 and 0.005 ≤ Y/T ≤ 0.2 is generally sufficient to capture all locations of the vortex position, as observed by watching instantaneous flowfields. A sensitivity analysis of the cutoff value of 0.75 for normalized q-criterion is also performed and indicated negligible changes in the distribution of the instantaneous vortex position, for a range of cutoff values between 0.6 and 0.9. Figure 2.7 shows output from the tool at two separate time sequences, which correspond to the well-known zero-flow mode and backflow mode of the HS vortex. The red crosshair indicates the instantaneous position of maximum q-criterion, and in the right set of figures, the black line is the prior track of the vortex before the current timestep.

Figure 2.7. Instantaneous images of the vortex tracking procedure. Shown are contours of vorticity (upper left), u and v vectors (upper right), the vortex tracking scatter plot (lower left), and contours of q-criterion (lower right) for two instants.
From the instantaneous tracking results, two-dimensional histograms of the vortex core location in x and y space, are given for each Reynolds number tested in Figure 2.8. The contours shown are of the number of instances per flow-through time recorded for each case, so represent the percent of time that the vortex is located at that position. In general, the histograms are elliptical in shape, with the major axis of the ellipse tilted from vertical. The elliptical shape is due to the bimodal switching phenomenon. For low Reynolds number, the vortex core is more likely to be found in a tight distribution close to the time mean position of the core. For higher Reynolds number, however, the histogram shows a broader distribution of vortex positions in the x-direction away from the time mean core location. The vortex core thus shows a higher likelihood to travel up and downstream from the mean core position within each flow-through time in the higher Reynolds number.

Figure 2.8. Histograms of number of instances of vortex core position normalized by the non-dimensional sampling frequency.
cases than in the lower Reynolds number cases. This suggests that at higher Reynolds number, the core is less stable and more easily affected by variations in the incoming boundary layer or the freestream. Additionally, it can be observed in the histograms that the highest distribution of instances per flow-through time occur generally in two peak locations for all cases. These positions correspond to the back-flow and zero-flow modes of the horseshoe vortex that have been described by many researchers. In Figure 2.8, it seems that the spacing between the two modes becomes less distinct with increasing Reynolds number, perhaps due to more frequent perturbations of the vortex by the large range of turbulent scales in the incoming boundary layer as the momentum thickness Reynolds number increases.

3. Time-Averaged Heat Transfer

Figure 2.9(a) shows endwall non-dimensional heat transfer coefficient represented in terms of local Stanton number (St) for \( \text{Re}_T \) of 6,920, 25,400, and 75,000 respectively. Due to the placement of thermocouples underneath the heaters, calibration marks were made on the heaters to indicate their locations for use in calibration and image coordinate transformation. These marks are seen as red isolated spots in the IR images. The lowest Reynolds number case (\( \text{Re}_T = 6,920 \)) shows high values of St around the junction flow region. This is caused by the strong swirling motion of the HS vortex in this region. For the highest Reynolds number case (\( \text{Re}_T = 75,000 \)), the upstream Stanton number is lower by a factor of 1.5 when compared with \( \text{Re}_T = 6,920 \) case at \( X/T = -1 \), which is expected since St will decrease with increasing Reynolds number. Unlike other studies of endwall heat transfer [2,15], these results do not indicate a distinct band of high heat transfer away from the junction, which is associated with inrush events between the primary and secondary vortices. The time-average flowfield results in Figure 2.6, however, do not indicate a distinct secondary vortex for this study, which may be why the high heat transfer band is not apparent in this work.

Figure 2.9(a) also suggests that the shape of the contours is fuller around the leading edge in the low \( \text{Re}_T \) case compared to the high \( \text{Re}_T \) case. This is more apparent in Figure 2.9(b), where the local St for a given case is normalized by the value of St from \( X/T = -2.00 \) upstream of the leading edge. Around the junction flow region, the normalized St is almost 300% higher than in the upstream turbulent boundary layer, which is corroborated by other
studies [2]. The legs of the HS vortex around the sides of the wing, which result in the high heat transfer close to the wing junction, appear to move closer to the wing as $Re_T$ is increased. This may be due to differences in the behavior of the vortex legs where they originate from the symmetry plane; Figure 2.8 suggests that the average position of the HS vortex is more distinct in the low $Re_T$ case relative to the high $Re_T$ case.

Figure 2.9. (a) Time-averaged IR images show endwall heat transfer (non-dimensionalized as Stanton number) around the Rood wing for three $Re_T$ cases; (b) for same $Re_T$ cases, endwall Stanton number is normalized by inlet Stanton number from $X/T = -2.00$

Figure 2.10 shows time-averaged normalized $z$-vorticity in front of the Rood wing leading edge for $Re_T$ of 6,920 and 75,000, overlaid with time-average velocity streamlines. Also, in the same figure, local Stanton number normalized by the inlet ($X/T = -2.00$) Stanton number is shown along the symmetry plane where the flowfield
measurements are taken. Both cases show similar non-dimensional vorticity in the symmetry plane, which correlates with the similar heat transfer behavior for various Re_T in Figure 2.9. Paik, et al. [7] points out the very thin layer of positive vorticity underneath the primary opposing vortex core. Both Re_T cases in Figure 2.10 also show this thin positive vorticity layer underneath the negative vortex core, which Paik, et al. found was a source of the unsteady breakdown initiation. Figure 2.10 shows that the lowest Re_T case has a slightly more concentrated region of positive vorticity, compared to the highest Re_T case. This may explain why the upstream normalized St is slightly higher in the lowest Re_T case at around X/T= -0.15. Note that for both Re_T cases, the time-average streamlines do not indicate strong flow turning toward the wall upstream of the positive vorticity band, which may explain the lack of a second peak in heat transfer that Praisner and Smith [2] described for their cylindrical bluff body.

Figure 2.10. Time-averaged z-vorticity for two extreme Reynolds numbers with time-averaged normalized local Stanton number.
Conclusions

This paper describes a new test rig designed for high speed flowfield measurements and surface heat transfer around the Rood wing research airfoil. Analysis of dynamic flowfield measurements taken using high speed Stereo-PIV support several conclusions in regard to the time-mean and dynamic behavior of the HS vortex within a wide range of Reynolds numbers. Following are some specific conclusions:

(a) Measurements showed that the mean position of the vortex does not significantly change with varying Reynolds number, a conclusion supported by previous studies [12,14].

