MEASUREMENTS OF THE HEAT TRANSFER COEFFICIENT DISTRIBUTION ON FLAT AND RIBBED SURFACES WITH INTERRUPTED HEATING USING THERMOCHROMIC LIQUID CRYSTALS

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Finally, I want to thank my biggest supporter and light of my life, Kari. Her love gives me the strength to take on some of life's biggest challenges – and succeed!
Abstract

Measurements of the heat transfer coefficient distribution on flat and ribbed surfaces with interrupted heating are presented. One application of this type of thermal boundary condition is the cooling of surface mounted modules in electronic packaging. Heating occurs at the modules, with no heating between the modules. The heat transfer measurements in the present study are made using the heated-coating method with a thermochromic liquid crystal (TLC). The “coating” is vacuum-deposited gold on a plastic sheet, which is mounted on a Styrofoam surface. The gold film is electrically heated to produce the surface heat flux. The surface temperature is measured by capturing color images of the TLC, using the hue technique. These surface temperature plots are transformed into heat transfer coefficient distributions on the surface of the models.

Interrupted heating on the flat surface is obtained by heating strips perpendicular to the freestream flow, with insulated spaces between the strips. The ribbed surface is heated on the top of the ribs only, with insulated unheated cavities in-between.

The results show that, as expected, the local heat transfer coefficient is higher on the heated strips of the flat surface interrupted heating case, than would be present at the same locations with a uniform heat flux. The interruption of the thermal boundary layer at each unheated section allows it to “reset”, thereby causing the higher heat transfer on the following heated section. The ribbed model shows a slight increase in heat transfer on the ribs above that of the flat plate interrupted heating model. The cavities appear to introduce mixing that causes this change. The increase in \( h \) due to the ribs is small, however, when compared to the effect of the interrupted heating.
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<td>A</td>
<td>Area of surface (m²)</td>
</tr>
<tr>
<td>b⁺</td>
<td>68% bias limit in x</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CF</td>
<td>Coverage Factor</td>
</tr>
<tr>
<td>DB</td>
<td>Decibels</td>
</tr>
<tr>
<td>f</td>
<td>Correction factor for resistance per square</td>
</tr>
<tr>
<td>h</td>
<td>Convective heat transfer coefficient (W/m²·K)</td>
</tr>
<tr>
<td>HP</td>
<td>Horsepower</td>
</tr>
<tr>
<td>HSV</td>
<td>Hue, Saturation, Value color space</td>
</tr>
<tr>
<td>I</td>
<td>Current (amps)</td>
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<td>k</td>
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<tr>
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<td>Kelvin</td>
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<td>N</td>
<td>Number of data points</td>
</tr>
<tr>
<td>NaN</td>
<td>Not-a-Number (Matlab uses)</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>qcond</td>
<td>Heat loss due to conduction</td>
</tr>
<tr>
<td>qₑ</td>
<td>Surface heat flux due to electrical heating (W/m²)</td>
</tr>
<tr>
<td>qᵣ</td>
<td>Radiative heat flux due to incident lighting (W/m²)</td>
</tr>
<tr>
<td>Q</td>
<td>Power (W)</td>
</tr>
<tr>
<td>R'</td>
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</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>RGB</td>
<td>Red, Green, Blue color space</td>
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<tr>
<td>R30C10W</td>
<td>Liquid crystal having a red start temperature of 30°C, with a bandwidth of 10°C</td>
</tr>
<tr>
<td>SEE</td>
<td>Standard Error of Estimate</td>
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\( S_x \) 68% precision limit in \( x \), or standard deviation in \( x \)

\( T_w \) Freestream air temperature

\( T_{LC} \) Surface temperature (of liquid crystal)

\( w \) Width of surface (m)

\( x \) Characteristic length used for \( Nu, Re \) calculations

**Greek letter symbols**

\( \varepsilon \) Emissivity of surface

\( \sigma \) Stefan-Boltzmann constant \( (5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4) \), standard deviation, in Equations (5) and (6)

\( \xi \) Unheated starting length (m)

**Subscripts**

\( \infty \) Freestream air property

\( LC \) Liquid crystal

\( \text{cond} \) Conduction

\( \text{conv} \) Convection

\( e \) Electrical

\( l \) Incident lighting

\( \text{rad} \) Thermal radiation
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Introduction and Background

There have been many studies of the heat transfer coefficient distribution on flat and ribbed surfaces. In most (if not all) of these studies the surfaces were at a uniform temperature or had a uniform surface heat flux, perhaps due to electrical heating. In these cases, a thermal boundary layer builds, resulting in a decrease in the heat transfer coefficient along the surfaces. In the present study, a non-uniform or interrupted heating is used on the surfaces. This causes an interruption in the thermal boundary layer, significantly changing the heat transfer. One application of this condition is in electronic component packaging, where transistors, microchips, and other modules are mounted on a printed circuit board (i.e., surface mounted modules). In these cases the heating is usually limited to the components, with the board acting like an insulated surface.

There are several recent attempts to model flow and heat transfer with this type of interrupted heating. For example, Ang and Yap (1998) numerically simulated the ribbed wall flow condition for laminar flow in a channel. They considered various inter-module spacing, channel heights, and heights of implanted barriers used to augment heat transfer. They found that the heat transfer rate (and Nusselt number) increased significantly near the leading edge of each module as inter-module spacing is increased. They also found that reduction in the channel height at a fixed flow rate results in higher heat transfer rates, as well as increased pressure drop across the modules. In another study, Hacker and Eaton (1997) investigated the effect of an arbitrarily varying thermal boundary condition on the convective heat transfer in a backward-facing step flow. Their results show that, in the separated flow, the effects of localized heating are felt only a short distance upstream and downstream, and the local heat transfer is less sensitive to thermal boundary conditions than in the laminar case.

In the present study, heat transfer coefficient distributions were investigated for three cases. First, a turbulent boundary layer over a flat plate with uniform heating is studied. The turbulent boundary layer is achieved by tripping the flow 0.1 m upstream of the model.
The second case involves a turbulent boundary layer over a flat plate with interrupted heating. The heating takes place on sections (i.e. strips) mounted perpendicular to the flow, with unheated strips between the heated ones. Three separate widths of heated and unheated strips are studied. They are:

- Spacing #1) 38 mm heated / 25 mm unheated
- Spacing #2) 25 mm heated / 38 mm unheated
- Spacing #3) 16 mm heated / 47 mm unheated.

For the third case, measurements are made of heat transfer from a ribbed model with a turbulent boundary layer. The model is heated on the top surface of the ribs only, with unheated insulated cavities between the ribs. The rib width and inter-rib spacing were of the same size as one of the flat plate interrupted heating models (spacing #1).

All three cases are studied at three flow velocities: 10 m/s, 14.2 m/s, and 20 m/s. It is hoped that testing these three models provides an interrupted heating database for future experimental data and numerical code comparisons.

A. Turbulent Boundary Layer over a Flat Plate with Uniform Heating

The heat transfer due to laminar and turbulent boundary layers over a flat plate has been investigated in great detail. Although more complicated than the laminar flow case, a turbulent boundary layer has been fully characterized by the early work of Reynolds, and later by many others. Kays and Crawford (1980) summarize results for both laminar and turbulent boundary layers. In both cases, the nature of the thermal boundary conditions is important in characterizing the flow. Maintaining a laminar flow over models in a wind tunnel is difficult. The boundary layer trips easily and not uniformly. Therefore, it was decided to purposefully trip the boundary layer upstream of the models in the present study, to obtain a constant turbulent boundary layer in the region of interest. The heat transfer solution for a uniform temperature thermal boundary condition in a turbulent boundary layer is given by the following equation (Incropera, Dewitt 1990):

\[ Nu_x = 0.0296 \cdot Re_x^{4/5} \cdot Pr^{1/3} \]  
for \(0.6 < Pr < 60\)  
(1)
The uniform heat flux boundary condition yields the following analytical solution, which is approximately 4% greater than the uniform temperature solution:

\[ \text{Nu}_x = 0.0308 \cdot \text{Re}_x^{4/5} \cdot \text{Pr}^{1/3} \] (2)

In the present study, we supply a uniform heat flux to the surface via an electrically energized gold film, so Equation (2) above is appropriate. However, this solution applies for a uniform heat flux that starts at the same location as the velocity boundary layer. Because the boundary layer is tripped 10 cm upstream of the leading edge of the plate, we have the special case known as an unheated starting length, where \( T_s = T_w \).

Figure 1, below, illustrates the difference in the velocity and thermal boundary layers for this condition.

This situation requires use of the following formula (Incropera, Dewitt 1990):

\[ \text{Nu}_x = \frac{\text{Nu}_x |_{\xi=0}}{[1 - (\xi / x)^{1/10}]^{1/9}} \] (3a)

where \( \text{Nu}_x |_{\xi=0} \) is found by Equation (2)

Determining the unheated starting length, \( \xi \), in Equation (3a) is not as clear as it may seem. Since \( \xi \) is
measured from the start of the turbulent boundary layer to the start of the constant heat flux boundary condition, it is important to know where the turbulent boundary layer begins. In this study, a 3 mm diameter brass dowel is placed 10 cm upstream of the leading edge of the heated plate, thus, we know that \( \xi \) is on the order of 10 cm. By convention, the location of the start of the turbulent boundary layer must be further upstream than the trip, as the boundary layer can not have zero thickness at the location of the trip.

Heat transfer coefficient is calculated using the Nusselt number results from Equations (2) and (3a), and the following equation:

\[
Nu_x = \frac{h \cdot x}{k}
\]  \hspace{2cm} (3b)

where \( x \) is shown in Figure 1

\( k \) is thermal conductivity of air (W/m-K)

B. Turbulent Boundary Layer over a Flat Plate with Interrupted Heating

In the second case, the thermal boundary layer is allowed to grow for a distance, \( x \), then begins to “reset” by the absence of any surface heat flux: i.e., an interrupted heating condition. The flat plate model above is modified so that heating occurs only on strips perpendicular to the flow direction, with an unheated strip immediately after each heated strip. In effect, the flow encounters a series of unheated starting length problems, with the thermal boundary layer growing again at the start of each heated section. In this case, the freestream air temperature (as it reaches the leading edge of each heated strip) is warmer for each successive strip due to upstream heating that has already occurred, until a steady, periodic condition is reached. The author is not aware of a theory that provides a solution for the interrupted heating case. Results are presented for three different lengths of flat plate interrupted heating in an attempt to characterize the thermal boundary layer growth and heat transfer coefficient profiles for this special situation.
C. Turbulent Boundary Layer over a Ribbed Surface with Interrupted Heating

Heat transfer from ribbed surfaces has been studied often. Most, if not all of the studies, however, have heating from the ribs as well as the cavities. Here, we investigate the case where the heating occurs on the top surface of the ribs only, with unheated insulated cavities in-between. The rib tops are aligned with the tunnel wall, so the first heated strip encounters the freestream air in much the same way as the flat plate model (see Figures 2-4). The ribs are 38 mm wide and have bordering channels that are 19 mm deep and 25 mm wide. These channels promote circulation and mixing in the velocity boundary layer. Therefore, it is expected that the ribs would do a more effective job of resetting the thermal boundary layer, causing higher heat transfer when compared to the heat transfer on successive interrupted heating sections of the flat plate model.

The ribbed flow condition has practical relevance to electronic cooling issues, as the geometry and thermal boundary conditions are similar to surface-mounted modules (chip arrays) on a printed circuit board. Recently, there is a trend toward higher densities of modules in electronic packaging. Researchers are working toward better thermal management, thereby increasing reliability and performance levels of the components. Bar-Cohen & Witzman (1993) noted that a relatively small 10°C -20°C increase in chip temperatures could lead to a 50% drop in component reliability levels. Others have performed experimental work to characterize the two-dimensional flow field, namely Sparrow et al. (1982), Kang et al. (1990), and Wirtz and Chen (1992). The latter group performed experiments in the laminar-transitional regime for air flowing over a two-dimensional array of rectangular ribs in a rectangular duct. The Reynolds number range, based on the approximate hydraulic diameter (2H) was 2000 < Re < 7500. They found that the heat transfer increased with increasing Re, due to an increase in the effective shear stress along the ribbed wall.

Numerical work has also been done in this field. In addition to the work of Ang and Yap (1998) discussed earlier, Agonafer and Moffat (1985) used a commercial finite-control-volume code, PHOENICS, to simulate fluid flow and heat transfer characteristics of electronics modules. Their heat transfer coefficient results agreed with experimental data in the fully developed region to within 8%.
II Experimental Method and Apparatus

A. Model Design and Fabrication

Diagrams of the flat plate with uniform heating, as well as the flat plate and ribbed models with interrupted heating are shown on the following pages. For the flat plate with uniform heating, the entire 0.42 m length is covered with gold film and is electrically heated. For the interrupted heating models, the heating takes place only on the gold film regions specified.

Several different materials were considered for the flat and ribbed models used in these experiments. Dow blue Styrofoam was chosen because of its ease of machining to exact specifications, insulating properties, and gold film mounting characteristics. Rough-cut machining of the Styrofoam pieces was performed in the UC Davis Student Machine Shop, using a rotary table saw. Rough edges were sanded by hand using fine grain sandpaper, as were the upper surfaces upon which the gold film was mounted.

