AN INVESTIGATION OF THE PHYSICAL MECHANISM OF HEAT TRANSFER AUGMENTATION IN BOUNDARY LAYER FLOWS SUBJECT TO FREESTREAM TURBULENCE

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Abstract

Water tunnel experiments have been performed to examine how large scale, high intensity freestream turbulence affects heat transfer through a laminar flat plate boundary layer. Time-Resolved Digital Particle Image Velocimetry (TRDPIV) was used to examine the flow field along with time-resolved heat transfer from the wall. The surface heat flux was measured with a newly developed thin-film sensor called the Heat Flux Array (HFA) capable of measuring heat flux at 10 locations at frequencies to 35 Hz. Freestream conditions were controlled using passive grids producing turbulence intensities of 5.5% with integral length scales of 2 and 3.5cm. This was shown to increase mean convective heat transfer coefficients by up to 15% with fluctuations to 40% above cases of very low freestream turbulence. It was also shown that fluctuations in heat flux traveled at approximately half the freestream velocity.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>b</td>
<td>diameter of bars</td>
</tr>
<tr>
<td>$D_f$</td>
<td>distance factor, $-U\tau/\Delta x$</td>
</tr>
<tr>
<td>$D_f\text{peak}$</td>
<td>$D_f$ corresponding to peak in $R_{qq}$</td>
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<tr>
<td>$h$</td>
<td>heat transfer coefficient, W/cm²K</td>
</tr>
<tr>
<td>$k$</td>
<td>conductivity of water, W/mK</td>
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<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
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<tr>
<td>$q''$</td>
<td>heat flux, W/cm²</td>
</tr>
<tr>
<td>$Re_x$</td>
<td>Reynolds number based on x</td>
</tr>
<tr>
<td>$Se$</td>
<td>Seebeck coefficient, $\mu V/°C$</td>
</tr>
<tr>
<td>$S_q$</td>
<td>HFA sensitivity $\mu V/W/cm²$</td>
</tr>
<tr>
<td>$Tu$</td>
<td>turbulence intensity</td>
</tr>
<tr>
<td>$U_o$</td>
<td>freestream velocity, cm/s</td>
</tr>
<tr>
<td>$u'$</td>
<td>fluctuating streamwise velocity</td>
</tr>
<tr>
<td>$v'$</td>
<td>fluctuating transverse velocity</td>
</tr>
<tr>
<td>$V_e$</td>
<td>event velocity ratio, $-1/D_f\text{peak}$</td>
</tr>
<tr>
<td>$x$</td>
<td>distance from leading edge, cm</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>thermal diffusivity, m²/s</td>
</tr>
<tr>
<td>$\mu$</td>
<td>spacing of bars</td>
</tr>
<tr>
<td>$\tau$</td>
<td>correlation lag time, s</td>
</tr>
<tr>
<td>$\delta_{99}$</td>
<td>boundary layer thickness, $u/U_\infty=.99$</td>
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<tr>
<td>$\Lambda_x$</td>
<td>integral length scale, cm</td>
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Introduction

How freestream turbulence affects heat transfer in a laminar boundary layer is not well understood. Many engineering problems involve heat transfer through a laminar boundary layer to a fluid with high levels of freestream turbulence. It is becoming increasingly important for these processes to be accurately modeled as designers push materials to their thermal limits, the classic example being turbine blades. Being able to accurately predict the highest heating loads on these components is paramount if peak efficiency is to be obtained.

Background and Related Studies

Many studies have been performed in the last 25 years to quantify the effects of freestream turbulence on heat transfer. These have focused on developing correlations for the increase in time-average heat transfer as a function of the turbulence intensity for particular geometries. More recently the effect of the length scale of the turbulence has been documented to also be important.

One key technique to understand the effect of freestream turbulence is to characterize the coherent structures present and how they interact with the boundary layer. It’s known that these structures may cause an early transition from laminar boundary layer flow to a turbulent boundary layer by various bypass mechanisms. Coherent structures have been identified to be important contributors to transport in turbulent boundary layers on flat plates, at stagnation regions and in jets and shear layers. The corresponding induced vortices affect the sublayer streaks in turbulent boundary layers.