(b) Additionally, however, time-mean measurements also showed the growth of high turbulent kinetic energy near the bottom wall below the mean vortex core with increasing Reynolds number. This was shown to be largely due to an increase in the relative magnitude of fluctuations in u-velocity in this region for increasing Reynolds number. High Reynolds number has been observed under the HS vortex in previous studies, but to this author’s knowledge no study has shown the evolution of this structure from lower to higher Reynolds number.

(c) Finally, the use of a newly developed vortex tracking tool identified a larger degree of unsteadiness in the vortex core’s position with higher Reynolds number, suggesting the effect of high Reynolds number may lead the vortex to be less stable and more easily perturbed by turbulence in the incoming boundary layer or in the freestream.

(d) The time-averaged heat transfer measurements around the Rood wing are also presented in this paper for various Reynolds numbers. The Stanton number contour plots show lowest Reynolds number case to have fuller contours, whereas highest Reynolds number case shows slimmer and compact contours around the wing body.

Acknowledgements

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References


Chapter 3

Unsteady Heat Flux Measurements of Junction Flow With Reynolds Number and Free Turbulence Effects*

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The Pennsylvania State University, University Park, PA, 16802

Abstract

Turbulent junction flow is a three-dimensional unsteady phenomenon occurring in the flow upstream of the leading edge of bodies attached to a surface, such as in turbine rotors and stators, heat exchangers, submarine appendages, and wing-fuselage attachments. One of the signature features of this type of flow is the presence of bimodal behavior in the probability density functions of velocity, but the bimodal phenomenon has not been observed in surface heat flux measurements. However, it is well-known that time-mean levels of heat flux are significant. In situations where the body experiences high freestream turbulence, mean heat flux is further increased, but the mechanisms of the enhancement are unclear. In this paper, a test section for simultaneous time-resolved heat flux and flowfield measurements in front of a common research wing is highlighted. Time-resolved unsteady heat flux is also reported for a range of Reynolds numbers at high freestream turbulence. Time-resolved heat flux measurements from the symmetry plane of the junction region are compared with measurements downstream of the airfoil to determine if there are correlated behaviors. Also, a comparison between the effects of baseline freestream turbulence and high freestream turbulence on junction heat transfer is presented. It is found that at the plane of symmetry, high freestream turbulence increases endwall heat transfer at low Reynolds number and has negligible influence on endwall heat transfer at high Reynolds number.

## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G )</td>
<td>Auto spectral density function</td>
</tr>
<tr>
<td>( C )</td>
<td>Chord length</td>
</tr>
<tr>
<td>( \text{DAQ} )</td>
<td>Data acquisition system</td>
</tr>
<tr>
<td>( U_{\text{ref}} )</td>
<td>Freestream velocity</td>
</tr>
<tr>
<td>( T_{\infty} )</td>
<td>Freestream temperature</td>
</tr>
<tr>
<td>( \text{HS} )</td>
<td>Horseshoe</td>
</tr>
<tr>
<td>( q'' )</td>
<td>Heat flux ([\text{W/m}^2])</td>
</tr>
<tr>
<td>( I )</td>
<td>Integral length scale</td>
</tr>
<tr>
<td>( \text{Ku} )</td>
<td>Kurtosis</td>
</tr>
<tr>
<td>( \text{LDV} )</td>
<td>Laser doppler velocimetry</td>
</tr>
<tr>
<td>( T )</td>
<td>Maximum thickness of Rood wing</td>
</tr>
<tr>
<td>( \text{PDF} )</td>
<td>Probability density function</td>
</tr>
<tr>
<td>( \text{PSD} )</td>
<td>Power spectrum density</td>
</tr>
<tr>
<td>( \text{PVC} )</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>( \text{RTS} )</td>
<td>Resistance temperature sensing element</td>
</tr>
<tr>
<td>( \text{Re}_T )</td>
<td>Reynolds number based on max body thickness</td>
</tr>
<tr>
<td>( \text{Re}_0 )</td>
<td>Reynolds number based on momentum thickness</td>
</tr>
<tr>
<td>( \text{Sk} )</td>
<td>Skewness</td>
</tr>
<tr>
<td>( \text{St} )</td>
<td>Stanton number</td>
</tr>
<tr>
<td>( \text{St}_{\text{RMS}} )</td>
<td>Stanton number RMS</td>
</tr>
<tr>
<td>( \text{St}_{\text{mean}} )</td>
<td>Stanton number time-averaged</td>
</tr>
<tr>
<td>( \text{SPIV} )</td>
<td>Stereo particle image velocimetry</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Surface temperature</td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>Temperature difference ((T_s-T_{\infty}))</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
</tr>
<tr>
<td>( Tu )</td>
<td>Turbulence intensity</td>
</tr>
</tbody>
</table>

## Greek

<table>
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<th>Description</th>
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<td>( \delta )</td>
<td>Boundary layer thickness</td>
</tr>
<tr>
<td>( \delta^* )</td>
<td>Displacement thickness</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Kinematic viscosity at T=300K</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Momentum thickness</td>
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</tbody>
</table>
Introduction

Turbulent junction flow, also known as the horseshoe (HS) vortex system, is formed when a two-dimensional boundary layer encounters a bluff body, which then separates from the wall to form a coherent vorticity. The unsteady behavior of the junction flow 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 cause severe degradation in hot-section turbomachinery components such as turbine rotors and stators. Han et al. [2] stated that a change of component temperature by 25°C in the incoming flow within the hot-section turbomachinery (where nominal temperature is 1800°C) can reduce the part life by almost half. Devenport and Simpson [3] presented a detailed study of the junction flow for a single Reynolds number, which is representative of turbomachinery conditions. According to their study, the probability density functions of velocity demonstrates a bimodal peak [3], which represents two preferred states for the junction flow. Measurements by Praisner and Smith [1] at a lower Reynolds number also indicated bimodal behavior in the flowfield, and its impact on the steady heat flux. Lewis et al. [4] presented probability density functions of wall heat flux measurements in the region near the observed bimodal velocity fluctuations, which surprisingly did not show the bimodal behavior. However, it is unknown whether this a function of Reynolds number, and what impact freestream turbulence might have (as is typical in turbomachines). In this paper, an experimental setup is presented that captures time-resolved unsteady heat flux measurements over a range of Reynolds numbers as well as a baseline low freestream turbulence and high freestream turbulence level. Also, time-resolved endwall heat transfer from the symmetry plane is compared with places around the wing body to investigate any coupling effects due to turbulence and/or Reynolds number.