Both models are constructed of two pieces of Styrofoam: a 1.5 in (38 mm) thick piece to span the entire width and height of the rear wind tunnel test section frame, and a \( \frac{3}{4} \) in (19 mm) piece used to construct the flat plate or ribbed sections, as appropriate. For an average surface temperature of 40°C, at the upper limit of our liquid crystal temperature range, it was determined that a rear section thickness of 38 mm would limit back-side conduction losses to less than 2%, which was deemed acceptable. The 19 mm section was chosen for the top side of the model because this thickness ensured a smooth match between the inside wind tunnel wall and the model surfaces to minimize leading-edge disturbances.

After sanding, the upper model surfaces were sprayed with 3M Super-77 Spray Adhesive and allowed to dry for approximately 2 minutes. The gold film, which had been cut to exacting specifications, was then carefully positioned on each glued surface. An artist’s rubber roller was used to smoothly apply the gold film to the Styrofoam surface and eliminate air pockets.
Figure 2 Flat Plate Uniform Heating Model, Top View

Figure 3 Flat Plate Interrupted Heating Model, Top View
To provide the heat flux to the surface, copper tape (0.038mm thick, 6.35mm wide) is connected to the edges of the gold film surface. An HP 6286A DC power supply is connected to the copper tape with large diameter, 14 gauge and 16 gauge, low resistance wire. The wire is soldered to the copper tape, and both the flat plate interrupted heating sections as well as the ribbed model heated sections are wired in parallel. To ensure better electrical contact between the copper tape and gold film, the juncture is painted with GC Electronics silver print and allowed to dry overnight. Flat black (tempera) paint is then applied to the silver print to prevent excessive light reflection from the model lighting into the camera.

A background coat of Hallcrest BB-G1 black paint is sprayed onto the gold film, and allowed to dry overnight. A microencapsulated Thermochromic Liquid Crystal (TLC) is then applied on top of the black paint.
B. Wind Tunnel

Aerolab built the wind tunnel used in this series of tests. It is an open circuit tunnel with a test section that is 12 inches square and 24 inches long. The test section has an aluminum floor, with hinged sides and a removable top made of Plexiglas. The 10 HP motor in this wind tunnel is capable of producing a maximum air velocity of 65 m/s. The tests were conducted at speeds of 10 m/s, 14.2 m/s, and 20 m/s. Although the wind tunnel is equipped to measure test section airspeed via onboard pressure ports, the author chose to install a Pitot-static probe and measure the velocity directly, using an inclined manometer.

Several modifications were made to the tunnel to permit more accurate velocity and temperature measurements, to support the precision required in this experiment. These modifications included replacing the Plexiglas top with a wooden replica through which a Pitot-static tube was inserted for accurate velocity measurement. Also, the force balance was removed, and the tunnel floor sealed with black duct tape to prevent light reflection and air leaks through the perforated surface. The top of the tunnel received the same covering as the bottom, to ensure symmetrical light reflection from both surfaces. The front Plexiglas door was held closed by the lighting apparatus, and the back Plexiglas door removed to enable installation of the Styrofoam models, which are discussed in the next section. A single screw hole at the vertical midpoint of the tunnel wall was opened up to permit installation of a thermistor probe into the freestream airflow. This probe was located approximately 0.5 m downstream of the test section, and extended about 0.15 m into the freestream flow. This location ensured stable and accurate freestream air temperature measurements for the duration of the testing. The top-down diagram on the following page shows the placement of the thermistor and Pitot-static probes in the wind tunnel, as well as lighting and camera positions in relation to the test model.
C. Data Reduction Equation

For these tests the local heat transfer coefficient is calculated using a surface energy balance on the models:

\[
q_{\text{conv}} = h(T_{LC} - T_{\infty}) = q_e + q_l - q_{\text{rad}} - q_{\text{cond}} \quad (4a)
\]

Neglecting the conduction losses through the styrofoam, expanding the radiation term and solving for the convective heat transfer coefficient yields:

\[
h = \frac{q_e + q_l - \varepsilon \cdot \sigma \cdot (T_{LC}^4 - T_{\infty}^4)}{(T_{LC} - T_{\infty})} \quad (4b)
\]

where
- \(q_e\) = heat flux from electrical power in (W/m\(^2\))
- \(q_l\) = heat flux from the incident lighting (W/m\(^2\))
- \(\varepsilon\) = emissivity of model surface
- \(\sigma\) = Stefan-Boltzmann constant
\( T_{LC} = \) temperature of the liquid crystal surface  
\( T_\infty = \) temperature of the freestream air

Note that the freestream temperature in Equation (4a) is a total temperature. Since we are working with flow at low Mach number, it is assumed that the temperature sensed by the thermistor is approximately equal to the total temperature. Therefore, Equation (4b) contains the term \( T_\infty \).

D. Gold Film (Heat Flux Term)

To produce the surface electrical heating (\( q_e \) in Equation (4)), it is necessary to supply a known power to the surface of the models in a uniform manner. Cortaulds gold film is used for this purpose. The gold film is a 0.007" (7 mil) thick sheet of flexible Mylar backing, with a very fine layer of vacuum-deposited gold on the upper surface. The resistance of the gold film is specified in terms of a resistance per square (\( R' \)). This is a common way to express the resistance of surface coatings, and is simply equal to the resistance of any size square sample. The actual resistance of an arbitrary rectangular piece is proportional to its length and inversely proportional to its width. The resistance of the gold film on the flat plate model, as well as the resistance of the film on the ribbed model sections, was measured. The resistance per square was found to be 2.42 \( \Omega \) at 24°C. Since the resistance per square is commonly expressed in terms of its value at 40°C (\( R_{40} \)), we must scale this value to account for the difference in temperature. Baughn et al. (1985) found the temperature coefficient of the gold coating to be 0.0011 per °C. The resistance of our coating at 40°C is: \[ R_{40} = 2.42 \Omega \times (1 + 0.0011 \times (40°C - 24°C)) = 2.46 \Omega, \] which agrees well with previous tests of samples using this particular gold film (Butler, 1995). When current is passed through the gold film via electrodes attached to the edges, the material behaves in a predictable manner, exhibiting surface heating proportional to the power applied to the film.
E. Surface Temperature Measurement using TLC's ($T_{LC}$ term)

The models' heated surfaces were coated with Thermochromic Liquid Crystals, which change hue with temperature. Hallcrest BM/R30C10W/C17-10 TLC's were used, with a red start temperature of 30°C. This liquid crystal had a bandwidth of 10°C. Liquid crystal selection is outlined in Appendix A. Images are captured, and hue data converted to temperature using 6th order temperature/hue calibration curves. Details of the liquid crystal calibration procedures are contained in Appendix B, along with calibration curves for the seven specific plate areas used.

F. Data Collection

Two primary concerns effected the development of the experimental plan. First, we had to ensure the models reached steady state with the environment. That is, to ensure that the power input was being balanced by the convective heat transfer from the surface, and the liquid crystal hue was not changing over time. The figure below shows mean plate hue over time for a representative flat plate run at a high power setting. Hue increases for times less than 10 minutes, after which point the hue fluctuates about a constant value and the test conditions have reached steady state. Therefore, each test condition was stabilized for a minimum of 10 minutes before an image was acquired.
Second, the test plan had to ensure that hysteresis in the liquid crystal would be avoided. Prior to its use in this series of tests, the R30C10W liquid crystal was tested for calibration curve performance and hysteresis occurrence. It was found that this particular liquid crystal has a bandwidth very close to the advertised 10°C, and that hysteresis on cooling could be avoided by keeping the temperature below 52.5°C. Because the upstream portion of our model experiences higher heat transfer than the downstream portion, the temperature of the downstream sections can be much higher than those toward the leading edge. Consequently, runs progressed from low power (and low temperature) to high power. Care was taken to ensure the trailing edge did not exceed the upper limit of the color play, or about 40°C, thereby avoiding hysteresis effects.

For each model tested, three or more images were captured at different power settings, at each of three freestream velocities, for a minimum of nine images per model. The wind tunnel was allowed to stabilize
after selecting each new test speed. Power, freestream velocity, and freestream temperature were monitored during the course of each run.

Images were captured using a 3-chip Sony XC003 CCD camera. This is connected to a Matrox Meteor RGB framegrabber card installed in a Micron 166 MHz PC with 128 MB of RAM. Each image is captured as a 3-D matrix of red, green, and blue values. The image size is 480×640 pixels, thus the matrix is 480x640x3 (approximately 0.9 MB). Settings used for the camera are listed below.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>+0 DB</td>
<td>H. Phase</td>
<td>00</td>
</tr>
<tr>
<td>Color Temperature</td>
<td>5600 K</td>
<td>Gamma</td>
<td>OFF</td>
</tr>
<tr>
<td>White Balance</td>
<td>MANUAL</td>
<td>DTL</td>
<td>OFF</td>
</tr>
<tr>
<td>Red/Blue Gain</td>
<td>-027/+042</td>
<td>G. Sync</td>
<td>ON</td>
</tr>
<tr>
<td>Shutter</td>
<td>OFF</td>
<td>Genlock</td>
<td>NORMAL</td>
</tr>
<tr>
<td>Frame/Field</td>
<td>FRM</td>
<td>D-SUB</td>
<td>VBS</td>
</tr>
</tbody>
</table>

A Macbeth Color Checker color rendition chart was used to adjust the balance of the color rendition system used in these experiments. Since the reflected light is a function of the incident light's spectral characteristics, it may be necessary to modify the camera settings whenever the light source is changed. To perform this adjustment, several of the Color Checker's gray squares were captured using the default settings on the RGB camera. Then, the red and blue gains were adjusted (green cannot be separately adjusted) so the average red and blue components for each square were equal to the respective green component for each square (any true gray has equal amounts of R, G, & B). These settings, Red -27, Blue +42, were used throughout all test runs. The same lights and UV filters were used for all measurements. Sufficient lighting was present to preclude the need for an overall gain setting. Instead, the camera iris was reduced to produce peak R, G, or B values under the 255 maximum for this 8 bit measurement. This iris setting remained constant for all runs as well.
Ill Data Reduction - Image Processing

Image processing is performed using MATLAB 5.1 and its Image Processing Toolbox. An image is captured for the entire flat plate or ribbed model with the RGB 3-chip camera. This image is a 3-D matrix of R, G, and B components, each of which are 480x640 pixels. The R, G, B image is converted to Hue, Saturation, and Value using a Matlab routine. The hue component is processed into temperature using a Temperature/Hue calibration curve. In order to account for the effect of changes in lighting angle across the plate, seven different calibration curves mentioned previously were used. Each curve corresponds to one of the heated ribs and its neighboring unheated section. In the span-wise direction, each image section is 57 pixels high (approximately 4 cm). Thus, our new image is 57x640 pixels, and is the same area used in both the calibration runs and the model image processing.

Matlab m-files were written to process the images, and contain 17 separate steps used to read the images, analyze the data, and output to a file. These image processing steps are detailed below, and are highlighted in the six page m-file code that comprises Appendix H.

Step 1. Read in images (each at a different power setting) for a given tunnel airspeed.
Step 2. Crop image from 480x640 to 57x640, corresponding to 3.8 cm x 42 cm.
Step 4. Considering one column at a time, calculate the mean hue and standard deviation in hue.
Step 5. Apply Chauvenet's Criterion to the column data and recalculate mean hue and standard deviation in hue. (For a more complete description of Chauvenet's Criterion, see Appendix E or ref. 12)
Step 6. If hue falls outside of calibration range (0.20 to 0.63), make it a NaN.
Step 7. Define the areas of interest - where the leading edge is, where the ribs and spaces lie on the plate.
Step 8. Load in the 6th order polynomial calibration curves and SEE data for each of the 7 areas.
Step 9. Convert hue to temperature using the calibration data specific to each area.
Step 10. Calculate the 68% uncertainty in temperature.
Step 11. Input power setting, \( q_e \), and freestream air temperature, \( T_{\infty} \), for the specified runs.
Step 12. Input uncertainty analysis data – bias and precision limits for each of the elemental source in h.

Step 13. Calculate h profile from temperature profile.


Step 15. Compare h values at each column position, for different power settings. Choose the h that has the lowest associated uncertainty.

Step 16. Calculate relative uncertainty in h and save to output matrix.

Step 17. Output results (h profile and uncertainty for each data point) to a file for use in MS Excel.

Calculating the uncertainty in h is an integral part of the data reduction. For details of the uncertainty analysis, the reader is directed to Appendix E.
**IV Results and Discussion**

A. Flat Plate

One of the captured RGB images from the flat plate (uniform heating) model is shown in Figure 7, below. The leading edge (red color) is at the lowest TLC temperature (near 30°C), the green region (middle) is at higher temperatures, and the blue (trailing edge) is at the highest temperature (near 40°C). It is clear that the left-to-right flow is cooling the plate more at the leading edge and less toward the trailing edge. The plate shows good spanwise temperature uniformity and a temperature gradient in the streamwise direction.

![Figure 7 Flat Plate RGB Image](image)

The performance at three different velocities was studied: 10 m/s, 14.2 m/s, and 20 m/s. An unheated starting length was present due to the boundary layer trip installed 10 cm upstream of the flat plate heated model. This caused a turbulent boundary layer to form, allowing comparison to turbulent theory instead of working with the difficult-to-control transitional case. The effective unheated starting length was estimated, since the precise starting point of the turbulent boundary layer was unknown. We would expect
the unheated starting length to be greater than the distance between the trip and the model, as the turbulent velocity boundary layer can not have zero thickness at the location of the trip. An estimated unheated starting length of 0.2 m matched experimental results closely, and is used in the theoretical curves shown in Figure 8, as well as in the flat plate data reduction found in Appendix I.