Heat and mass transport at the wall appear to be directly affected by the sweeping of these large vortices into the boundary layer, particularly at high levels of turbulence intensity. Van Fossen and Simoneau used wires to create large vortices perpendicular to a downstream cylinder and studied the surface heat transfer and fluid flow near the surface with a combination of liquid crystals and smoke visualization. The region of increased heat transfer was located where the vortices
pulled in freestream fluid to the surface. Measurements of the fluctuating heat flux at the surface, $q'$, have shown direct correlation with the velocity fluctuations in the free stream \(^{14-20}\) and similarly for mass transfer \(^{21}\). Dullenkopf and Mayle \(^{22}\) identified a dominant frequency band that most strongly affects the heat transfer in a laminar boundary layer. This dominant frequency corresponds to an eddy size that is about 16 times the boundary layer thickness. They then defined an effective turbulence intensity for predicting heat transfer in the presence of strong free stream turbulence.

There have been several attempts to develop mechanistic models of the effect of turbulent coherent structures on heat transfer at a stagnation point. Wilson and Handford \(^{23}\) imposed an unsteady velocity at the edge of the boundary layer and numerically solved the unsteady laminar equations. Correlations were also developed using a surface renewal model to estimate the effect of the turbulent structures from the free stream \(^{24-25}\). The characteristic frequency was determined by how often the value of the fluctuating velocity exceeded a threshold limit. In all cases, however, only an average increase in heat transfer was calculated.

Recent research has begun to demonstrate the power of time-resolved PIV and time-resolved heat flux measurements to understand the mechanisms of structured flows. Sabatino and Smith \(^{26}\) have used this combination to study the effect of a turbulent spot in a laminar boundary layer. Williams et al. \(^{27}\) have demonstrated the use of a high speed PIV system in the near wake region of a cylinder to refine LES calculations.

**Water Tunnel Facility**

The low speed water tunnel facility used to conduct this research is located in the Virginia Tech AETHER Laboratory. This tunnel uses a propeller mounted on a variable frequency driven motor to control tunnel speeds from 0.05 to 1.0 m/s with freestream turbulence intensity, $Tu$, of 1-2%. The test section is a square channel 61cm by 61cm with a length of 177cm. The sides and floor of the test section are fabricated from clear acrylic to allow optical access for Time Resolved Digital Particle Image Velocimetry (TRDPIV).

**Turbulence Generation**

The turbulent characteristics in the test section were controlled through the use of passive grids. These grids were used to produce large integral length scale, high intensity turbulence similar to what is encountered in turbomachinery. With these goals in mind, the grids were designed using the correlations given by Baines and Peterson \(^{28}\). The design and testing of these grids is described by Gifford \(^{29}\). For these tests, $Tu$ was held constant at approximately 5.5% while the integral length scale, $\Lambda_x$, was varied from 2.0 to 3.6cm.

Two grids were designed for this study. The smaller of the two, Grid B, had bar spacing of $\mu=3.4$ cm and bar diameter of $b=1.58$ cm. The other grid used, Grid A, had $\mu=4.8$ cm with $b=2.1$ cm. When placed at $x/\mu$ upstream of 17.3, these two grids gave $Tu$ of approximately 5.5% with integral length scales of 2.0 and 3.25 cm respectively. The grid properties are outlined in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Grid specifications</th>
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<tr>
<td>Diameter, $b$</td>
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<tr>
<td>Grid A</td>
</tr>
<tr>
<td>Grid B</td>
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</table>

**Flow Measurement**

The flow characteristics in this study were measured using TRDPIV. The flow field was illuminated using New Wave Research’s Pegasus dual head laser. Using an optical train, this laser was focused and then opened into a sheet which was approximately 12cm wide and 1mm thick at the test section. The laser sheet was brought from the bottom of the tunnel and viewed from the side as shown in Figure 1.

The flow was seeded with 10 micron, neutrally buoyant, glass spheres manufactured by Potters Industries. Particle displacements were tracked using a Photron APX RS high speed camera sampling at 125Hz with a 2.67ms delay between double pulsed images. The integration region was 924 pixels by 700 pixels with a resolution of 73 microns/pixel. The images were processed using in-house developed software described by Eckstein \(^{30}\).