Previous Studies

The turbulent junction flow or horseshoe (HS) vortex system is a three-dimensional vortical structure commonly found in aircraft wing roots, fin-tube interfaces in heat exchangers, submarine hulls/appendages, and in junctions of turbomachinery components
such as rotors and stators. An adverse pressure gradient is formed by an obstacle [3] which causes the approach boundary layer to separate. A primary vortex, as well as secondary and tertiary vortices are formed, and follow the outline of the obstacle before merging with vortices generated by the trailing edge [5]. Several previous studies have described the causes of high turbulence intensities, pressure fluctuations, and endwall heat transfer within the HS vortex region ([1],[3]). Devenport and Simpson reported the unstreadiness in the incoming large-scale eddies contributed to the high turbulence intensities in the vortex core [3].

One of the signature features of a horseshoe vortex is the presence of two quasi-steady modes in the PDFs of streamwise velocity components ([3],[5]). The coherent upstream mode is called “backflow mode” and a more chaotic mode near the leading edge is called “zero-flow mode”[3]. Anderson and Lynch [6] also showed the presence of these two quasi-steady modes in their measurements of the HS vortex in front of a circular pin in a fully developed channel flow. Numerical simulations by Paik et al. [7] and Yakhot et al. [8] further supported the existence of quasi-steady modes in the vortex behavior in front of bluff bodies. Recent studies by Apsilidis et al. [9] and Chen et al. [10] on junction flow using cylindrical bodies demonstrated a third mode called “intermediate mode” which persists between the backflow mode and zero-flow mode.

Praisner and Smith [1] and Hada et al. [11] complemented time mean flowfield measurements with time mean heat transfer measurements to help explain the convective heat transfer at the junction. They found a primary high heat transfer band very close to the junction, which follows the leading edge contour, and a further upstream secondary high heat transfer band linked to the secondary vortex upstream of the large primary vortex. Hada et al. [11] also examined the effects of varying boundary layer thickness, body thickness of the bluff body, and incoming Reynolds number on the surface Stanton number and found that the double bands of high wall heat transfer persisted in all those instances. Swisher et al. [14] investigated the unsteadiness in heat flux along the stagnation streamline in front of a streamlined cylinder using a high-frequency-response heat flux microsensor (HFM) and found an increase in the RMS of heat flux unsteadiness as much as 30% over the mean heat flux in the vortex core. However, there has not been much research in exploring the spatially and time-resolved heat flux over a range of Reynolds numbers (Re).
and turbulence intensities (Tu). For example, Lewis et al. [4] examined the spatially and time-resolved heat flux, but their results were limited to single Re and Tu.

Several efforts were made previously to understand the contributions of high freestream Tu and Re on time-averaged endwall heat transfer in gas turbine vanes ([15],[16]). Blair [12] and Dunn et al. [13] were among the initial researchers who investigated the endwall heat flux rates between turbine cascade blades and reported an increase by a factor of 3 near the leading edge of endwall and turbine junction. Radomsky and Thole [15] introduced a freestream turbulence of 20% and found a 15% increase in endwall heat transfer underneath the horseshoe vortex core. Kang et al. [16] reported that secondary flows contributed to the increase of the trailing edge endwall heat transfer of a vane. Ames et al. [17] furthered the research efforts of understanding vane endwall heat transfer by introducing a mock aero-derivative combustion system upstream of a turbine vane cascade, where turbulence levels ranged from 0.7% to 14% and inlet Reynolds numbers based on true chord length and exit conditions were as high as 2,000,000. Ames et al. [17] reported that while secondary flows (including the leading edge junction flow) had noticeable impact on surface heat transfer at low turbulence levels, they had negligible impact at higher turbulence levels, especially for high Reynolds numbers.

Only a limited number of studies have provided both mean and RMS of heat transfer, and of those studies, there has been no investigation over a range of Reynolds number and freestream turbulence levels. Thus, the effects of those two parameters on the convective heat transfer in a junction flow is not well-understood. This paper investigates the effect of high freestream turbulence on junction region heat transfer over a range of Reynolds numbers. A particular interest here is examining the temporally resolved nature of the junction heat transfer, which may be linked to the bimodal nature of the junction flow and could be sensitive to freestream turbulence effects.

**Experimental Setup**

1. **The Facility**

A large recirculating low speed wind tunnel is used to conduct all experiments for this paper. As highlighted in Figure 3.1, a fan is used to circulate air around the wind tunnel and different stages of pre-conditioning to the flow are applied via heat exchangers to
maintain the freestream air temperature at the desired levels. Also shown in Figure 3.1 is a test section with sufficient optical accessibility for flow and surface heat transfer diagnostics. Polycarbonate is used for constructing the sidewalls as well as the top wall. Also, sections from the side and top walls have glass for better optical accessibility. For the current studies, freestream turbulence is generated via a grid system of parallel vertical cylinders, which is positioned 14.6 grid bar diameters upstream of a modified NACA 0020 airfoil, also known as Rood wing (3:2 semi-elliptical airfoil leading ledge and NACA 0020 trailing edge connected at the maximum thickness) \[3\]. The width and height of the test section around the airfoil are 1.12m and 0.55m respectively.

**Figure 3.1.** A recirculating low speed wind tunnel is presented with high speed flowfield measurement capabilities as well as endwall heat transfer measurement tools.

Also shown in Figure 3.1, 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 origin of the coordinates is position at the leading edge of the Rood wing. The single airfoil shown in Figure 3.1 has a 0° angle of attack with a symmetry along the centerline. The dimensions of this airfoil are a chord (C) of 40 cm, a
span (S) of 54.50 cm, and a maximum thickness (T) of 9.42 cm. This airfoil is hollow in the middle and is made out of stereolithographic process. Also, there are pressure taps at the 3% and 50% spans to ensure flow uniformity around the airfoil [18].

A stereo particle image velocimetry system (SPIV) is also used to measure three velocity components in the junction symmetry plane at up to 2 kHz sample rates. The dual-head Photonics laser source outputs light at a wavelength of 527 nm with maximum repetition rate of 10 kHz per head, and a maximum output pulse energy of 20 mJ per head. The SPIV system includes two Photron FASTCAM Mini UX100 high speed cameras with resolution of 1280 × 1024 pixels at 4 kHz. The captured images are processed using DaVis 8 software, and further processed using an in-house Matlab code. A detailed description of the wing pressure distribution validation and flow measurement design can be found in an earlier publication [18]. A hotwire probe has been used to obtain inlet turbulence intensity and length scales. Detailed information on the PIV and hotwire measurement techniques can be found in a parallel publication from the same laboratory [19].