The heat transfer results for the flat plate runs at 10 m/s, 14.2 m/s, and 20 m/s are shown in Figure 8. They are compared to flat plate theory for a turbulent boundary layer, with a uniform heat flux thermal boundary condition. Each point on the curves represents the mean temperature value of a column of pixels, which is converted to heat transfer coefficients (as described in Section III). Each column is 0.68 mm wide; so the entire plate length of 0.42 m is represented by a smooth curve of 620 column values. For clarity, only every 8th point is shown on the flat plate graph.
In both cases, agreement was quite good between experimental results and theory, especially in the region between 0.05 m and 0.2 m. The forward region (under 0.05m) is experiencing several phenomena worth mentioning. The boundary layer is being artificially tripped to turbulence, with wall Reynolds numbers in this forward region of $1.6 \times 10^5$ or less. This is below that normally associated with transition to a turbulent boundary layer. Hence, turbulent boundary layer theory is unable to provide a good match. Additionally, this forward region is near the leading edge of the Styrofoam insulation behind the gold film, so end effects (conduction losses) cause the surface temperature to be lower than in a perfectly insulated case. Also, due to the steep temperature profile (and correspondingly steep h profile) near the leading edge, high conduction between neighboring pixels lowers the temperature of adjoining pixels. Both influences cause the h profile to appear higher than it actually is, which helps explain the variance near the leading edge.
Nevertheless, the results support the validity of the experimental method performed. For the region of the flat plate past 0.05 m, the experimental results for the 10 m/s case are within 9% of theoretical predictions, while the 14.2 m/s and 20 m/s results are within 8% and 5%, respectively. The computed uncertainties in $h$ over the entire plate length are 4.1%, 4.1%, and 3.9%, respectively. The close agreement with flat plate theory allows us to move forward with further tests. We are confident that the temperatures sensed and the convective heat transfer profiles computed are reasonably accurate.

Furthermore, the results for the three flow velocities show proper scaling. Since $h \propto \text{Nu}$, and $\text{Nu} \propto \text{Re}^{0.8}$ from Equation (2), we expect $h \propto \text{Re}^{0.8}$. As the velocity increases from 10 m/s to 14.2 m/s, the $h$ values should increase 32%, while the 20 m/s experimental data should show an increase of 74% over the 10 m/s data. In fact, these theoretical increases are closely matched by the experimental data in Figure 8. Actual increases are 33% and 79% for the two velocities.

For the remaining discussion of results, only the 10 m/s experimental data is shown for simplicity. The results from the 14.2 m/s and 20 m/s tests are contained in Appendix F, Effect of Velocity. Additionally, a discussion on the effect of power setting is contained in Appendix G.

**B. Flat Plate with Interrupted Heating**

Several different heated and unheated lengths were studied in the flat plate models with interrupted heating. First considered is the model with similar spacing to the ribbed model: 38 mm heated sections with 25 mm unheated sections. An image from one of the runs is shown below, at a heat flux setting of 709 W/m².
To better see how the $h$ profile changes, we can compare the first interrupted heating model to the uniformly heated flat plate model. The following graph shows the 10 m/s experimental results for this modification:
As is expected, the $h$ profile is high at the leading edge, like the flat plate model. The absence of heat flux in the unheated regions, however, causes the thermal boundary layer to begin to "reset" and we see a similar $h$ profile repeated on each successive heated section. Although the thermal boundary layer "resets", the freestream air is warmer when it arrives at the second heated strip due to the upstream heating that has occurred. There is evidence of this in the lowest heat transfer coefficients on the trailing edge of each heated section. The minimum $h$ value continues to decrease and stabilizes by about the 5th heated section. This suggests that the profile reaches a steady-state condition, where the freestream air temperature is in balance with the heat transfer from the plate, and the $h$ profiles become self-similar. Similar results have
been seen in the numerical work on this subject (Ang, Yap 1997). The sharp upturn in the h profile at the trailing edge of each heated section may be an artifact of wall conduction and should be ignored.

For this case and those remaining, it is interesting to establish how much of an increase in h exists, when compared to the flat plate uniform heating model. For comparison purposes, we choose to evaluate the average h value at the 5th heated section (since stability occurs after this) and compare it to the flat plate data at the same location. For this case, on the 5th heated section, there is a 38% average increase in h. It should be noted that the average is higher on the heated strips, but the overall average is lower, due to the absence of any heat transfer on the unheated strips.

We next look at the second spacing tested in the study of the heat transfer coefficient over a flat plate with interrupted heating. This modification involved decreasing the heated length to 25 mm, while increasing the unheated section length to 38 mm. Figure 11, below, shows the experimental results for 10 m/s.
As in the previous case, we see a steep h profile for each successive heated section, with the solutions becoming self-similar after approximately 5 ribs. Again, the trailing edge of each section shows some bleed-off of the temperature into the non-heated sections, causing an artificial rise in the heat transfer coefficient over the last 5-10 columns. Because the areas of non-heating are larger, the thermal boundary layer resets more than in the previous case, hence, the h profile is steeper, with higher maximum h values and higher average h values across each heated section. When compared to the uniformly heated model, the average h on the 5th heated section increases approximately 64%.
Finally, the heated strips are reduced in size to 16 mm, with a corresponding increase in the size of the unheated strips to 47 mm. The following figure shows a typical image, at 10 m/s with a heat flux setting of 791 W/m².

Figure 12 RGB Image of Flat Plate Interrupted Heating, Spacing #3

Figure 13 on the following page shows the experimental results for Spacing #3 at 10 m/s.
In this example, the effect of shortening the heated section and lengthening the unheated section is amplified. The $h$ profile is steeper, and the maximum $h$ values at the leading edge are higher. A steady-state heat transfer profile appears to take shape at the 5th heated section as before. Trailing edge bleed-over into the non-heated sections are observed here as well, with the artificially high $h$ values in the 5 columns aft of the trailing edge of the heated sections.

The average $h$ on the 5th heated strip is nearly double that of the uniform heating case (93%) for this spacing at 10 m/s.

Figure 13 Comparison of $h$ vs. $x$ for Flat Plate Interrupted Heating and Uniform Heating, Spacing #3
C. Ribbed Model

The ribbed model studied has heated/unheated sections similar to one of the flat plate interrupted heating models (spacing 1). The heated ribs are 38 mm wide, with unheated channels between the heated sections that are 25 mm wide. The channels are recessed 19 mm below the top surface of the ribs. This allows air to circulate in the cavities between the ribs, cooling and effecting the thermal boundary layer. An RGB image from the 10 m/s data set is presented below. Notice the lack of color bleed to the neighboring unheated sections, and the distinct color play that occurs on each heated rib.

![RGB Image of Ribbed Model](image)

Figure 14 RGB Image of Ribbed Model

The next figure shows the heat transfer coefficient distribution over the ribbed model for 10 m/s flow. Notice the same repeated steep $h$ profile as seen in the interrupted heating flat plate models.
The downstream edge of each rib shows an upturn in the $h$ profile as well. Again, this is caused by conduction losses. These losses occur in the pixels near the edge of the Styrofoam insulation, much as they did in the flat plate model near the leading edge. Due to these losses, the surface is cooler there than in a perfectly insulated case and the computed $h$ profile shows an upturn, larger than actually exists. Each column is 0.68 mm wide; end effects are seen in approximately the last 8 columns, or 5 mm of the 38 mm rib width.

The average $h$ increase on the 5th heated rib, when compared to the flat plate uniform heating model, is 57%.
It is interesting to compare the ribbed model heat transfer results with the flat plate interrupted heating (spacing 1) results. The dimensions of the heated and unheated sections are the same. Therefore, the comparison shows the effect of the cavities on heat transfer. As stated previously, we would expect the ribs to increase circulation and mixing of the thermal boundary layer, thereby bringing cooler air to the surface, and increasing heat transfer when compared to a surface without the ribs. In fact, this does occur. The following figure shows a comparison between the flat plate interrupted heating and the ribbed model results. Heat transfer is 13% higher along the entire profile for the ribbed model, apparently due to the increased flow mixing which promotes lower thermal boundary layer temperatures and higher heat transfer coefficients. Note that the two h profiles are very similar in shape and are simply shifted higher for the ribbed case (heated sections 2 through 7).

![Figure 16 Comparison of h vs. x for Ribbed and Flat Plate Interrupted Heating](image-url)
Although we do not place much confidence in the heat transfer results near the leading edge of the flat plate due to end effects and the breakdown of our turbulent boundary layer heat transfer theory, it is interesting to note the difference between the ribbed model and flat plate interrupted heating cases on the first heated section. The ribbed model heat transfer is actually lower than the flat plate interrupted heating case. This is probably due to the flow dynamics occurring at the leading edge of the plate versus those occurring at the first rib, where each meets the wind tunnel wall. Perhaps the juncture with the flat plate was smoother, and the ribbed model caused some separation to occur.

This section has focused on results obtained for the 10 m/s freestream velocity condition. Data was also collected for 14.2 m/s and 20 m/s test conditions, and can be found in Appendices F and G. This data agrees well with the 10 m/s data, with only a few exceptions.

The following table summarizes the increase in average \( h \) value at the 5th heated section, when compared to the flat plate uniform heating case.

**Table 2 Summary of \( h \) profile results**

<table>
<thead>
<tr>
<th>Model Configuration</th>
<th>Flow Velocity, m/s</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing #1</td>
<td>10</td>
<td>38</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing #2</td>
<td>10</td>
<td>64</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing #3</td>
<td>10</td>
<td>93</td>
</tr>
<tr>
<td>Ribbed Model</td>
<td>10</td>
<td>57</td>
</tr>
</tbody>
</table>
V Conclusions

Studies of local convective heat transfer were conducted for three cases with a turbulent boundary layer. These studies yielded the following results:

- For a flat plate with uniform heating, good agreement (better than 10%) was found between flat plate uniform heat flux theory and the experimental results. The small difference is easily explained by the experimental uncertainty and the lower than normal Reynolds numbers for the tripped turbulent boundary layer.

- For a flat plate with interrupted heating, the heat transfer was found to be significantly higher on each heated strip, compared to the uniform heating case. As the heated sections become narrower, (and the non-heated sections wider), the h profile increased further.

- For a ribbed model, the heat transfer from the top of the ribs is also higher than that for the flat plate with uniform heating. It is slightly greater than the heat transfer over the flat plate with interrupted heating (same heated and unheated lengths). The cavities enhance flow circulation, increasing heat transfer from the top surface of the ribs.

- The studies show that for a known surface heat flux, the heat transfer is higher, and the corresponding temperature is lower, for surface-mounted modules than would be predicted with flat plate uniform heating theory. Interruption of the heating has a significant effect on the local heat transfer, far more than the rib/cavity effects.

- The heated-coating method with TLC's proved to be an excellent means of mapping the local heat transfer coefficient data.

- The uncertainty in h for all three models studied, with a 95% confidence level, is approximately 5%.

- The benefits of future studies in this field are clear: better heat transfer in electronic packaging and other applications, and reduction of problems caused by high operating temperatures.

- It is hoped that numerical calculations can be performed for comparison with the specific cases studied here. This would help validate these results, as well as help advance the capabilities of predicting interrupted thermal boundary condition heat transfer results on flat and ribbed surfaces.
VI References


Appendix A: Liquid Crystal Selection

Hallcrest BM/R30C10W/C17-10 TLC's were chosen for this application, for several reasons. First, broadband liquid crystals allow visualization of a wide range of surface temperatures. Because the TLC's used in this application have a ten degree bandwidth, a wide range of temperatures and heat transfer coefficients can be captured in one image with a particular power setting. This is useful, as both the data collection and data reduction are simplified. The following graph shows several different liquid crystals and their corresponding h ratios, for ambient temperatures of 25°C-30°C. The h ratio shown is the ratio of the maximum measurable h to the minimum measurable h.

Figure 17 Measurable h ratios for Several TLC's vs. Ambient Temperature
The reader will note that the broad-band TLC's, when compared to the narrow-band ones, produce the largest ratios. Additionally, lower "red start" temperatures increase the h ratio even more, and are desirable.

A red start temperature of 30°C was also beneficial in affording lower uncertainties in our results. From the previous work of Baughn et al. (1998), calibration of wide band liquid crystals which avoids high temperatures and hysteresis can achieve uncertainties in temperature on the order of 4% of the useful range. Using this predicted value of surface temperature uncertainty, and the anticipated freestream air temperature of 25°C to 31°C in the wind tunnel lab, the following equation was used to determine the "relative uncertainty" in surface temperature difference.

\[
\frac{U_{Surface}}{(T_s - T_w)} = 0.04 \cdot \frac{(T_{High} - T_{Low})}{(T_s - T_w)}
\]  

(5)

Estimating a color play range of 32°C to 38°C for the R30C10W TLC, a relative uncertainty of 5% or less is possible with lab temperatures as high as 27°C. Figure 18 shows this relative uncertainty for a range of ambient temperatures.
Minimizing uncertainty for all measured temperatures at high ambient temperatures is a priority; therefore, the R30C10W TLC provided low uncertainty levels along with a large measurable h range. Another liquid crystal which performed well in terms of uncertainty and h range is the R31C15W. The 10W crystal was chosen over the 15W liquid crystal because of the author’s experience with 10W liquid crystals, and because of the anticipated range of surface temperatures that would be present during testing.
Appendix B: Liquid Crystal Calibration and Calibration Image Processing

Calibration of the Hallcrest BMR30C/10W liquid crystal began with a series of tests conducted to determine its hysteresis characteristics. The tests were conducted alongside several other liquid crystals in a separate calibration apparatus. This apparatus was used previously in such tests as described in the paper, “Hysteresis and Uncertainty of Thermochromic Liquid Crystal Temperature Measurement Based on Hue” (Baughn et al. 1998). The tests revealed, as previously experienced with other wide band liquid crystals, that hysteresis on cooling does occur with this liquid crystal, but only when heated to 52.5°C or higher. Although the models would be heated in actual tests, it was determined that calibration of this liquid crystal could be done using a cooling procedure, as long as the initial temperature for cooling was kept under about 50°C to avoid hysteresis. The author further reduced this temperature to provide an extra margin of safety, allowing the calibration block to reach a maximum temperature of only 43°C during all phases of calibration conducted.