![TRDPIV setup](image)

**Heat Flux Measurement**
Heat flux is measured using sensors designed and fabricated by our group. Copper and nickel is deposited on a Kapton® substrate using vacuum chamber electron beam deposition. This is a process where the deposition metal is melted using an electron beam and the metal vapor sticks to the substrate in the extreme vacuum of the deposition chamber.

The copper and nickel traces form thermocouple pairs which directly measure the temperature difference across the Kapton®, which acts as the thermal resistance. This temperature difference can be equated to heat flux using Fourier’s Law.

\[ q'' = -k \frac{dT}{dx} \]  

This was done at 10 points in a line creating the Heat Flux Array (HFA) shown in Figure 2. The areas of measurement were spaced evenly 6.35mm apart. By connecting a nickel wire to the nickel trace, the surface temperature at each point could also be measured by treating the outer copper-nickel junction of the HFA as an independent thermocouple. Each sensing point measures the average heat flux over an area of approximately 2mm x 2mm.

The HFA was calibrated as outlined in 31 giving a sensitivity of \( S_q = 42.6 \ \mu\text{V/W/cm}^2 \). The Seebeck coefficient for these Copper-Nickel junctions was measured as \( S_e = 20 \ \mu\text{V/}^\circ\text{C} \). Heat flux signals were sampled at 1kHz using a National Instruments 6015 DAQ with 16 bit resolution. All signals were preconditioned using 1000 gain amplifiers and 480 Hz anti-aliasing filters. Due to amplifier channel limitations, only two surface temperatures were measured. The two surface temperature measurements were taken from sensor 1 and 7. This means that it is at these two locations only that heat transfer coefficients can be determined.

Figure 2 Heat Flux Array

All heat flux measurements were low pass filtered at 30 Hz. This removed all high frequency noise without the loss of any information as the response time of the heat flux array is approximately 35Hz. This does not represent a problem as all the largest, most energetic, structures in the flow field occur at well under 30Hz.

**Experimental Model**

A flat plate model was constructed as shown in Figure 3. A 12.7mm thick piece of acrylic was machined with a rounded leading edge and a pocket to accept an 88.9mm by 317.5mm aluminum plate 5mm thick. The plate fit perfectly flush with the surface so as to not disturb the flow. The plate was heated from above and was placed facing down in the water tunnel so that a laser plane could be positioned directly in line with array of heat flux sensors. A pocket was left above the plate to allow for the resistance heater, insulation, and electrical connections for the HFA. These were carried out of the tunnel through a section of pipe attached to the cover of the pocket. The model was affixed to thick acrylic on either side which in turn was clamped to the top of the test section to hold it securely in place.

**Flow Analysis**

Figure 4 compares mean velocity profiles within the boundary layer subject to three different flow conditions: Grid A, Grid B, and open tunnel all at a freestream velocity of 10cm/s. Note that the three profiles are nearly identical to each other and the open tunnel case almost perfectly follows the Blasius solution. The proximity of the grid in cases to the Blasius curve indicates that the freestream turbulence has not disturbed the shape of the mean velocity profile in the boundary layer. This shows that freestream turbulence has not caused transition to a turbulent boundary layer. Freestream turbulence has been shown to increase heat transfer coefficient by causing early transition to a
turbulent boundary layer but that is not the case here where the boundary layer remains laminar.

Noting the fit of the Blasius curve to the experimental data allows us to define the boundary layer thickness as:

\[ \delta_{99} = \frac{4.9x}{\sqrt{Re_x}} \]  

(2)

Experimental data falls very close to this prediction along the length of the region of interest. This thickness is shown as a reference in several of the following plots.

\[ U/U_\infty \]

Figure 4 Mean velocity profiles

Heat Flux Signal Analysis

The most obvious first step in comparing heat flux signals to velocity signals is to simply plot them one above the other and see how they look. Figure 5 shows a heat flux signal plotted above the velocity signal measured 1mm above it. The similarity between the two signals is evident, especially in the larger, slower events.