2. Turbulence Grid

Figure 3.2 shows parallel PVC pipes, each with a diameter of 11.43 cm, which also equals the spacing between them. This design is based on the results of Roach [20]. The turbulence intensity (Tu) generated from this grid depends on the pipe diameter, spacing between the pipes, and distance from the grid to where turbulence intensity is measured. Using a hotwire probe, the turbulence intensity and the length scale are measured at X/T = 5.10 upstream of the Rood wing and at Y/T = 3.00 from the endwall. In this paper, unsteady surface heat flux measurements are also taken with and without turbulence grid to investigate the effects of added freestream turbulence levels on endwall heat transfer on the symmetry plane and around the wing body.

Figure 3.2. A parallel array of round PVC pipes is used as a turbulence grid.
3. Test Conditions

Figure 3.3 shows a cross-sectional view of a constant surface temperature boundary condition in front of Rood wing achieved by applying constant heat flux ($q''$) on the underside of a 3.81 cm thick aluminum plate. To ensure the homogeneity of surface temperature, aluminum 6061 with a thermal conductivity of 167 W/m-K has been chosen. A conjugate CFD analysis has been performed to ensure that the aluminum would represent a constant surface temperature boundary condition around the junction. Also, surface thermocouples and an infrared camera have been employed to monitor the constant temperature of the surface during data collection. The heaters that provide constant heat flux both upstream as well as to the underside of the aluminum plate are made out of specially designed serpentine Inconel circuit encapsulated in Kapton. To increase the uniformity of surface heat flux, a very thin layer of copper is placed on top of the encapsulated Inconel circuit. Insulating foams with very low thermal conductivity are used to limit the conduction losses from the heaters. A CFD model of the mixed boundary conditions shown in Figure 3.3 (constant heat flux upstream, constant surface temperature downstream) showed negligible change to the turbulent thermal boundary layer, relative to a constant surface temperature condition over the entire thermal boundary layer development length. The temperature difference between the two heating types is maintained to less than 1.5°C at the joint of both boundary conditions. The wind tunnel freestream velocity is measured with a pitot probe at the mid-span of the test section and the freestream temperature ($T_\infty$) is measured with thermocouples at 10%, 25% and 50% of the test section span.

![Image](image.png)

**Figure 3.3.** Time-resolved surface heat transfer measurements are taken by applying constant surface temperature boundary condition.

Time-resolved endwall heat transfer measurements are reported in this paper using a thermopile-based heat flux sensor [21]. Heat flux is determined through a Vatell HFM-7E/L heat flux microsensor (HFM). The sensor has a 6.32mm diameter face that measures
surface temperature through a resistance temperature sensing element (RTS) on the outer edge of the cylindrical sensor, and heat flux (HFS) through a thin-film thermopile on face of the sensor. Both mechanisms output respective voltages that can be converted to surface temperature and heat flux using calibration constants from the manufacturer [21]. The RTS and HFS signals are amplified using a low-noise amplifier provided by Vatell Corporation before they are sent to a DAQ system [22]. The HFM sensor has a thin highly emissive black coating on its surface as well as a rise time of 900 μs from 0 to 95% [22]. The sampling of unsteady heat transfer is conducted with a sampling rate of 5 kHz and the data is taken for 30s. Two HFM sensors and amplifiers are used in this study to examine how leading edge vortices interact with downstream secondary vortices. A process has been implemented using a standardized reference gauge by the manufacturer to calibrate both sensors and amplifier simultaneously [21].

The operational procedure for the sensors is as follows: before turning on the wind tunnel, RTS and HFS signals from HFM sensors are zeroed at room temperature with no heat flux applied. The desired Reynolds number is then achieved in the wind tunnel by changing the fan speed and power is supplied to both upstream heaters as well as to the heaters on the underside of the aluminum plate. The aluminum plates reach a steady temperature in about three hours. The voltage data is collected from the HFM sensors when it is determined that aluminum plates have reached a steady temperature condition. This process of getting to steady plate temperature is repeated every time tunnel fan speed is changed to obtain a different Reynolds number.

An in-house post-processing routine is implemented to convert the instantaneous voltages to heat flux measurements using the guidelines provided from the HFM sensor manufacturer ([21],[22]). At first, the instantaneous RTS voltage ($V_{RTS}(t)$) from the DAQ system is low-pass filtered with a cutoff frequency of 2 kHz using a 20th order filter. This low pass filtered voltage is then used to calculate instantaneous resistance as shown in Eq. (1). Here, $I_{RTS}$ and $G_{RTS}$ are the excitation current and amplifier gain respectively. $R_a$ is the ambient sensor resistance at ambient temperature. In Eq. (2), the HFM temperature $T(t)$ is found using instantaneous resistance ($R(t)$) and the RTS linearity and zero constants such as $c$ and $d$, which are obtained from the calibration sheet provided by the manufacturer [21].
The instantaneous heat flux is then found from the instantaneous voltage signals from HFS and sensor temperature $T(t)$ as shown in Eq. (3). In Eq. (3), $G_{\text{HFS}}$ is the amplifier gain for HFS channel and $g$ and $h$ are calibration coefficients provided by the manufacturer [21].

$$q''(t) = \frac{v_{\text{HFS}}(t)}{G_{\text{HFS}}}$$  \hspace{1cm} \text{Eq. (3)}$$

The heat flux signals from HFM sensors have been corrected for radiation losses using an emissivity constant of 0.95. Radiation losses account for 26% to 7% of the total heat flux measured by the sensor as the freestream velocity is increased in the tunnel. Conduction losses are deemed negligible because the heat flux sensor is fully embedded in the large aluminum plate, and the sides of plates are well-insulated during data collection. The contribution from natural convection is not accounted for in the heat flux measurements as an analysis indicates negligible effects for the test conditions studied.

In this study, the HFM sensors are installed in five designated areas as shown in Figure 3.4. Two HFM sensors are used for simultaneous measurements. Both sensors are independently validated against a two-dimensional turbulent boundary layer correlation at the far upstream location 1, which is unaffected by the horseshoe vortex. The sensors remain completely flush with the surrounding aluminum surfaces ensuring no obstruction in the flowfield. The sensors are fully embedded and in thermal equilibrium with the large aluminum plate which results in negligible impact to the thermal boundary layer. Also, the sensors are press-fitted into their positions which ensures minimum flow leakage. To capture the influence of the unsteady horseshoe vortex on the unsteady surface heat transfer in front of the leading edge, instantaneous voltage signals from HFM sensors have been acquired from location 2 and 3 concurrently. Furthermore, to understand how horseshoe vortex after being generated in front of the leading edge interacts with the downstream secondary vortices, instantaneous voltage signals are also taken from location 3 and 4 concurrently. Similar instantaneous voltage signals from HFM sensors are also taken from location 3 and 5.
4. Approach Boundary Layer and Heat Transfer Parameters

Unsteady surface heat transfer measurements are taken at a baseline freestream turbulence level as well as at a high freestream turbulence level representative of turbomachinery applications [15]. For each turbulence level, the tunnel flow speeds have been varied to obtain different Reynolds numbers based on Rood wing maximum thickness (T) as illustrated in Table 3.1. Table 3.1 also indicates inlet boundary layer conditions as well as surface and freestream temperatures for each Reynolds number case.