An in-situ calibration was performed to expose the liquid crystal to the same lighting and camera angles, as well as the same amount and quality of incident light, as falls on the models themselves. With regard to this last item, camera adjustment was performed to ensure the recorded hues matched those of the MacBeth Color Checker standard. Four gray squares (having equal amounts of red, green, and blue components) were photographed, and the output RGB values matched with camera gain settings to ensure a neutral color balance. A red gain setting of -27 and blue gain setting of +42 provided a close match.

The lighting used for the calibration as well as the data collection runs were two GE Soft White lights, with Spectrum 574 UV filters in place to eliminate transmission of wavelengths below 400 nm. The magenta-colored filter (it reduces the green component of the light), when combined with the Soft White lights, produces a nearly flat spectrum in the 400 nm to 700 nm range. This is ideal for a balanced calibration curve that is nearly linear in the temperature vs hue relation.
Hallcrest BB-G1 black paint (4:1 water to paint ratio) was airbrushed onto the copper calibration block, and allowed to dry. Liquid crystal (2:1 water to LC ratio) was then applied, with the desired coverage assessed during painting using a heat gun. The amounts of coverage were recorded, so that the models could be painted with the same amount (per area) as the copper calibration block. This ensured equal reflectivity of the liquid crystal, as well as an equal contribution to the perceived hue by the black background. Amounts used per 100 in\(^2\) area (0.07 m\(^2\)) were: black paint: one 4 oz glass jar. Liquid crystal: 6 thimbles. Care was taken to ensure an even coverage of paint and liquid crystal, to reduce the standard deviation as well as any end-to-end variations on the calibration block.

The total length of the flat plate and ribbed models is 0.42 m. It was necessary to collect calibration data with the 0.23 m calibration block in two positions: left and right. This data were then combined to form calibration data for the entire area of interest. Since the camera and lighting angles change from left to right across the plate, it was necessary to form separate calibration curves for different areas. There are seven heated sections on the flat plate model, and 7 ribs on the ribbed model. Therefore, seven different areas were chosen to calculate individual calibration curves. Each area corresponds to one heated section and its neighboring downstream, unheated section. This breakdown allows a more precise calibration of each point on the plate. Figure 18 shows how the calibration runs were broken down into seven areas.

![Figure 19 Area Distribution of Calibration Runs](image-url)
Figure 20 shows how the standard deviation of the mean hue varies across the areas of calibration. The peaks at areas 1, 4, and 7 may occur because of calibration block conduction losses near the edges, and the influence of lighting reflections from neighboring tunnel walls at the block ends.

The calibration block height matches the area of interest at 15 cm. However, sufficient variation was seen top to bottom, to warrant the choice of a smaller area to calibrate and collect data. This desire for a smaller area size is balanced by the fact that more pixels in a sample actually lowers the standard deviation of the mean hue. The standard deviation of the mean hue is reduced by the square root of the number of items in the sample (Coleman, Steele 1989):

\[
S_{h_{\text{mean}}} = \frac{S_h}{\sqrt{N}}
\]  

(6)
To better study the effects of area size and relative position on the plate, we analyzed the mean hue and standard deviation of five different areas. These areas are shown on Figure 21, below: i) middle 2.5 cm, ii) middle 5 cm, iii) middle 7.5 cm, iv) 2.5 cm above the hole, v) 5 cm above the hole.

![Figure 21 Plate Areas Used for Standard Deviation Comparison](image)

Figure 22 on the following page shows a comparison of the average pixel-to-pixel standard deviation throughout the 10°C calibration range for the five different plate areas.
Figure 22 Standard Deviation in Hue for Various Plate Areas

It is expected that the middle 2.5 cm (Area i) would show the lowest standard deviation. From a calibration and data reduction standpoint, it is simpler to use an area above the existing masked hole in the Plexiglas window. The graph shows that the standard deviation of this 2.5 cm portion (Area iv) is within 10% of the best area (i), so we chose to use this area for the present study.

Related to the standard deviation in hue of each area is the method we use to analyze the mean hue and the standard deviation for the specified area. According to a recent paper on the subject (Baughn et al. 1998), a median filter is a good method to use. The median filter takes an [N x M] area about a selected pixel and computes the median hue of the block, assigning that value to the selected pixel. The effect of the median filter is to reduce the standard deviation from pixel to pixel, with an associated loss in spatial resolution.
If a median filter is used the standard deviation of the sample is related to the standard deviation of the population by the following equation (Arkin, Colton 1970).

\[ S_{h_{\text{median}}} = 1.2533 \frac{S_h}{\sqrt{N}} \]  

(7)

The median does not reduce the standard deviation as much as a mean. However Arkin and Colton (1970) point out that the median has several advantages over a mean including the fact that "It is not distorted in value by unusual items." In TLC images bad pixels in the CCD camera, regions with poor TLC coverage, or dust can introduce "outliers" or wild readings. The use of a median filter reduces the effect of these "outliers" at the cost of less reduction in standard deviation than a mean filter.

A median filter degrades the spatial resolution because each pixel now contains information from surrounding pixels. A 3×3 and a 5×5 block degrades the spatial resolution by a factor of 3 and 5, respectively. Whether this loss in spatial resolution is worth the reduced standard deviation (and corresponding reduced uncertainty) depends on the application. Figure 23 shows the effect of a median filter on the hue standard deviation of one of the seven calibration areas studied. The advantage of a 5×5 median filter is clear, especially in the absence of any spatial resolution requirements.
Several calibration runs were performed prior to the tests being conducted. Over a 27-hour period, three calibration runs were made with the block on the left and right sides (6 total runs). These three calibration runs on each side were plotted to determine repeatability. As Figure 24 on the following page shows, they are highly repeatable.
Since all three runs showed identical performance (within 0.1°C), the calibration run having the lowest standard deviation in hue for the seven areas was chosen for final data analysis. This run was then combined with a calibration run conducted at the conclusion of testing (approximately 3 weeks later). This ensured that the average calibration information (actually the curvefit through both sets of data) most closely approximates the actual output of the liquid crystal on the test models during the testing period.

The “before” and “after” calibration curves for a representative area (3) shows the comparison between these two data sets. It is clear that the middle and upper portion of the calibration range (33°C -40°C) show better agreement between the two runs than the lower portion (30°C -33°C). It is this lower portion that contributes the most to the curvefit Standard Error of Estimate (SEE).
The curvefit performed in Microsoft Excel is a 6th order fit of the data in the calibration range of 30°C - 40°C. The SEE associated with the curvefit is considered a 68% measure of the precision error in the curvefit, only when the bias contribution to the uncertainty is small (Schenck 1979). Because the calibration curve shifted slightly over the course of the two weeks of testing, there is a bias present between the first calibration curve and the second. However, if we want to represent both sets of data with one curvefit, then the SEE is the best means to identify the uncertainty in this curvefit. The SEE is computed using the following equation (Coleman, Steele 1989):

$$SEE_T = \left[ \frac{\sum_{i=1}^{N} [T_i - (a h_i^6 + b h_i^5 + c h_i^4 + d h_i^3 + e h_i^2 + f h_i + g)]^2}{N - 7} \right]^{1/2}$$  \hspace{1cm} (8)
In the preceding equation, the \((N-7)\) arises in the denominator because we use a 6\(^{th}\) order curvefit, with 7 constants in the equation. Therefore, the SEE computation must account for the loss of 7 degrees of freedom. For the seven curvefit calibration areas, the SEE is:

**Table 3 SEE summary**

<table>
<thead>
<tr>
<th>Area #</th>
<th>SEE (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.098</td>
</tr>
<tr>
<td>2</td>
<td>0.109</td>
</tr>
<tr>
<td>3</td>
<td>0.103</td>
</tr>
<tr>
<td>4</td>
<td>0.124</td>
</tr>
<tr>
<td>5</td>
<td>0.112</td>
</tr>
<tr>
<td>6</td>
<td>0.112</td>
</tr>
<tr>
<td>7</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Using SEE in computing the overall precision limit in \(T\) is covered in Appendix E, Uncertainty Analysis. The following graphs show the calibration curves and 6\(^{th}\) order curvefit equations for the seven different calibration areas used.

\[
y = -6.11749641E+04x^6 + 1.53806501E+05x^5 - 1.54917645E+05x^4 + 7.98982682E+04x^3 - 2.20991549E+04x^2 + 3.11341553E+03x - 1.43881993E+02
\]

*Figure 26 Temperature/Hue Calibration Curve for Area 1*
Figure 27 Temperature/Hue Calibration Curve for Area 2

\[ y = -6.2913743E+04x^8 + 1.57603036E+05x^5 - 1.58626887E+05x^4 + 8.16780411E+04x^3 - 2.25668414E+04x^2 + 3.17767664E+03x - 1.47404950E+02 \]

Figure 28 Temperature/Hue Calibration Curve for Area 3

\[ y = -5.80519113E+04x^8 + 1.45179306E+05x^5 - 1.45645431E+05x^4 + 7.48018846E+04x^3 - 2.04551439E+04x^2 + 2.85226062E+03x - 1.27181803E+02 \]
Figure 29 Temperature/Hue Calibration Curve for Area 4

\[ y = -6.34531428E+04x^6 + 1.55082411E+05x^5 - 1.51827350E+05x^4 + 7.56976687E+04x^3 - 2.01174511E+04x^2 + 2.70189801E+03x - 1.12036258E+02 \]

Figure 30 Temperature/Hue Calibration Curve for Area 5

\[ y = -6.52716072E+04x^8 + 1.61754319E+05x^7 - 1.61021552E+05x^6 + 8.19758473E+04x^5 - 2.23848959E+04x^4 + 3.11395078E+03x - 1.41552424E+02 \]
\[ y = -6.52990792E+04x^6 + 1.61671200E+05x^5 - 1.60745573E+05x^4 + 8.17115890E+04x^3 - 2.22730509E+04x^2 + 3.09284870E+03x - 1.40105704E+02 \]

**Figure 31** Temperature/Hue Calibration Curve for Area 6

\[ y = -5.82801249E+04x^6 + 1.41960605E+05x^5 - 1.38244141E+05x^4 + 6.83793320E+04x^3 - 1.79655155E+04x^2 + 2.37661179E+03x - 9.22813799E+01 \]

**Figure 32** Temperature/Hue Calibration Curve for Area 7
Appendix C: Thermistor Calibration

The same thermistor was used to calibrate the copper block (to obtain the temperature/hue calibration curves) and to measure the freestream air temperature, $T_{\infty}$. The same thermistor was used to reduce the uncertainty in heat transfer coefficient by providing a correlated bias term. It is a glass-coated bead type thermistor from Thermometrics. This particular thermistor is #2 of 10, which were calibrated together against a Rosemount 162CE Platinum Resistance Thermometer (PRT) in a constant temperature oven. The calibration process used 8 points ranging from 20°C to 50°C. Since our calibration and testing were conducted between 30°C and 40°C, this range was suitable for the thermistor calibration used. Both the thermistor 2-wire resistance output and the PRT 4-wire resistance output ran to an HP 3455A DVM, which was controlled by Labview.

From an uncertainty standpoint, there are two elemental bias sources in the temperature measurement: that due to the platinum resistance thermometer used in thermistor calibration, and that due to the DVM resistance measurement accuracy, evaluated at a 6 month interval since calibration. For the first bias source, the PRT manual states that over time, the resistance of the PRT increases due to small scratches, dings, dents, etc. on its surface. To find just how much bias exists, the author prepared an ice bath in a vacuum-insulated container, and allowed the PRT to stabilize at a 0°C point for several hours. The ice bath was continually drained and repacked over this time as well. Upon reaching the lowest temperature, a PRT reading was made, which corresponded to a temperature of 0.075°C. Assuming this resistance measurement is correct, this becomes the bias limit in the PRT ($B_{\text{PRT}}=0.075 \, \text{K}$, $b_{\text{PRT}}=0.0375 \, \text{K}$). This seems possible, as the PRT was last calibrated in 1977, and this would allow for a modest 0.004 K shift per year since then. The PRT readings could be corrected for this bias, but it is not certain that it remains the same at all resistance levels, and there could be some uncertainty associated with our ice bath method. Realizing that a bias exists in the PRT, which contributes to an uncertainty in temperature, allows us to propagate this throughout our data reduction equation for $h$. 
The DVM used for the thermistor calibration was last calibrated in March, 1998. Since all tests were conducted within six months of the calibration date, the bias limit due to the DVM is calculated using the six-month accuracy table in the HP 3455A manual. The maximum deviation in resistance (dR) from calibration accuracy occurs near the upper end of the copper calibration block range (43°C). This value is used in the thermistor calibration equation (which relates temperature in degrees Celsius to log(resistance)), to find the resulting deviation in temperature. Figure 33 shows the calibration curve and equation for this thermistor.

\[ y = 0.0053x^3 - 0.0927x^2 + 0.5515x - 1.0929 \]

The calibration equation used is 3rd order, as recommended by the thermistor manufacturer for best accuracy. When the maximum dR value of 0.0204 Ω is inserted in this equation, the value of dT is 0.0107°C, which is a 95% confidence estimate. Therefore, the 68% confidence level estimate for the bias in temperature due to DVM calibration is \( b_{dvm} = \) 0.0535°C.
One conservative approach is to consider the DVM and PRT uncertainties independent and combine them using the root-sum-square method. This yields an overall 68% bias limit in the temperature measurements of $\Delta T_{LC} = \Delta T_{IE} = 0.0653^\circ C$, which is used in the uncertainty analysis equations in Appendix E.