To determine what locations in the flow field exhibit this behavior and had the most influence on the heat transfer, the cross correlation was used. The heat flux signal from the first sensor on the array was correlated with the u and v velocity histories at each point in the flow field. This was done using the cross covariance given in Eqn 3.

\[ RxY(m) = \frac{1}{N} \sum_{n=0}^{N-|m|} (x(n + m) - x\bar{})(y(n) - y\bar{)} \]  

(3)

The cross covariance is identical to the cross correlation except the signals are first mean removed so that the DC component does not bias the level of correlation. To normalize these such that they can easily be compared, they are converted to correlation coefficients. This is done by normalizing the sequence so the autocorrelations at zero lag are identically 1.0. Therefore, 2 signals that give a cross covariance of greater than about .5 are considered very similar.

Figure 5 Mean removed velocity and heat flux signals, velocity taken 1mm from plate directly above sensor

The peak correlation of each point in the flow with the heat flux for each sensor was saved. These peak correlations from sensor 1 are shown as contour plots in Figures 6 and 7. The black line defines the extent of the boundary layer and the dots at the bottom represent the locations at which heat transfer data was collected. The axes are in cm. Note that in Figure 6, there was high correlation near the first sensor (.6-.8 correlation coefficient) when inside the boundary layer. This was not the case outside the boundary layer. This is very different in stagnating flows where much of the high correlation areas fall well outside the boundary layer.

Figure 6 Cross covariance of q" with u'  

This high correlation in the boundary layer does not occur in the correlation with v' (Figure 7) as there appears to be very little correlation anywhere in the vicinity of the sensor.
Models used to predict heat transfer augmentation due to turbulence are often functions of parameters such as integral length scale and \( u'_{RMS} \). One such model was proposed by Nix \(^{32} \) and is given in Eqn. 4. This model describes the increase in heat transfer coefficient over a laminar baseline.

\[
\Delta h_i = \frac{k}{\sqrt{\frac{\pi \alpha}{u'_{RMS}} \Lambda_x}}
\]  

(4)

This model was tested extensively in the stagnation region but not in a laminar flat plate boundary layer as is the case in this study.

Difficulty arises when applying these models because the turbulence parameters change as you move away from the plate as shown in Figure 8. This raises the question at what location do you pick the flow parameters? While properties in the freestream are generally easier to measure, they are also further from the plate making them less likely to strongly influence the heat transfer.

The primary goal of this work is to show how laminar boundary layer heat transfer is affected by turbulence in the freestream. With time-resolved heat flux and surface temperature measurements, the convective heat transfer coefficient was also able to be calculated in a time-resolved manner as shown in Eqn. 5.

\[
h(t) = \frac{q''(t)}{\Delta T_i(t)}
\]

(5)

These values of heat transfer coefficient were then divided by the mean value from the laminar baseline test to give a percent augmentation. Figure 9 shows a plot of these values for the sensor at position 1 for the three cases: open tunnel, Grid A, and Grid B.

It can be seen that, with no grid in place, the fluctuations in \( h \) are very slow and of small magnitude. With grids generating turbulence, the mean of each is raised slightly and the fluctuations are an order of magnitude larger. Note that for the larger of the two grids, \( h \) can fluctuate anywhere from 40% above laminar down to the laminar level. Grid B causes fluctuations from 30% above to 10% below laminar levels.

The effect of the grids on the mean heat transfer coefficient can be seen in Table 2. The values reported for Nix’s model were calculated using conditions at the edge of the boundary layer, which is where the plots cross in Figure 8. This augmentation of up to 15% on the mean is significant but perhaps more importantly is much different from what is seen in the stagnation region. Gifford \(^{29} \) reports mean augmentation of approximately 43% and fluctuations in \( h \) up to 100% above laminar levels for the same turbulence intensities and integral length scales implying a completely different mechanism. They saw the stretching and amplification of coherent structures in the near wall region. It is in this stagnation region in which Nix’s model seems to work. Since the
augmentation seen in this study is much less than that seen in stagnating flows, it is not surprising that the model over predicts the augmentation in boundary layer flow by up to a factor of 10. This shows that freestream turbulence is much less effective at augmenting heat transfer in this case as compared to stagnating flows.