**Table 3.1. Summary of experimental cases**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Low Tu</th>
<th>High Tu</th>
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<tr>
<td>$T_u$ (%)</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$T$ (cm)</td>
<td>9.42</td>
<td>9.42</td>
</tr>
<tr>
<td>$U_{ref}$ (m/s)</td>
<td>1.16</td>
<td>4.19</td>
</tr>
<tr>
<td>$Re_f = U_{ref} T/v$</td>
<td>7,000</td>
<td>25,000</td>
</tr>
<tr>
<td>$Re_p = U_{ref} \theta/v$</td>
<td>452</td>
<td>1279</td>
</tr>
<tr>
<td>$\delta/T$</td>
<td>0.50</td>
<td>0.39</td>
</tr>
<tr>
<td>$\delta'/T$</td>
<td>0.091</td>
<td>0.075</td>
</tr>
<tr>
<td>$\theta/T$</td>
<td>0.061</td>
<td>0.053</td>
</tr>
<tr>
<td>$l$ (m)</td>
<td>0.177</td>
<td>0.218</td>
</tr>
<tr>
<td>$T_s$(K)</td>
<td>311.7</td>
<td>312.3</td>
</tr>
<tr>
<td>$T_w$(K)</td>
<td>286.3</td>
<td>287.3</td>
</tr>
</tbody>
</table>

Figure 3.4. HFM sensor locations are shown both in front of and around the Rood wing. X and Z coordinates are non-dimensionalized by maximum body thickness of the Rood wing, $T = 9.42$ cm.
Measurement Validation and Uncertainty Analysis

To validate the sensor measurements, time-averaged Stanton number is captured from sensor location 1 and plotted in Figure 3.5(a). Figure 3.5(a) also shows two-dimensional turbulent flat plate boundary layer correlation results at body thickness Reynolds number of 25,000 and 50,000. Only baseline freestream turbulence (1.0%) is provided in this figure to validate the results against the turbulent flat plate boundary layer correlation. As seen in Figure 3.5(a), time-averaged Stanton number decreases with increasing body thickness Reynolds number for the current study as well as for turbulent flat plate boundary layer correlation. Also evident in Figure 3.5(a), the time-averaged Stanton numbers from the current study agree well with the turbulent correlation at both Reynolds number cases. In Figure 3.5(b), time-averaged Stanton numbers from sensor location 2 and 3 are compared with the time-averaged Stanton numbers from the same upstream locations in Lewis et al. [4] and Elahi et al [18]. Additionally, the X distance is non-dimensionalized by the maximum wing thickness (T). The percent differences between Lewis et al. [4] and current study are 9% and 4% at sensor locations 2 and 3 respectively. Also, the percent differences between Elahi et al. [18] and current study are 3% and 12% at locations 2 and 3 respectively. Lewis et al. [4] reported an uncertainty of 15.2% in the HFM measurements. Elahi et al. [18] reported an uncertainty of 9% in the Stanton number measurements.

![Figure 3.5](image_url)

Figure 3.5. (a) Time-averaged Stanton numbers from current study are compared with 2D turbulent correlation at Reynolds number of 25,000 and 50,000 and (b) time-averaged Stanton number from sensor locations 2 and 3 are plotted with findings from Lewis et al. [4] and Elahi et al. [18]
The overall uncertainty in time-averaged Stanton number ($St_{\text{mean}}$) and root mean square of instantaneous Stanton number ($St_{\text{RMS}}$) are found by taking seven sample datasets from location 2 as shown in Figure 3.4. For each dataset, an in-house Matlab routine calculates the mean and RMS of Stanton number from 150,000 data points (30 seconds at 5 kHz). The bias uncertainty of the HFM is 3.0% as provided by the manufacturer [21]. The precision uncertainty has been calculated using the standard 95% confidence interval. Table 3.2 shows the percent overall uncertainty in time-averaged and RMS of Stanton number for two extreme Reynolds number cases. The uncertainties are dominated by uncertainty in the sensor calibration as well as by the variations in freestream temperature and surface temperature.

### Table 3.2. Summary of experimental uncertainties

<table>
<thead>
<tr>
<th>Turbulence Level</th>
<th>Low Tu</th>
<th>High Tu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re_T$</td>
<td>7,000</td>
<td>80,000</td>
</tr>
<tr>
<td>% uncertainty in $St_{\text{mean}}$</td>
<td>4.00</td>
<td>4.80</td>
</tr>
<tr>
<td>% uncertainty in $St_{\text{RMS}}$</td>
<td>3.90</td>
<td>4.10</td>
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</table>

**Results and Discussion**

1. **Comparison Between Symmetry Plane Sensor Locations**

   To show the respective locations of sensor 2 and 3 on the endwall in front of the wing leading edge, Figure 3.6 highlights the sensor locations in time-averaged normalized streamwise velocity magnitude contour plots for $Re_T$ of 7,000 and 80,000 [19]. The time-averaged vortex core is shown to be in between the two sensors in both flowfields. In an instantaneous flowfield not shown in Figure 3.6, the vortex core is found to be extremely dynamic and unsteady over the sensor locations as Reynolds number increases. Also, Figure 3.6 shows a spatially and time-resolved endwall heat transfer contour plots [18] in terms of local Stanton number along with respective sensor locations with white circles. More details on measurement techniques and results of spatially and time-resolved endwall heat transfer can be found in Elahi et al. [18].

   Unsteady heat transfer measurements are taken from sensor locations 2 and 3 (shown in Figure 3.4 & 3.6). Locations 2 and 3 are on the plane of symmetry and within the turbulent junction flow dominated region [18]. Two HFM sensors are employed to capture time synchronized data at a sampling rate of 5 kHz over the duration of 30 seconds.
per collection. Three trials are taken from locations 2 and 3 for a given Reynolds number
and turbulence level.