In terms of the precision limit associated with the thermistor calibration, there are two sources which affect temperature: the readability of the Labview screen display, and the curvefit performed to obtain the thermistor calibration curve and equation. The first source yields a precision limit of $0.02^\circ C$, at a 95% confidence level. Our 68% level precision limit is therefore $0.01^\circ C$. Second, the curvefit of temperature versus the logarithm of resistance has a standard error of estimate (SEE) of $0.065^\circ C$. This is plotted in Figure 34, below.

Figure 34 Thermistor #2 Calibration with 95% Uncertainty Limits
The +/- 2*SEE bands shown on the calibration curve in Figure 34 represent a 95% confidence estimate of the uncertainty associated with the curvefit shown (Schenck 1979). As can be seen, the SEE bounds are small. When the two precision limit sources are combined using the root-sum-square method, an overall precision limit in temperature of 0.066°C is calculated, with 68% confidence. This value is used in the uncertainty analysis of h as well.
Appendix D: Calculation of radiation correction term

There are two methods one can use to solve for the absorbed radiation incident on the surface from the fluorescent lights used in the experiments. The first method is based on an assumption that for a given set of tests at multiple power settings, at a constant wind tunnel speed, the convective heat transfer coefficient will be constant as well. Therefore, one can solve the following equation N times (for N power settings):

\[
(q_l + q_{radinlight}) - \varepsilon_p \sigma \cdot T_{lc1}^4 - T_{infl}^4 = h (T_{lc1} - T_{infl})
\]  

(9a)

where
- \( q_{radinlight} \) is the absorbed radiation incident from the lights
- \( q_l \) is the electrically-supplied heat flux to the surface
- \( T_{lc1} \) is the temperature of the liquid crystal
- \( T_{infl} \) is the freestream air temperature

We choose to solve this equation three times, using information from four columns across the plate: #100, #200, #300, #400.

<table>
<thead>
<tr>
<th>Power settings</th>
<th>Freestream air temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_1 := 5.033 )</td>
<td>( T_{infl} := 299.23 )</td>
</tr>
<tr>
<td>( I_2 := 5.598 )</td>
<td>( \sigma := 5.67 \cdot 10^{-8} )</td>
</tr>
<tr>
<td>( I_3 := 4.404 )</td>
<td>( \varepsilon_p := .95 )</td>
</tr>
</tbody>
</table>

The three liquid crystal temperatures and freestream air temperatures listed below correspond to the three power settings used on these runs:

<table>
<thead>
<tr>
<th>Power settings</th>
<th>Freestream air temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{lc1} := 308.434 )</td>
<td>( T_{lc1} := 307.93 )</td>
</tr>
<tr>
<td>( T_{lc2} := 306.782 )</td>
<td>( T_{lc3} := 306.28 )</td>
</tr>
<tr>
<td>( T_{lc3} := 307.052 )</td>
<td>( T_{lc3} := 307.605 )</td>
</tr>
<tr>
<td>( T_{lc3} := 307.052 )</td>
<td>( T_{lc3} := 307.605 )</td>
</tr>
<tr>
<td>( T_{lc3} := 307.052 )</td>
<td>( T_{lc3} := 307.605 )</td>
</tr>
<tr>
<td>( T_{lc3} := 307.052 )</td>
<td>( T_{lc3} := 307.605 )</td>
</tr>
</tbody>
</table>
Plate dimensions:

\[ I := 7.68751 \quad w := 16.5 \]

\[ lw ratio := \frac{1}{w} \quad lw ratio = 0.466 \quad A plate := \frac{I \cdot w}{1550} \quad A plate = 0.082 \]

Plate resistance information:

\[ R prime := 2.42 \]

\[ R plate := R prime \cdot lw ratio \]

\[ R plate = 1.128 \]

Current from three power settings:

\[ q_1 := I_1 \cdot \frac{R plate}{A plate} \quad q_1 = 349.006 \]

\[ q_2 := I_2 \cdot \frac{R plate}{A plate} \quad q_2 = 431.763 \]

\[ q_3 := I_3 \cdot \frac{R plate}{A plate} \quad q_3 = 267.223 \]

Now we have all the information needed to solve equations (9a,b,c) simultaneously for 3 different power settings. There are three equations for only two unknowns, so the system of two equations can be solved 3 times, obtaining three answers for \( h \) and qradinlight. The answers should be reasonably close (assuming \( h \) remains constant regardless of the power setting). The system of equations below yields one of the three solutions:

\[
(q_2 + q radinlight) - s p \cdot c \cdot (Tlc 2^4 - T inf 2^4) = h \cdot (T lc 2 - T inf 2) \quad (9b)
\]

\[
(q_3 + q radinlight) - s p \cdot c \cdot (Tlc 3^4 - T inf 3^4) = h \cdot (T lc 3 - T inf 3) \quad (9c)
\]

Unfortunately, this procedure does not work well. Instead, \( h \) does appear to vary slightly from power setting to power setting. Therefore, several different values of the radiation term are obtained, although it should be a constant. The average radiation term (for all power settings and locations on the plate) is on the order of 10 W/m\(^2\).
Another method is tried to estimate the radiation term.

The overall radiation power output from the fluorescent lights used in the experiments is primarily in the visible spectrum. When the light is energized, the gases inside give off UV which excite phosphors on the tube, which change state and give off light. The phosphors in the fluorescent light are largely opaque in the visible and IR regions of the spectrum. Because we have UV filters covering the light, no UV is transmitted through the Plexiglas. Roughly half of the tubes' circumferences are visible to the plate, and the light sources have an approximate color temperature of 4500K.

Consulting Thermal Radiation Heat Transfer (Siegel, Howell 1995), we find that at this temperature, 27% of the light's total energy is emitted in the visible spectrum. We estimate the transmissivity of the Plexiglas in this region of the spectrum to be 0.95. The shape factor, evaluated from a light to the model, is calculated using Hottel's String Method to be 0.201.

\[
\text{Power} := 20 \text{ Watts} \quad \text{ShapeFactor} := 0.201
\]
\[
\text{partial} := 0.5 \quad \varepsilon := 0.95
\]
\[
\text{number} := 2 \quad \text{visible} := 0.27
\]

When these terms are combined in the following equation, we get:

\[
Q_{\text{light}} := \text{Power} \times \text{partial} \times \text{ShapeFactor} \times \text{number} \times \text{visible} \times \varepsilon
\]

(10)

\[
Q_{\text{light}} = 1.031 \text{ W}
\]

\[
q_{\text{light}} := \frac{Q_{\text{light}}}{A_{\text{plate}}}
\]

\[
q_{\text{light}} = 12.6 \frac{\text{Watts}}{\text{m}^2}
\]

Since this calculation also yields a radiation correction on the order of 10 W/m², this value is used with an uncertainty of +/- 50%. The 68% bias limit is then +/- 2.5 W/m². In all cases, this radiation term is small, i.e. less than 4% of the electrical power input per unit area.
Appendix E: Uncertainty Analysis

In analyzing the uncertainty associated with the convective heat transfer coefficient, $h$, the author consulted Experimentation and Uncertainty Analysis for Engineers, by Coleman and Steele (1989). This book is a good guide to handling many common experimental sources of uncertainty, and serves as a baseline to conduct the analysis. The ISO method of approach (as presented in the Guide to the Expression of Uncertainty in Measurement, published in late 1993) supplements this book with updated ISO-approved procedures. Furthermore, for the latest in uncertainty analysis procedures, Coleman and Steele’s methods (1995) are used.

For this discussion, recall that the data reduction equation is:

$$h = \frac{q_e + q_i - \varepsilon \cdot \sigma \cdot (T_{LC}^4 - T_w^4)}{(T_{LC} - T_w)}$$

(4b)

Where

$q_e =$ electrical power in
$q_i =$ radiation in from light source
$\varepsilon =$ emissivity of surface
$\sigma =$ Stephan/Boltzmann constant
$T_{LC} =$ Temperature of liquid crystal-coated surface
$T_w =$ Temperature of freestream air

Each of the five items shown above are either constants or are directly measured, with the exception of $q_e$, which is calculated in the data reduction equation shown below:

$$q_e = \frac{f \cdot I^2 \cdot R_{plate}}{A_{plate}} = \frac{f \cdot I^2 \cdot R'(l/w)}{(l \cdot w)} = \frac{f \cdot I^2 \cdot R'}{w^2}$$

(11)

Where

$f =$ non-uniformity factor for resistance per square, $= 1.0$
$I =$ current through gold film (amps)
$R' =$ resistance per square of gold film($\Omega$)
$w =$ width of plate (m)
The overall uncertainty in $q_e$ can be divided into two parts: precision limits, (those due to random phenomenon), and those due to bias. The precision limit in $q_e$ is due to the elemental precision limits of the four variables shown. It is convenient to directly solve for the sensitivity coefficients, as our equation is in the "special form" (Coleman, Steele 1989). Therefore, it is convenient to solve for the relative precision limit in $q$. For the 68% precision limit, we have:

$$\frac{Sq_e}{q_e} = \sqrt{\left(4 \cdot \frac{S_L}{L}\right)^2 + \left(\frac{S_R}{R}\right)^2 + 4 \cdot \left(\frac{S_w}{w}\right)^2}$$ (12a)

Beginning with the first term, the precision limit of the current measurement, $I$ derives from the "readability" of the Fluke digital multimeter connected to our HP power supply. During each image acquisition, the power supply was held at a constant power setting for ten minutes to ensure stability. Since there was no "flicker" observed in the output, we could use $\frac{1}{2}$ least digit for this value. However, the reading often would change by as much as 4 milliamps during the ten-minute period. Therefore, the 68% confidence level precision limit in current is estimated at 2 milliamps. The precision limit in $R'$, resistance per square of the gold film, derives from a series of tests conducted on nine identical samples of gold film used in building the ribbed model. A 4-wire resistance measurement was made of each rib, and the standard deviation of the nine measurements was found to be 0.01 Ω. The precision limit for the width measurement is equal to $\frac{1}{2}$ the least division on the ruler used to measure the gold film. This is $\frac{1}{32}$ inches for the flat plate model, or a relative precision limit of 0.0019. Notice that Equation (12a) does not contain a term for $f$, the gold film non-uniformity factor. This variable only contains a bias limit, as it is not measured multiple times nor has random errors associated with it.

An uncertainty of +/-20%, ($v=12.5$) is assigned to our estimate of each of these precision limits with the exception of the precision limit in $R'$, which consisted of nine measurements ($v=8$). Therefore, the result has an overall 11 degrees of freedom.

Combining the elemental precision limits defined above, and solving Equation (12a), we find that:
\[
\frac{S_{q_\text{e}}}{q_\text{e}} = 0.0056 \quad (12b)
\]

Similarly for the bias limit in \( q_\text{e} \), we have:

\[
\frac{b_{q_\text{e}}}{q_\text{e}} = \sqrt{\left(\frac{b_f}{f}\right)^2 + 4 \cdot \left(\frac{b_\text{l}}{\text{l}}\right)^2 + \left(\frac{b_\text{R}}{\text{R}}\right)^2 + 4 \cdot \left(\frac{b_\text{w}}{\text{w}}\right)^2} \quad (13a)
\]

In this equation, we are interested in estimating the 68% bias limits of the four elemental sources present in Equation (13a). The first term, the correction factor in resistance per square, we consider accurate within 1% since this is a 95% confidence level estimate, our bias limit is \( \frac{1}{2} \) this amount for a 68% level. For the second term, current measurement, the HP power supply used in this experiment was last calibrated 3 years ago. However, since we are measuring its current output with a digital multimeter in series with the heated models, we are only interested in the accuracy of this instrument. We consider the Fluke digital multimeter accurate to within 0.5% of the actual current, so this 68% relative bias limit is 0.0025 amps, or one-half of 0.5%. Finally, the ruler used to measure the width of the plate. Since we do not have an exemplary method to compare our ruler against, we must estimate its performance as no better than 1% of the ruler's length, 18 inches. This is a more conservative estimate of the uncertainty than \( \frac{1}{2} \) least scale, for a 68% bias limit of 0.09 inches. All of the elemental bias limits are estimated to be within 20% of their actual value, for an overall 13 degrees of freedom in the resulting relative bias limit in \( q_\text{e} \).