Table 2 Effect of grids on mean convection coefficient

<table>
<thead>
<tr>
<th></th>
<th>Increase in h Over Laminar Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>Sensor 7</td>
</tr>
<tr>
<td>Grid A</td>
<td>15%</td>
</tr>
<tr>
<td>Grid B</td>
<td>5%</td>
</tr>
</tbody>
</table>

To gain insight into the structures that are causing these large fluctuations in the heat flux, the cross correlation was done between each sensor and it’s nearest downstream neighbor, that is sensor 1 with sensor 2, sensor 2 with sensor 3 and so on. This was plotted against the lags which were converted to a distance factor as described by Moss and Oldfield and is shown in Figure 10. This distance factor is defined as the distance that freestream fluid would have moved during the correlation lag time, divided by the spacing of the two gages, as given in Eqn. 6.

\[ Df = \frac{-U_\infty \tau}{\Delta x} \]  

While Figure 10 shows the correlations for the case of Grid A, these cross correlations look identical for the two different grid cases. Any conclusions drawn from Figure 10 would be applicable to the case with Grid B.

These correlations can be used to calculate the velocity of the events responsible for the heat flux spikes by Eqn. 7

\[ V_c = \frac{-1}{Df_{\text{peak}}} \]  

where \( Df_{\text{peak}} \) is the distance factor at which the peak correlation occurs. This could be useful in showing whether the most important events are within the boundary layer or are caused by large freestream structures, moving at the freestream velocity \( U_\infty \), having an immediate impact on the heat transfer.

Note that Figure 10 shows a distance factor of approximately 2 for all nine correlations. This implies that the structures responsible for the heat transfer events are moving at about half the freestream velocity and are therefore most likely within the boundary layer. This differs from the values of 1.3 to 1.5 reported by Moss and Oldfield in their turbulent boundary layer. This implies that the structures that are causing the heat transfer events are moving faster than in the laminar boundary layer case investigated here. This might be due to the steeper velocity profile of a turbulent boundary layer bringing faster structures closer to the plate.

Interestingly, the thickness of the thermal boundary layer crosses the velocity profile at about \( u/U_\infty = 0.5 \). Also, since in turbulent boundary layers the thermal boundary layer is nearly the same thickness as the velocity boundary layer, this crossing would occur in a region where \( u/U_\infty \) was closer to one. This is what was seen in the turbulent boundary layer discussed by Moss and Oldfield. This is an indication that the edge of the thermal boundary layer could represent an area of extreme importance to convective heat transfer.

In order to see how structures affecting the heat transfer convect down the plate, the cross correlation was performed on sensor 1 with all other sensors 2-10. These are shown as a function of lag time in Figure 11. As one would expect, sensors close together give higher correlation with the lag being roughly proportional to the sensor’s distance from sensor 1 divided by half the freestream velocity. Interestingly, \( R_{1,6} - R_{1,10} \) start giving more and more negative correlation when one would expect the correlation coefficient to simply trend towards zero. The reason for this is not understood.

![Figure 10 Cross correlation of heat flux sensor with nearest downstream neighbor](image-url)
Figure 11 Cross correlation between sensor 1 and sensors 2-10

Conclusions

This body of work demonstrates the successful implementation of simultaneous TRDPIV and HFA measurements on a flat plate with a laminar boundary layer. The results demonstrate two important concepts. First, freestream turbulence does play an important role in heat transfer through the laminar boundary layer, both on the mean and on heat flux fluctuations. Second, the mechanism at work is much different than that in stagnating flow with similar freestream conditions. Freestream turbulence caused a 15% increase in mean heat transfer coefficient as well as fluctuations up to 40% above the low freestream turbulence case. Similar conditions in stagnating flow causes an increase in mean h values of 43% with fluctuations up to 100% above laminar due to the stretching and amplification of the coherent structures in the near wall region.

It was also shown that, due to the velocity of the heat flux fluctuations, the structures responsible for these fluctuations were well within the boundary layer. The location in the boundary layer with the appropriate velocity was shown to be at about the thermal boundary layer thickness.

Acknowledgements

The principle author would like to thank several AETHER laboratory members for their help on this work; Andrew Gifford for assistance from plate design all the way to paper layout, and Adric Eckstein and Christopher Weiland for help with TRDPIV analysis. Also, we wish to thank program manager Patrick Phelan for supporting this research under contract number 0423013 with the National Science Foundation.

References