As shown in Figure 3.7, time-averaged Stanton number and RMS in Stanton
number are displayed at baseline and high freestream turbulence cases. In Figure 3.7(a),
time-average St decreases with increasing Re_T (also Re_0; see Table 3.1) for a given
turbulence level. This is not necessarily due to movement of the time-average vortex away
from a sensor location; Figure 3.6 indicates that the time-average flowfield is similar
despite the order of magnitude difference in Reynolds number, and the decrease is
primarily due to the definition of St with the reference velocity in the denominator.

The effect of turbulence on the junction heat transfer appears to be a function of
Reynolds number also. Focusing on location 2 in Figure 3.7(a), time-averaged Stanton number is shown to increase with increasing freestream turbulence at Re_T of 7,000 and 25,000. However, time-averaged Stanton number is shown to remain almost unchanged with increasing freestream turbulence at Re_T of 80,000. This conclusion of negligible change in time-averaged Stanton number as Re_T increases is in agreement with Ames et al. [17], who reported that the lack of influence of freestream turbulence on Stanton number at high Re_T is mainly due to a large inlet momentum thickness. Similar to location 2,

Figure 3.6. Sensor locations are shown in time-averaged flowfield and heat
transfer measurements.

As shown in Figure 3.7, time-averaged Stanton number and RMS in Stanton
number are displayed at baseline and high freestream turbulence cases. In Figure 3.7(a),
time-average St decreases with increasing Re_T (also Re_0; see Table 3.1) for a given
turbulence level. This is not necessarily due to movement of the time-average vortex away
from a sensor location; Figure 3.6 indicates that the time-average flowfield is similar
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Reynolds number also. Focusing on location 2 in Figure 3.7(a), time-averaged Stanton number is shown to increase with increasing freestream turbulence at Re_T of 7,000 and 25,000. However, time-averaged Stanton number is shown to remain almost unchanged with increasing freestream turbulence at Re_T of 80,000. This conclusion of negligible change in time-averaged Stanton number as Re_T increases is in agreement with Ames et al. [17], who reported that the lack of influence of freestream turbulence on Stanton number at high Re_T is mainly due to a large inlet momentum thickness. Similar to location 2,
location 3 also reports negligible augmentation in time-averaged Stanton number at \( \text{Re}_T \) of 80,000 as shown in Figure 3.7(a).

Figure 3.7(b) highlights the fluctuation in Stanton number at locations 2 and 3 with two freestream turbulence cases. Location 3, which is closer to the junction, experiences higher fluctuations in heat flux than location 2 at a respective turbulence level. It is also evident from Figure 3.7(b) that RMS in Stanton number is relatively large in low \( \text{Re}_T \) case as opposed to high \( \text{Re}_T \) case. In both sensor locations, the impact of added freestream turbulence on the RMS values is more significant at \( \text{Re}_T \) of 7,000 than at 80,000. This is mainly due to the relative increase in the strength of heat flux fluctuations at low \( \text{Re}_T \) case with added turbulence.

![Figure 3.7](image)

**Figure 3.7.** (a) Time-averaged Stanton number upstream of the wing on the symmetry plane, and (b) RMS in Stanton number from same upstream locations.

The flowfield measured with the PIV system helps to explain the trend of turbulence level insensitivity in the St fluctuations at high Re. Figure 3.8 shows contour plots of the RMS of normalized u-velocity fluctuations obtained with the PIV system in the symmetry plane upstream of the wing, for the four cases investigated here. Overlaid vectors indicate the in-plane time-average velocity components, and the boxes below each subfigure indicate the heat flux sensor location. In general, the RMS of u-fluctuations is high underneath the time-average vortex core due to the aperiodic switching between the backflow and zero-flow modes of the vortex, which contributes to high RMS of St. When comparing between low and high Reynolds number cases at low turbulence level in Figure 3.8, the levels of normalized u-velocity fluctuations near the sensor locations are generally
similar, which would imply similar heat flux fluctuation levels. Note that in Figure 3.7(b), the RMS of St decreases with ReT since the denominator of St (and St_{RMS}) includes the reference velocity, which is increasing with ReT.

The more interesting comparison in Figure 3.8 is the difference in u-velocity fluctuations between low and high turbulence levels, for a given Reynolds number. For the low ReT, there is a distinct increase in u-velocity fluctuations in the time-average vortex core region and the heat flux sensor locations. This is due to the sensitivity of the horseshoe vortex to the freestream turbulence. However, at high ReT, the fluctuation levels in the vortex core region and near the endwall are not significantly affected by high freestream turbulence, which agrees with the trend of the heat flux fluctuations in Figure 3.7(b).

Figure 3.8. Contours of normalized u-velocity fluctuations, overlaid with time-average velocity vectors, and heat flux sensor locations given in the boxes.
The PDFs shown in Figure 3.9 are of the heat flux fluctuations for locations 2 and 3. These PDFs are normalized by subtracting the time-mean heat flux from the instantaneous heat flux signals and then dividing the outcome by the RMS of the same instantaneous heat flux signals [4]. PDFs of heat flux fluctuations in the turbulent horseshoe vortex dominated region (i.e. sensor locations 2 and 3) do not exhibit a bimodal nature, which is consistent with the findings by Lewis et al [4]. A bimodal structure is present in the PDFs of fluctuating streamwise velocity components reported by Devenport and Simpson [3]. The effects of the unsteady behaviors in heat flux fluctuations are exhibited by the distortions of the PDF from a Gaussian PDF. The skewness (Sk) and kurtosis (Ku) of each PDF are also highlighted in Figure 3.9. For reference, a Gaussian distribution would have a Sk and Ku of 0 and 3 respectively. For high turbulence in both sensor locations, the Sk values are more positive than the low turbulence case suggesting that there is an increased number of positive-value fluctuations events with freestream turbulence, especially for low \( \text{Re}_T \). Ku levels are also higher for the high turbulence cases, suggesting a broader distribution of heat flux events.

![PDFs of heat flux fluctuations at location 2 and 3](image)

Figure 3.9. (a) PDFs of heat flux fluctuations at location 2 are shown for low and high Reynolds number and turbulence cases, (b) PDFs of heat flux fluctuations at location 3 are shown in the same fashion.