Combining the elemental precision limits defined above, and solving Equation (13a), we find that:

\[
\frac{b_{q_\text{e}}}{q_\text{e}} = 0.0122 \quad (13b)
\]
Similar to the study of the uncertainty in $q_e$, the uncertainty in $h$ can be broken down into precision and bias limits as well. We will handle each of these separately, starting with the precision limits. The governing equation for the overall precision limit (68% coverage) in $h$ is:

$$S_h = \sqrt{\left(\frac{\partial h}{\partial q_e} \cdot \frac{S_{q_e}}{q_e}\right)^2 + \left(\frac{\partial h}{\partial T_{LC}} \cdot S_{T_{LC}}\right)^2 + \left(\frac{\partial h}{\partial T_\infty}\right)^2}$$

(14)

Similarly, the governing equation for the overall 68% bias limit in $h$ is:

$$b_h = \sqrt{\left(\frac{\partial h}{\partial q_e} \cdot b_{q_e}\right)^2 + \left(\frac{\partial h}{\partial q_i} \cdot b_{q_i}\right)^2 + \left(\frac{\partial h}{\partial \varepsilon} \cdot b_{\varepsilon}\right)^2 + \left(\frac{\partial h}{\partial \sigma} \cdot b_{\sigma}\right)^2 + \left(\frac{\partial h}{\partial T_{LC}} \cdot b_{T_{LC}}\right)^2 + \left(\frac{\partial h}{\partial T_\infty}\right)^2}$$

(15)

The partial derivatives in the above equations are called sensitivity coefficients. We could solve for these directly, using Equation (4b). However, since the governing equation is somewhat complicated, we chose instead to encorporate a "jitter program" in the Matlab code to calculate these coefficients numerically. The program performs this calculation for each of the sensitivity coefficients in Equations (14) and (15) each time the convective heat transfer coefficient is found. When performing this calculation, we increment each of the variables a very small amount (0.1% of its value), yielding reliable values for the coefficients.

In terms of the precision limits of the elemental sources in $h$, we have already examined the electrical power in, stating that the relative precision limit is:

$$\frac{S_{q_e}}{q_e} = 0.0056$$

(12b)
Since we chose to compute a relative precision limit, the first term in Equation (14) contains the value of $q_e$ itself. Next, we consider the precision limit in the temperature of the liquid crystal. This quantity is not directly measured, however. Instead, the standard deviation in $T_{LC}$ must be calculated from two contributors: first, the standard deviation in hue, and second, the SEE$_T$ from the hue/temperature calibration curvefit. This procedure is similar to the one followed in the recent paper by Baughn et al. (1998). For the first part, we have a column averaged hue from $N=57$ pixels on our models. The standard deviation in the mean hue is simply the measured standard deviation in this column average divided by the square root of $N$.

This brings up an interesting topic: how do we handle hue values which lie far outside of the rest of our values? What if an outlier occurs due to absence of liquid crystal coverage or damage to the surface which precludes a hue reading, or a random phenomenon causes a "wild" hue value in a pixel, well outside the rest of the data points? We must invoke an accepted method of "throwing out" these data points, on the basis of their deviation from the mean of the 57 pixels in our column. This method is called Chauvenet's criterion, and is well documented (ref. 12). We apply Chauvenet's criterion to the 57 data points, which allows us to discard all points which lie outside the range:

$$h_{\text{mean}} \pm 2.62 \cdot S_h$$

(16)

Although this criterion is evaluated at each column, it is not used to throw out points in every one. In 200 of the 600 columns across the plate, one point is discarded. In 19 columns, 2 points are discarded. Three of more points are discarded less than 1% of the time. After the points are discarded, a new mean and standard deviation are calculated from the modified data set, and are used in further calculations.

The mean hue is multiplied by the sensitivity coefficient ($\partial T/\partial \text{hue}$) computed at this location, which yields the standard deviation in temperature. Since we are now talking about specific values for a column calculation, we will look at column number 300 (the midpoint of the flat plate) on the 20 m/s run.

Substituting the specific values for this column into this equation yields:
For the second part, $\text{SEE}_T$ from the temperature/hue calibration curvefit, the correct area must be chosen from the 7 calibration areas determined previously. Since column #300 lies in area four, $\text{SEE}_4 = 0.124^\circ C$ (from Appendix B). This is then combined with the standard deviation in $T_{LC}$ for the following overall precision limit in the liquid crystal temperature:

$$ST_{LC} = \sqrt{ST_{LC}^2 + (\text{SEE}_A)^2} = \sqrt{(0.0273)^2 + (0.124)^2} = 0.127^\circ C$$  \hspace{1cm} (18)

It is apparent that the primary contributor to the result (95%) is the curvefit $\text{SEE}$. It is necessary to represent the temperature/hue calibration information as an equation, so that individual hue values can yield discrete temperature values. It would be nice to reduce this $\text{SEE}$, however, a 6th order curvefit equation is the best available. This represents some segments of the calibration curve well and others poorly.

The final elemental precision limit contributor to $h$ is $S_{T_{\infty}}$. The freestream air temperature is measured using the same thermistor used in the calibration of our liquid crystals. Linked to the HP 3455 DVM, and controled by Labview, the temperature can be read to within 0.02 K. However, temperature fluctuations during a five second segment preceding and following an image acquisition limits our accuracy to no better than 0.05 K, outside this limit. This is a 95% estimate, so we take the 68% estimate of $S_{T_{\infty}}$ to be 0.025 K.

Another precision limit exists in both the frestream temperature and calibration block temperature measurement. This is a correlated precision limit of 0.065°C, from the $\text{SEE}$ in the thermistor calibration equation. Since this correlated precision limit does not increase the overall precision limit in $h$, it is removed from Equation (16) and the discussion above on $S_{T_{\infty}}$. For more details on thermistor calibration consult Appendix C.
Combining the precision limits in Equation (14) yields a 68% confidence precision limit in \( h \) of 0.988 W/m\(^2\)-K. The relative impact of each of the variables in (14) relating to the overall precision limit in \( h \) is shown in the following table:

<table>
<thead>
<tr>
<th>Variable (( x ))</th>
<th>( \delta h/\delta x )</th>
<th>( S_x )</th>
<th>( (\delta h/\delta x*S_x)^2 )</th>
<th>Relative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_e ), electrical power in: 776 W/m(^2)</td>
<td>0.0944</td>
<td>0.0056</td>
<td>0.01684</td>
<td>17.3</td>
</tr>
<tr>
<td>( T_{LC} ), temperature of liquid crystal</td>
<td>-6.9433</td>
<td>0.127</td>
<td>0.7776</td>
<td>79.7</td>
</tr>
<tr>
<td>( T_{\infty} ), freestream air temperature</td>
<td>6.8833</td>
<td>0.025</td>
<td>0.0296</td>
<td>3.0</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td>( \Sigma=0.9756 )</td>
<td>100</td>
</tr>
</tbody>
</table>

Next, the bias limits of the elemental sources in \( h \) are considered. Recall that:

\[
b_h = \sqrt{\left(\frac{\partial h}{\partial q_e} \cdot \frac{b q_e}{q_e} \cdot q_e\right)^2 + \left(\frac{\partial h}{\partial q_f} \cdot bq_f\right)^2 + \left(\frac{\partial h}{\partial \sigma} \cdot b \sigma\right)^2 + \left(\frac{\partial h}{\partial T_{LC}} \cdot b T_{LC}\right)^2 + \left(\frac{\partial h}{\partial T_{\infty}} \cdot b T_{\infty}\right)^2}
\]

Equation (15)

We have already studied electrical power in, stating that

\[
\frac{b q_e}{q_e} = 0.0122
\]

Again, this is a relative bias limit in \( q_e \), which means that the first term in Equation (15) must include the actual value of \( q_e \). The second term pertains to the radiative power in from the light source, \( q_f \). This value, 10 W/m\(^2\), was calculated in two separate manners outlined in Appendix D, Radiation Correction. We assign a 95% confidence estimate of +/-5.0 W/m\(^2\) (+/-50%) to this value, for a resulting 68% estimate of +/-2.5 W/m\(^2\). The third term pertains to the emissivity of the model. An experimentally determined emissivity has not been found for the surface with black paint and liquid crystal coverage. Instead, experience with the TLC, and tables for the emissivity of various black painted surfaces were consulted (ref. 19), and a mean value of 0.95 +/-0.03 was chosen. The 68% bias limit for this quantity is then 0.015.
The next term is the Stefan-Boltzman constant, \( \sigma \). This constant has only a fossilized bias limit associated with it, which will be estimated at 0.5% of the value, or \( 2.835 \times 10^{-10} \) W/ m\(^2\)-K\(^4\). The last two terms in Equation (17) are the bias limits associated with the temperature measurements, both of the liquid crystal, and of the freestream air. Since both measurements used the same thermistor, DVM, and Labview display, these biases are not only identical, but are also perfectly correlated, an advantage we will see shortly.

Next, it is necessary to identify the elemental sources of bias which combine to form the bias in temperature measurement. Appendix C provides details of thermistor calibration, and resulting biases. The 68% bias limit in the temperature measurement is \( b_{T_{LC}} = b_{T_{oo}} = 0.0653^\circ C \).

The correlated bias term has been removed from under the radical of Equation (15) for simplicity, but will be shown here for reference in the upcoming discussion:

\[ b_{TC} = \sqrt{2 \cdot \frac{\partial h}{\partial T_{LC}} \cdot \frac{\partial h}{\partial T_{oo}} \cdot b_{T_{LC}} \cdot b_{T_{oo}}} \]  

(19)

This correlated bias term, when included in the bias limit estimate for \( h \), removes the combined bias contribution from the elemental temperature sources. This reduces the overall bias in the result, \( h \), by 47.1%, and is the primary reason for using the same thermistor probe to measure both the temperature of the liquid crystal calibration block and the freestream air temperature.

All degrees of freedom for this bias limit study were considered to be 13, which indicates that our estimates are within 20% of the true estimates of elemental bias limits. Table 5 shows the relative contributions of the 6 variables to the bias limit in \( h \).

<table>
<thead>
<tr>
<th>Variable (x)</th>
<th>( \delta h/\delta x )</th>
<th>bx</th>
<th>((\delta h/\delta x * bx)^2)</th>
<th>Relative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_e ), electrical power in: 776 W/m(^2)</td>
<td>0.0944</td>
<td>0.0122</td>
<td>0.7987</td>
<td>92.4</td>
</tr>
<tr>
<td>( q_l ), radiative power from lights</td>
<td>0.0944</td>
<td>2.5</td>
<td>0.0557</td>
<td>6.4</td>
</tr>
<tr>
<td>( \varepsilon ), emissivity of models</td>
<td>-6.4229</td>
<td>0.015</td>
<td>0.0093</td>
<td>1.1</td>
</tr>
<tr>
<td>( \sigma ), Stephan-Boltzman constant</td>
<td>-1.076E08</td>
<td>2.835E-10</td>
<td>9.31E-04</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The 68% bias and precision limits are combined in the following equation to obtain the overall uncertainty in $h$, with 95% coverage (ref

$$U_h = k \cdot \sqrt{S_h^2 + b_h^2}$$

(20a)

where $k$ is the coverage factor, $= 2.0$

Because the number of degrees of freedom in our elemental sources of all the variables in the precision and bias limits in $h$ were estimated to be greater than 9, the number of degrees of freedom in the result, $h$, is greater than 9. Therefore, the “large sample assumption” holds, and the coverage factor does not need to be calculated using the Welch-Satterthwaite formula (Coleman, Steele 1995). Instead, for 95% coverage, the coverage factor is set equal to 2.0, and used to calculate the overall uncertainty in $h$:

$$U_h = 2.0 \cdot \sqrt{.9877^2 + .9298^2} = 2.71 \frac{W}{m^2 \cdot K}$$

(20b)

At this particular location on our 20 m/s flat plate run (column #300), the $h$ value is 68.24 W/m²·K, yielding a relative uncertainty of 4.0%. For the entire length of the plate, the average uncertainty is calculated to be 3.9%. Average uncertainty values are presented in the table below for the entire series of tests.

<table>
<thead>
<tr>
<th>Model</th>
<th>Velocity (m/s)</th>
<th>Average $U_h/h$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate</td>
<td>10</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>14.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating (Geometry 1)</td>
<td>10</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>14.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating (Geometry 2)</td>
<td>10</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>14.2</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>3.7</td>
</tr>
<tr>
<td>Model</td>
<td>Velocity (m/s)</td>
<td>Average Uh/h (%)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>----------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating (Geometry 3)</td>
<td>10</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.1</td>
</tr>
<tr>
<td>Ribbed</td>
<td>14.2</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Appendix F: Effect of Velocity

Results have been presented for the 10 m/s flow velocity for all models tested. Also, the results for all three velocities for the flat plate uniform heating model have shown that the h profile scales as $Re^{0.8}$, or $(V_2/V_1)^{0.8}$ as the velocity increases. We now look at the effect of velocity on the interrupted heating results. Because no fundamental change has occurred in the freestream conditions or the models, the scaling relationship should hold true here as well.

Figure 35 on the next page shows the flat plate model (spacing #1) at 14 m/s. Notice that again, the heat transfer from the interrupted heating case is greater than that of the uniform heating model. Here, comparing the average h over heated strip #5, an increase of 31% is observed.
Figure 35 Comparison of $h$ vs. $x$ at 14 m/s for Flat Plate Interrupted Heating and Uniform Heating, Spacing #1

This spacing was also run at a speed of 20 m/s. The results for this test condition are shown in Figure 36, on the following page.
The reader will notice that the results from this test condition matched the trend of the previous runs. The heat transfer coefficients once again increase when evaluated at the heated sections. The average increase over the uniform heating of the flat plate model, for heated section #5 is 26%.

Results from the flat plate with interrupted heating (spacing #2) are considered next. First, results from the 14 m/s test condition are shown in the figure below. Notice that this test condition shows a greater increase than spacing #1 for the interrupted heating versus the flat plate uniform heating. The 10 m/s results showed an increase of 64%, whereas the increase on heated section #5 is about 56% for this test condition.
Experimental Results, Interrupted Heating, 14 m/s

Figure 37 Comparison of $h$ vs. $x$ at 14 m/s for Flat Plate Interrupted Heating and Uniform Heating, Spacing #2

The results from the 20 m/s test condition for spacing #2 are shown in figure 38, below. The interrupted heating heat transfer profile is fully above the uniform heating profile. An increase in $h$ of 43% is observed this time.
The heat transfer profiles in both the 14 m/s and 20 m/s runs appear to stabilize after the 4th or 5th rib, which has been noted in the 10 m/s data as well.