2. **Comparison Between Leading Edge and Side of Wing**

To understand how the unsteady horseshoe vortex upstream of the leading edge interacts with the secondary vortices downstream of the leading edge and influences the endwall heat transfer, time synchronized heat flux measurements are captured from
locations 3 and 4 at a sampling rate of 5 kHz over the duration of 30 seconds. In Figure 3.10(a), at the baseline turbulence as well as at the high turbulence level, time-averaged Stanton number drops significantly between locations 3 and 4 at $Re_T$ of 7,000. The higher values of time-averaged Stanton number at the location 3 are mainly caused by the swirling motion in the horseshoe vortices. However, as the $Re_T$ approaches 80,000, the influence of added freestream turbulence becomes negligible in sensor locations 3 and 4 validating the findings by Ames et al [17]. Furthermore, the effect of increased turbulence on time-averaged Stanton number in location 4 is shown to be insignificant in all $Re_T$ cases. This suggests that freestream turbulence may have more impact on the horseshoe vortex dominated region at the plane of symmetry than in the downstream secondary vortex dominated region (location 4). Figure 3.10(b) highlights the RMS in the Stanton number at locations 3 and 4. RMS values in locations 3 and 4 are relatively high when $Re_T$ is 7,000 for both turbulence levels. When $Re_T$ equals 80,000, RMS values are shown to become relatively low. Also, it is noted that RMS values change dramatically with added freestream turbulence at lower $Re_T$ than they do at higher $Re_T$.

![Figure 3.10](image.png)

Figure 3.10. (a) Time-averaged Stanton number is compared between leading edge and side of the wing, and (b) RMS in Stanton number is reported from the same locations.

The PDFs shown in Figure 3.11 are of the heat flux fluctuations for locations 4 and 5. Note that locations 4 and 5 are both downstream from the wing leading edge. These PDFs are normalized in the same way as Figure 3.9. The double-peaked or bimodal structures are also absent in PDFs at locations 4 and 5. This absence of bimodal structures is expected in locations 4 and 5 where the leg of the horseshoe vortex, and a mild skewed
turbulent flat plate boundary layer (due to the wing pressure field) tend to dominate, respectively. The Figure 3.11 also includes Sk and Ku for each PDF. Sk and Ku both increase with turbulence level for \( \text{Re}_T \) of 7,000. Also, for \( \text{Re}_T \) of 80,000 at low Tu, Sk and Ku follow a Gaussian distribution, and are increased with increasing Tu due to an increase in positive-magnitude fluctuation events.

![PDFs of heat flux fluctuations at location 4](image)

![PDFs of heat flux fluctuations at location 5](image)

**Figure 3.11.** (a) PDFs of heat flux fluctuations at location 4 are shown for low and high Reynolds number and turbulence cases, (b) PDFs of heat flux fluctuations at location 5 are also shown in the same fashion.

3. **Comparison Between Leading Edge and Far Downstream**

To further the understanding in the interaction between the unsteady horseshoe vortex and downstream secondary vortices, in Figure 3.12, time-averaged Stanton number from location 5 (which is even further downstream from the leading edge) is compared with the Stanton number at location 3 where horseshoe vortex dominates. Figure 3.12(a) shows sensor location 5 is not much affected by either the increased freestream turbulence or by the increased Reynolds number. This behavior may suggest that location 5 is in a 2D turbulent boundary layer region where neither the secondary vortices nor the swirling motion from the symmetry plane played any role to influence endwall heat transfer. Figure 3.12(b) shows the RMS in Stanton number at locations 3 and 5. Just like the RMS values in locations 3 and 4, RMS values in locations 3 and 5 are higher at the low Reynolds number cases for both turbulence levels. When \( \text{Re}_T \) equals 80,000, RMS values are shown to become considerably low.
4. Augmentation in Stanton Number

Time-averaged Stanton number for high turbulence case is divided by the time-averaged Stanton number for baseline turbulence case to calculate the net augmentation in Stanton number due to turbulence. Figure 3.13 illustrates a summary of augmentation in Stanton number at all four sensor locations at three Reynolds number cases. Locations 2 and 3 are located in the horseshoe vortex dominated region [18]. The Stanton number augmentation in this horseshoe vortex region varies from 1.20 to about 1.00 as Reynolds number is increased from 7,000 to 80,000. This shows that at high Reynolds number case, freestream turbulence does not influence the endwall the heat transfer, which is one of the conclusions drawn by Ames et al [17]. The augmentation in Stanton number in horseshoe vortex dominated region (locations 2 and 3) at Reynolds number of 25,000 is further validated by comparing to Radomsky and Thole [15], who reported an augmentation of 1.15 within the horseshoe dominated region of the leading edge of a vane at a similar approach Reynolds number. Sensor location 4 is placed relatively closer to the wing body compared to location 5, which is further downstream and away from the wing body. The augmentation in Stanton number in location 4 tends to stay around 1.00 as the Reynolds number is increased as shown in Figure 3.13. This behavior apparently shows that freestream turbulence played little role in increasing endwall heat transfer at location 4.
However, at location 5 freestream turbulence contributes to increase endwall heat transfer by a factor of 2.50 at Re$_T$ of 7,000.

Figure 3.13. Augmentation in Stanton number due to turbulence.
5. Power Spectra Analysis

The normalized power spectrum density (PSD) in Figure 3.14 demonstrates the frequency content of the unsteady Stanton number both on symmetry plane and around the airfoil. The frequency is normalized by $T/U_{ref}$ on the x-axis and on the y-axis, power spectrum density $G$, is normalized by $U_{ref}/T$ and the square of the time-averaged Stanton number. This normalization technique allows for the area under the PSD curve to be representative of the variation in Stanton number. Three different Reynolds numbers are used as shown in Figure 3.14. Also, in Figure 3.14, comparisons are made between high and low Tu intensities at four sensor locations. The results in Figure 3.14 are not corrected for the finite size of the HFM sensors and the PSD curves at very high frequencies may have been attenuated [4].

In Figure 3.14, PSD curves for locations 2 and 3 in both low and high turbulence cases have a slight downward slope at low frequency spectral levels followed by a rolloff as the frequency increases. The PSD for $Re_T$ of 7,000 is shown to plateau at high frequencies due to possible attenuation in both locations 2 and 3. The rolloff slopes for $Re_T$ of 25,000 and 80,000 seem to match at low and high turbulence cases. In low frequency region, the spectral density amplitudes are larger at $Re_T$ of 7,000 and 25,000 than 80,000, which is found to be consistent for both low and high turbulence cases. This increase in amplitude at lower Reynolds numbers is contributed by the high levels of heat flux fluctuations also evident in the RMS values in Figure 3.7(b). At low turbulence case, the spectral density amplitudes seem to decrease slightly at all three Reynolds numbers compared to high turbulence case also evident in the RMS values in Figure 3.7(b). Figure 3.14 also shows the spectral density amplitudes for sensor locations 4 and 5, which are from the downstream region, appear to be a little low for location 4 and much lower for location 5 when compared with the amplitudes for locations 2 and 3. This is again consistent with the heat flux fluctuations found in locations 4 and 5 from the Figure 3.10(b) and Figure 3.12(b).
Figure 3.14. Normalized power spectrum density curves show heat flux fluctuations are higher on the plane of symmetry at the high turbulence level.
Conclusions