For the final flat plate interrupted heating case, the 20 m/s test condition for spacing #3 is considered. Test data at 14 m/s was not gathered. Once again, the $h$ profile increases above that seen in the uniform heating data set. The magnitude of this increase is 69%, less than that seen for this spacing at 10 m/s (93%).
Figure 39 Comparison of $h$ vs. $x$ at 20 m/s for Flat Plate Interrupted Heating and Uniform Heating, Spacing #3
Finally, the ribbed model heat transfer at various speeds is studied. Recall that the 10 m/s case showed an increase of 57% over the flat plate uniform heating data. The 14 m/s data is presented in the figure below.

![Comparison of h vs. x at 14 m/s for Ribbed Model Interrupted Heating and Flat Plate Uniform Heating](image)

**Figure 40** Comparison of h vs. x at 14 m/s for Ribbed Model Interrupted Heating and Flat Plate Uniform Heating

It is noted that the heat transfer increases for this case, similar to the 10 m/s flow velocity. Stability is seen after 5 ribs, as before. The magnitude of the heat transfer coefficient increase is 36%, evaluated at rib #5.
The increase in $h$ over the flat plate uniform heating case for this test condition is not as great, and is calculated to be 27%.

As before, we can compare the ribbed results to the flat plate with interrupted heating results, since the spacing of heated and unheated sections is the same. In the 10 m/s case, recall that the ribbed model showed a 13% increase, likely because of the additional mixing that takes place, and the cooler air that reaches the heated surfaces. At the two higher flow velocities, the ribbed model does not appear to make as large of a difference in heat transfer. The 14 m/s results are shown on the following page.
In spite of the addition of cavities to promote circulation, a large increase in $h$ is not seen. Over ribs 2 through 7, the increase is only 7% over the flat plate with interrupted heating. The $h$ profile appears to be slightly greater toward the leading edge of each rib, which could be attributed to conduction losses on the leading edge of the rib that would not occur on the flat plate.

This spacing was also evaluated at the 20 m/s flow velocity. Figure 43 on the following page shows the $h$ profiles for the flat plate with interrupted heating compared to the ribbed interrupted heating. Again, only a slight increase in $h$ is seen for the ribbed model (4% over ribs 2 through 7). Although the profile is greater toward the leading edge, conduction losses out the front of the rib could explain this.
The following table shows a summary of all $h$ profile results.

**Table 7 Summary of $h$ profile results for all speeds**

<table>
<thead>
<tr>
<th>Model Configuration</th>
<th>Flow Velocity</th>
<th>% Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing 1</td>
<td>10 m/s</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>14 m/s</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>20 m/s</td>
<td>26</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing 2</td>
<td>10 m/s</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>14 m/s</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>20 m/s</td>
<td>43</td>
</tr>
<tr>
<td>Flat Plate with Interrupted Heating, Spacing 3</td>
<td>10 m/s</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>20 m/s</td>
<td>69</td>
</tr>
<tr>
<td>Ribbed Model</td>
<td>10 m/s</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>14 m/s</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>20 m/s</td>
<td>27</td>
</tr>
</tbody>
</table>

**Figure 43** Comparison of $h$ vs. $x$ at 20 m/s for Flat Plate Interrupted Heating and Ribbed Interrupted Heating
Appendix G: Effect of Power Setting

The calculation of heat transfer coefficient across each test model used this equation from section II:

\[
h = \frac{q_e + q_i - \varepsilon \cdot \sigma \cdot (T_{LC}^4 - T_{e}^4)}{(T_{LC} - T_{e})}
\]

Where
- \( q_e \) = heat flux from electrical power in (W/m\(^2\))
- \( q_i \) = heat flux from the incident lighting (W/m\(^2\))
- \( \varepsilon \) = emissivity of model surface
- \( \sigma \) = Stefan-Boltzman constant
- \( T_{LC} \) = temperature of the liquid crystal surface

Because the specific power setting used should not influence the value of \( h \), data collection at each test velocity was done multiple times, each at different power settings. It was thought that a lower power setting would give better results at the trailing edge of each heated section (where the surface temperatures are higher), and a higher power setting would allow for more complete data at the leading edge. The uncertainty in each \( h \) value was calculated in the Matlab code (as explained in section III). A larger uncertainty in \( h \) was associated with those values obtained at a lower power setting (primarily from the low temperature difference between the surface and the freestream air). Due to this high uncertainty, \( h \) data for each column position was usually chosen from the higher power settings for each run.
The graph below shows one curve for each of the four power settings used on the 10 m/s ribbed model test.

Figure 44 Comparison of Four Power Settings Used in Calculating h

The reader will notice that all four power settings yield results for $h$ that are very similar, so that choosing the one with the lowest uncertainty is a reasonable practice. Again, it is usually the run with the highest power setting that has the lowest uncertainty, and is therefore chosen in most of the graphs presented in this paper.
Appendix H: Matlab Data Analysis Code

%Wolf Master's Thesis
%Flat Plate Image Files a35.tif-a37.tif

clear

%Step 1. Read in images (at different power settings) for one tunnel speed
path=['E:\FLATPLATE\']; %Change according to folder name
fileprefix='a';
filenames=dir(path);
filenamesall={filenames.name}';
y=strncmp(filenamesall, fileprefix,1);
filenames=filenamesall(y==1);

for i=35:37 %image numbers
    image=imread([path, fileprefix, int2str(i),'.tif']);
    %Step 2. Crop image from 480x640 to 57x640, approx. 3.8 cm x 42 cm
    imagesmall=image(180:236,lower:upper,:);
    %Step 3. Convert cropped image from R,G,B to Hue, Saturation, Value
    clear H S V;
    [H S V]=rgb2hsv(imagesmall); %get HSV from smallimage
    for c=1:numcol %count through the columns, one at a time
        k=0;
        Hcol=H(:,c);
        %Step 4. Considering one column at a time, calculate the mean hue
        %and standard deviation in hue.
        hueout(i,c,:)=huestats(Hcol);
        huemean=hueout(i,c,1); % (mean hue is the first component of hueout,
        %standard deviation is the second component)
        [counts,x]=imhist(Hcol); %determine the center of the Hcol data
        center=x(find(counts==max(counts)));
        center=center(1)/length(x); %shift the data so that it is centered about the midpoint
        if center<.5
            Hcol=Hcol-(Hcol>=(center+.5));
        end
        if center>.5
            Hcol=Hcol+(Hcol<=(center-.5));
        end
        %Step 5. Apply Chauvenet's Criterion to the column data and recalculate
        %mean hue and standard deviation.
        k=find((Hcol>(huemean-(2.62*hueout(i,c,2))))&(Hcol<(huemean+(2.62*
        hueout(i,c,2)))))); %use 2.62 because we have 57 points
        chauvenet(i,c,1)=mean(Hcol(k)); %returns the mean of all data within
        %2.62 Standard Deviations of the mean
        %now wrap it back around if it fell a bit outside the (0,1) bounds
        if chauvenet(i,c,1)<0
            chauvenet(i,c,1)=chauvenet(i,c,1)+1;
        end
        if chauvenet(i,c,1)>1
            chauvenet(i,c,1)=chauvenet(i,c,1)-1;
        end
chauvenet(i,c,2)=std2(Hcol(k)); % find new standard dev of data
chauvenet(i,c,3)=chauvenet(i,c,2)/sqrt(57); % find Sh bar
chauvenet(i,c,4)=CF*sqrt(chauvenet(i,c,3)^2+SEEh^2); % combine SEE
% and Sh bar to get total Uh
end
filenumber(i)=i;
end

% Step 6. If hue is outside calibration range (0.2 to 0.63), make it a NaN
huecal min=0.20;
huecal max=0.63;
for i=35:37
    huecalmask=(squeeze(chauvenet(i,:,1))>=huecal min) &
    (squeeze(chauvenet(i,:,1))<=huecal max);
    huechauvfin(i,:,1)=(chauvenet(i,:,1)).*(0./huecalmask+1);
    % Nan the means outside the calibration range
    huechauvfin(i,:,2)=(chauvenet(i,:,2)).*(0./huecalmask+1);
    % Nan the St Dev's outside the calibration range
end

% Step 7. Define the areas of interest - where the leading edge is, where
% the ribs and spaces lie on the plate.
% All areas are the 4 cm portion above the plexiglas hole blockage, 57 pix
% All areas have format (xstart, xfinish, ystart yfinish)
area(1,:)=\[180 236 540 628\]; % first rib and space 52+37=89
area(2,:)=\[180 236 447 539\]; % second rib and space 56+37=93
area(3,:)=\[180 236 354 446\]; % third rib and space 56+37=93
area(4,:)=\[180 236 261 353\]; % fourth rib and space 56+37=93
area(5,:)=\[180 236 168 260\]; % fifth rib and space 56+37=93
area(6,:)=\[180 236 75 167\]; % sixth rib and space 56+37=93
area(7,:)=\[180 236 19 74\]; % seventh rib 56
lower=19;
upper=628;
numcol=upper-lower+1;

% Step 8. Load in the 6th order polynomial calibration curves and SEE data
% for each of the 7 areas.
% Area 1 Calibration Equation and SEE from Excel:
pl=[8.80478482E+03 -1.38428428E+04 7.29109023E+03 -1.30776721E+03
  5.71414179E-01 2.13746093E+01 2.95127204E+01];
SEE1=0.167;
% Area 2
p2=[8.55366000E+03 -1.33118574E+04 6.87361050E+03 -1.15776036E+03
  -2.46697444E+01 2.35552657E+01 2.95461203E+01];
SEE2=0.167;
% Area 3
p3=[7.81519249E+03 -1.19736547E+04 5.97227115E+03 -8.89325561E+02
  -5.64021901E+02 2.42047098E+01 2.95643830E+01];
SEE3=0.166;
% Area 4
p4=[5.40080630E+03 -7.40308686E+03 2.71619085E+03 2.0804817E+02
  -2.23735106E+02 3.40999374E+01 2.9543710B+01];
SEE4=0.214;
% Area 5
p5=[5.61044299E+03 -8.02456290E+03 3.32458898E+03 -7.15036413E+01
  -1.71679095E+02 3.04392207E+01 2.95111459E+01];
SEE5=0.197;
%Area6
p6=[5.44478898E+03 -7.67615223E+03 3.04431247E+03 3.05179786E+01
-1.86995444E+02 3.10377217E+01 2.95628180E+01];
SEE6=0.201;
%Area7
p7=[4.09617356E+03 -5.10016888E+03 1.16930897E+03 6.63263848E+02
-2.81896714E+02 3.60627891E+01 2.95874227E+01];
SEE7=0.232;
for i=35:37
  %Step 9. Convert hue to temperature using the calibration data
  %specific to each area.
  tempout(i,522:610,1)=polyval(p1,huechauvfin(i,522:610,1));
  tempout(i,429:521,1)=polyval(p2,huechauvfin(i,429:521,1));
  tempout(i,336:428,1)=polyval(p3,huechauvfin(i,336:428,1));
  tempout(i,243:335,1)=polyval(p4,huechauvfin(i,243:335,1));
  tempout(i,150:242,1)=polyval(p5,huechauvfin(i,150:242,1));
  tempout(i,57:149,1)=polyval(p6,huechauvfin(i,57:149,1));
  tempout(i,1:56,1)=polyval(p7,huechauvfin(i,1:56,1));

  %Step 10. Calculate the 68% uncertainty in temperature
  tempout(i,522:610,2) = (polyval(p1, (huechauvfin(i,522:610,1)+.0001))-
                          polyval(p1, (huechauvfin(i,522:610,1)-.0001)))/.0002;
  tempout(i,429:521,2) = (polyval(p2, (huechauvfin(i,429:521,1)+.0001))-
                          polyval(p2, (huechauvfin(i,429:521,1)-.0001)))/.0002;
  tempout(i,336:428,2) = (polyval(p3, (huechauvfin(i,336:428,1)+.0001))-
                          polyval(p3, (huechauvfin(i,336:428,1)-.0001)))/.0002;
  tempout(i,243:335,2) = (polyval(p4, (huechauvfin(i,243:335,1)+.0001))-
                          polyval(p4, (huechauvfin(i,243:335,1)-.0001)))/.0002;
  tempout(i,150:242,2) = (polyval(p5, (huechauvfin(i,150:242,1)+.0001))-
                          polyval(p5, (huechauvfin(i,150:242,1)-.0001)))/.0002;
  tempout(i,57:149,2) = (polyval(p6, (huechauvfin(i,57:149,1)+.0001))-
                          polyval(p6, (huechauvfin(i,57:149,1)-.0001)))/.0002;
  tempout(i,1:56,2) = (polyval(p7, (huechauvfin(i,1:56,1)+.0001))-
                        polyval(p7, (huechauvfin(i,1:56,1)-.0001)))/.0002;
  for c=1:610
    tempout(i,c,2)=tempout(i,c,2)*(huechauvfin(i,c,2)/sqrt(57));
  end
  %Use a coverage factor of 1 to get 68% UT, using ST and SEE
  cf=1;
  for c=522:610
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE1^2));
  end
  for c=429:521
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE2^2));
  end
  for c=336:428
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE3^2));
  end
  for c=243:335
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE4^2));
  end
  for c=150:242
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE5^2));
  end
  for c=57:149
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE6^2));
  end
  for c=1:56
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE7^2));
  end
  for c=1:610
    tempout(i,c,3)=tempout(i,c,3)*(huechauvfin(i,c,3)/sqrt(57));
  end
end
for c=1:56
    tempout(i,c,3)=cf*sqrt((tempout(i,c,2))^2+(SEE7^2));
end
end

hresult(:, :) = tempout(35, :, :);
hprofile = tempout;

%Step 11. Input power setting, qe and freestream air temperature, T infinity, for the specified runs.
ql = 349.006;
q2 = 431.763;
q3 = 267.223;
Tinf1 = 299.23;
Tinf2 = 299.3;
Tinf3 = 299.35;

%Step 12. Input uncertainty analysis data - bias and precision limits for each of the elemental source in h.
%qe, electric power in:
relplq = 0.0056;
relblq = 0.0122;
%ql, power from light radiation:
ql = 10;
absblql = 2.5;
%emissivity of block:
eps = 0.95;
asbleps = 0;
abspleps = 0.015;
%Stephan-Boltzman constant, sigma:
sigma = 5.67E-08;
absbsig = 2.835E-10;
dsig = 5.67E-11;
%Liquid Crystal temp, Tlc:
%absolute precision limit contained in tempout(:, :, 3) (combined ST, SEE)
absblt = 0.067;
%Freestream air temp:
abspltinf = 0.067;
abspltinf = 0.025;

%Step 13 Compute h profile
for c=1:610
    hprofile(35, c, 1) = (ql + ql - eps * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1);
    % Step 14. Calculate h sensitivity coefficients for uncert. analysis
    dhdq = (((ql + 1.01) - eps * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1)) - ((ql - 1.01) - eps * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1) / .01;
    dhdlq = ((ql + (ql + .01) - eps * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1)) - ((ql + (ql - .01) - eps * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1)) / .02;
    dhde = ((ql - eps * .001) * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1) - (ql - (eps - .001) * sigma * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1) / .002;
    dhsig = ((ql - eps * (sigma + dsig)) * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1) - (ql - eps * (sigma - dsig)) * ((tempout(35, c, 1) + 273.15)^4 - (Tinf1)^4)) / (tempout(35, c, 1) + 273.15 - Tinf1) / (2 * dsig);
\[ dhdtlc = \frac{(q_l - \varepsilon \cdot \sigma \cdot ((T_{out}(35,c,1) + 273.25)^4 - (T_{infl})^4))}{(T_{out}(35,c,1) + 273.05)^4 - (T_{infl})^4)} \]

\[ dhdtinf = \frac{(q_l - \varepsilon \cdot \sigma \cdot ((T_{out}(35,c,1) + 273.15)^4 - (T_{infl} + 0.1)^4))}{(T_{out}(35,c,1) + 273.15 - (T_{infl} + 0.1)) - (q_l - \varepsilon \cdot \sigma \cdot ((T_{out}(35,c,1) + 273.15)^4 - (T_{infl} - 0.1)^4))/2; \]

\% the line below puts the 68% precision limit in h into 2nd indice
hproule(35,c,2)=sqrt((dhdt*ql*relplq)^2+(dhdtlc*tempout(35,c,3))^2+(dhdtinf*abspltinf)^2);

\% the line below puts the 68% bias limit in h into the 3rd indice
hproul(35,c,3)=sqrt((dhdt*ql*relplq)^2+(dhdtlc*abspltlc)^2+(dhdtinf*abspltinf)^2);

\% the next line puts the combined uncertainty in h into the 4th indice
hproul(35,c,4)=k*sqrt(hprofile(35,c,2)^2+hprofile(35,c,3)^2);

\% second image: perform same steps as first image
\% third image: perform same steps as first and second image

\% Step 15. Compare h values at each column position, for different power settings. Choose h that has lowest associated uncertainty.
\% hresult(c,2)=min(hprofile(35:37,c,4)); % holds the min Uh value for i=35:37
\% if hprofile(i,c,4)==hresult(c,2);
\% hresult(c,1)=(hprofile(i,c,1)); % holds corresponding h value
end

end

\% Step 16. Calculate relative uncertainty, save to 3rd position in hresult
for c=1:610
hresult(c,3)=(hresult(c,2)/hresult(c,1))*100;
end

\% plot temps
for i=35:37
figure;
plot(tempout(i,:,1)); hold on;
end

\% plot all three solutions for h
figure;
for i=35:37
plot(hprofile(i,:,1)); hold on;
end

\% plot all three solutions for h
\% plot all h profiles and U bars
figure;
i=35;
plot(hprofile(i,:,1),'r'); hold on;
plot(hprofile(i,:,1)+hprofile(i,:,4),'r'); hold on;
plot(hprofile(i,:,1)-hprofile(i,:,4),'r'); hold on;
i=36;
plot(hprofile(i,:,1),'g'); hold on;
plot(hprofile(i,:,1)+hprofile(i,:,4),'g'); hold on;
plot(hprofile(i,:,1)-hprofile(i,:,4),'g'); hold on;
i=37;
plot(hprofile(i,:,1),'b'); hold on;
plot(hprofile(i,:,1)+hprofile(i,:,4),'b'); hold on;
plot(hprofile(i,:,1)-hprofile(i,:,4),'b'); hold on;
plot the resulting h profile and uncertainty bars
figure;
plot(hresult(:,1)); hold on;
plot(hresult(:,1)+hresult(:,2)); hold on;
plot(hresult(:,1)-hresult(:,2));

Step 17. Output results (h profile and uncertainty for each data point)

to a file for use in Excel.
dataout=(hresult(:,:)); %the last two remove the first dimension
%(which incidentally is called a singleton dimension because it exists
%but does not contain any data) resulting in a 2-D matrix output
save (['E:\Thesis\hprofileFP10.dat'],'dataout','-ascii','-tabs');
## Appendix I: Data for Flat Plate

### 10 m/s

**Air Properties:**
- Pressure (mb): 1006.16
- Pressure (N/m²): 100616
- density (kg/m³): 1.17E+00
- viscosity (kg/ms): 1.85E-05
- Velocity (m/s): 10

**Universal Gas Constant:** 2.87E+02

**Pressure (mb):**
- 1006.16

**Temperature (°C):**
- 3.86E+05

**Re(x):**
- 797.52

**NuM:**
- 803.35

**NuftO USL:**
- 857.03

**Zl (Unheated starting length, m):**
- 0.387

**Other Values:**
- 690.59
- 708.68
- 726.66
- 744.53
- 762.30
- 785.82
- 803.35
- 822.88
- 845.68
- 857.03
- 881.69
- 911.44
- 941.29
- 971.15
- 1001.01
- 1030.87

### Experimental Results:

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**Avg UH:** 4.06545

**Avg Diff (%):** 8.74
# Appendix J: Data for Flat Plate with Interrupted Heating

## 10 m/s

### Air Properties:
- Pressure (mb): 1006.16
- T (C): 26.15
- T (K): 299.3
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0.112 | 0.312 | 76.093 | 3.41 | 4.48 |
0.111 | 0.311 | 51.32 | 2.053 | 4.00 |
0.110 | 0.310 | 48.887 | 1.891 | 3.87 |
0.109 | 0.309 | 48.667 | 1.884 | 3.87 |
0.108 | 0.308 | 48.658 | 1.882 | 3.87 |
0.107 | 0.307 | 48.765 | 1.881 | 3.86 |
0.106 | 0.306 | 48.99 | 1.9 | 3.88 |
0.105 | 0.305 | 49.108 | 1.904 | 3.88 |
0.104 | 0.304 | 49.52 | 1.924 | 3.89 |
0.103 | 0.303 | 49.492 | 1.919 | 3.88 |
0.102 | 0.302 | 49.464 | 1.921 | 3.88 |
0.101 | 0.301 | 49.705 | 1.931 | 3.89 |
0.100 | 0.300 | 49.852 | 1.939 | 3.89 |
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0.098 | 0.298 | 50.459 | 1.967 | 3.90 |
0.097 | 0.297 | 50.311 | 1.966 | 3.91 |
0.096 | 0.296 | 50.523 | 1.972 | 3.90 |
0.095 | 0.295 | 50.664 | 1.979 | 3.91 |
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0.093 | 0.293 | 51.392 | 2.016 | 3.92 |
0.092 | 0.292 | 51.705 | 2.027 | 3.92 |
0.091 | 0.291 | 51.791 | 2.04 | 3.94 |
0.090 | 0.290 | 51.926 | 2.045 | 3.94 |
0.089 | 0.289 | 51.998 | 2.053 | 3.95 |
0.088 | 0.288 | 52.327 | 2.062 | 3.94 |
0.087 | 0.287 | 52.873 | 2.097 | 3.97 |
0.086 | 0.286 | 53.174 | 2.114 | 3.98 |
0.085 | 0.285 | 53.434 | 2.12 | 3.97 |
Section #2: | |
0.083 | 0.283 | 53.928 | 2.142 | 3.97 |
0.082 | 0.282 | 54.848 | 2.185 | 3.98 |
0.081 | 0.281 | 54.737 | 2.183 | 3.99 |
0.080 | 0.280 | 54.784 | 2.187 | 3.99 |
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## Appendix K: Data for Ribbed Model with Interrupted Heating

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**Air Properties:**
- Pressure (mb): 1006.16
- Pressure (N/m²): 100616
- Density (kg/m³): 1.17E+00
- Viscosity (kg/ms): 1.85E-05
- Velocity (m/s): 10

**Universal Gas Constant:** 2.87E+02

**Properties:**
- Pr
- T (K)
- T (°C)
- k (W/mK)

**Zl (unheated starting length, m):** 0.2

---

### Additional Data

- Uh: 
- H: 
- Zl: 

---

### Conversion Factors

- 1E0² = 100E²
- 1E0⁻² = 0.01E⁻²

---

**Table Notes:**
- "diff(%)" represents the percentage difference between the observed and expected values.
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\[
\text{Average } \frac{Uh}{h} = 381.00, \quad \text{Average Incr.} = 1557.25
\]

\[
\text{Average Incr.} = 4.09, \quad \text{Average Incr.} = 12.92
\]
APPENDIX L: Equipment Inventory

Power Supply:

- HP 6286A DC Power Supply
- Fluke 45 Dual Display Multimeter
- 1.5m X 16 gauge power lead wires (2)
- Powerstat 120V AC Variac

Lighting:

- GE Cool White Fluorescent Tube, 20 Watt, T12-0.61 m (2)
- Spectrum 574 UV sleeve filters (2)

Model Fabrication:

- Dow Blue Styrofoam, ¾" and 1.5" thick (19 mm, 38 mm)
- Elmer's Stix-All cement
- Courtauld's Gold Film
- 3M Super-77 Spray Adhesive
- Printmasters Speedball Soft Rubber No. 66 Brayer Roller
- MasterFoil Plus Copper Tape, 6.35mm x 33m (1/4" x 36 yds)
- Hallcrest BBG-1 Black Paint
- ProArt Liquid Tempera Paint
- Badger 150M Airbrush
- Hallcrest BM/R30C10W/C17-10 Liquid Crystal

Temperature Acquisition:

- Gateway 2000 P5-90 PC running Labview V4.1
- HP 3455A DVM
- Thermistor

Data Acquisition/Reduction:

- Macbeth ColorChecker
- Sony 3-chip XC-003 CCD camera
- Matrox Meteor RGB Framegrabber
- Micron 166 MHz PC (128 MB RAM)
- Matlab 5.1 with Image Processing Toolbox
- Microsoft Excel

Wind Tunnel:

- Aerolab Educational Wind Tunnel, 12" x 12" test section
- Epic (Wilh. Lambrecht KG Gottingen) Inclined Manometer, 0.834 specific gravity red oil

Miscellaneous:

- X-Acto Knives
- Carpenter's Square
- Breathing Apparatus with charcoal filters
- Black 20 oz. "duck" fabric
- Vanguard Professional Series Camera Tripod
Appendix M: Heat Transfer Picture Gallery Submission

The 1998 International Mechanical Engineering Congress and Exhibition
Special Session
Heat Transfer Picture Gallery

HEAT TRANSFER DISTRIBUTION ON FLAT AND RIBBED SURFACES WITH AN INTERRUPTED THERMAL BOUNDARY CONDITION

J. D. Wolf* and J. W. Baughn
University of California, Davis
Department of Mechanical and Aeronautical Engineering
One Shields Avenue, Davis CA 95616

These photographs show the surface temperature distribution on both flat and ribbed surfaces with interrupted heating. The photographs are of Thermochromic Liquid Crystals (TLC's) on the wall of a wind tunnel. The wall is made of Styrofoam and is covered with a polyester sheet of gold-coated film used for electric heating. The surfaces are airbrushed with a TLC that has a red start temperature of 30°C, with a 10°C range. The liquid crystal images are captured using an RGB camera, and converted into hue, then into temperature distributions. The gold film is electrically heated as shown to produce the interrupted thermal boundary condition. Regions of low temperature represent high heat transfer coefficients, whereas regions of high temperature represent low heat transfer coefficients.

The photos demonstrate the high heat transfer at the leading edge of each heating length and the effect of the cavities on the ribbed surface heat transfer. An example of this type of thermal boundary condition is surface-mounted modules in electronic packaging.

*address after 12/98:
USAF Academy, Department of Aeronautics
2410 Faculty Drive, USAFA, CO 80840
Flat Plate Interrupted Heating
Styrofoam with electrically heated film as shown
Surface Temperature

V=10 m/s

RGB Image

38mm 25mm 19mm

Ribbed Model

Styrofoam with electrically heated film on top surface of ribs
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