A recirculating low-speed wind tunnel is used to understand the effects of high freestream turbulence and various Reynolds numbers on turbulent junction flowfield and endwall heat transfer. Time-resolved heat flux measurements from turbulent junction endwall as well as from the downstream of the Rood wing leading edge are presented in this paper. Statistical analyses on the normalized heat flux fluctuations are also shown for all four sensor locations. A thorough comparison of the one-sided autospectral density functions are presented for four sensor locations at all three Reynolds numbers to highlight the variance of the local Stanton number. Following are some specific conclusions:

(a) At lower Reynolds numbers (i.e. 7,000 and 25,000), time-averaged endwall Stanton number in the turbulent junction flow region is shown to increase dramatically with added freestream turbulence. At high Reynolds number (i.e. 80,000), the change in endwall Stanton number near the junction becomes negligible with increasing turbulence, which agrees with the prior work by Ames et al. [17].

(b) In the turbulent junction flow dominated region, the fluctuations in heat flux increase as the junction is approached from upstream, and it is found to be true at low and high turbulence levels. The PDFs of heat flux fluctuations near the junction (i.e. sensor locations 2 and 3) do not exhibit a bimodal distribution, which is consistent with prior work in this field [4].

(c) The endwall Stanton number augmentation due to turbulence in the junction flow region varies from 1.20 to about 1.00 as Reynolds number is increased. Insignificant augmentation in Stanton number in sensor location 4 (which is located around the wing body) shows freestream turbulence played a little role in increasing endwall heat transfer.

(d) Power spectrum density (PSD) amplitudes are found to be larger at lower Reynolds number cases than the high Reynolds number case showing that high levels of heat flux fluctuations are present at lower Reynolds number cases. Also, amplitudes are shown to decrease at the low turbulence case for all four sensor locations meaning with decreasing freestream turbulence, the fluctuations also decrease near the junction and around the wing body.
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References


Chapter 4
Conclusions

Chapter 2 has presented contour plots of the non-dimensional velocity magnitudes, turbulent kinetic energy, and the root mean square of the streamwise fluctuating velocity from the turbulent junction flow dominated region at five body thickness Reynolds number cases. In the time-averaged velocity magnitude contour plots, only a primary vortex core that is elliptical in shape is observed, and the contour plots do not indicate the presence of secondary or tertiary vortex cores. These observations on the absence of secondary and tertiary vortex cores for this wing geometry are supported by other researchers as highlighted in Chapter 2. The turbulent kinetic energy contour plots show that the strength of turbulence increases in the vortex core with increasing Reynolds number. The root mean square of the streamwise fluctuating velocity component is found to be higher underneath the primary vortex core in the highest Reynolds number case. Also, a technique is discussed in Chapter 2 to track the position of the vortex core as a function of time based on normalized Q-criterion, which suggests that the bimodal nature is slightly more distinct at low versus high Reynolds number.

The time-averaged endwall heat transfer measurements for three body thickness Reynolds numbers are also presented in chapter 2 using infrared thermography. It is found that in the lowest body thickness Reynolds number case, surface heat transfer is high around the junction flow region. The strong downward motion of the horseshoe vortex is responsible for this high heat transfer. Unlike some previous studies, the time-averaged endwall heat transfer contour plots do not indicate two distinct bands of high heat transfer, which would be associated with the inrush events between the primary and secondary vortices. The time-averaged flowfield measurements also do not indicate a secondary vortex core, which may be why two bands are not apparent in the contour plots. Chapter 2 also compares time-averaged normalized z-vorticity for lowest and highest Reynolds number cases with their corresponding time-averaged normalized local heat transfer from the plane of symmetry. It is shown that a thin layer of positive vorticity underneath the primary horseshoe vortex increases local endwall heat transfer.

While chapter 2 focuses on the effects of Reynolds number on the time-resolved flowfield and spatially-resolved heat transfer in the turbulent junction flow region, chapter
3 adds a new dimension to the analyses of endwall heat transfer by introducing the effects of freestream turbulence on the time-resolved heat transfer measurements. Three body thickness Reynolds numbers 7,000, 25,000, and 80,000 are reported and as for the freestream turbulence, a baseline turbulence and high turbulence level representative of turbomachinery applications are used. An in-depth analysis has been presented in chapter 3 using local time-averaged Stanton number, root mean square of the Stanton number, probability density function of the fluctuating components of the heat flux measurements, and power spectrum density of the frequency contents from two locations on the plane of symmetry and two locations around the wing body. The results from these analyses have agreed with the previous literature outcomes as shown in chapter 3.

Chapter 3 reports that on the plane of symmetry in front of the airfoil leading edge, added freestream turbulence has more influence on the endwall heat transfer at low body thickness Reynolds number than at high Reynolds number. It is also noted that the effects of freestream turbulence is almost negligible at the high Reynolds number case, which is consistent with some previous research findings. The probability density functions of the fluctuating component of the heat flux do not show bimodal behavior although the probability density functions of the streamwise fluctuating component of the velocity right below the vortex do have bimodal structures. The distortions of the probability density functions are representative of the fluctuations in heat flux. These fluctuations in heat flux are increased with freestream turbulence as evidenced by the increase in skewness values with freestream turbulence. In the junction flow dominated region, augmentation in the endwall heat transfer due to turbulence varies from 1.20 to about 1.00 as the Reynolds number is increased. The amplitudes of the power spectrum density are found to increase at lower Reynolds number cases showing the variance in heat flux fluctuations is higher in the lower Reynolds numbers.

The time-resolved heat transfer results with high freestream turbulence effects show that in higher Reynolds number applications such as in gas turbine engines increasing freestream turbulence has negligible impact on endwall heat transfer. However, in low Reynolds number applications such as in heat exchangers, an increase in freestream turbulence could be advantageous because it would increase the potential heat transfer at the surface. As for the near future goals, time-resolved heat transfer measurements will be
taken with variable integral length scale while keeping freestream turbulence relatively same to understand if length scale augments heat to the endwall of horseshoe vortex region. Also, the effects of variable freestream turbulence on spatially-resolved endwall heat transfer will be explored using infrared thermography. As for the long term goals, a representative model of a first-stage turbine vane with an angle of attack will be used to investigate the effects of Reynolds number and freestream turbulence on spatially and time-resolved endwall heat transfer using infrared thermography and heat flux microsensors respectively.