A Combined Numerical and Experimental Study of Heat Transfer of a Turbine Airfoil Cooling Channel with Angled Ribs and a 180-Degree U-bend Turn

A Thesis Presented
By
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# Nomenclature

<table>
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_{cross}$</td>
<td>Test section cross section area</td>
</tr>
<tr>
<td>$Area$</td>
<td>Green color area</td>
</tr>
<tr>
<td>$Area_{ref,i}$</td>
<td>Green color area for the $i^{th}$ run</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$D$</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>$EF$</td>
<td>Enhancement Factor</td>
</tr>
<tr>
<td>$ΔF$</td>
<td>Uncertainty of a linear function</td>
</tr>
<tr>
<td>$f$</td>
<td>Darcy friction factor</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Smooth wall friction factor</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>$k$</td>
<td>Turn loss factor</td>
</tr>
<tr>
<td>$L$</td>
<td>Channel length</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>$\overline{Nu}$</td>
<td>Area average Nusselt number</td>
</tr>
<tr>
<td>$Nu_{smooth}$</td>
<td>Nusselt number of smooth surface</td>
</tr>
<tr>
<td>$Nu_{tur}$</td>
<td>Nusselt number of roughened surface</td>
</tr>
<tr>
<td>$Nu_{tur,i}$</td>
<td>Nusselt number of roughened green color surface</td>
</tr>
<tr>
<td>$P$</td>
<td>Perimeter of test section</td>
</tr>
<tr>
<td>$P_{amb}$</td>
<td>Ambient pressure</td>
</tr>
<tr>
<td>$P_{ven}$</td>
<td>Upstream pressure of Venturi</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$P_{inlet}$</td>
<td>Pressure at inlet</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Cooling air density</td>
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<tr>
<td>$Δp$</td>
<td>Pressure drop</td>
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<tr>
<td>$Q$</td>
<td>Total heat flux</td>
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<tr>
<td>$Q_{loss}$</td>
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<tr>
<td>$R_{gas}$</td>
<td>Gas constant</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Mean temperature</td>
</tr>
<tr>
<td>$T_{inlet}$</td>
<td>Temperature at inlet</td>
</tr>
<tr>
<td>$T_{ven}$</td>
<td>Upstream temperature of Venturi</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Surface Temperature</td>
</tr>
<tr>
<td>$TP$</td>
<td>Thermal performance factor</td>
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<tr>
<td>$U_m$</td>
<td>Mean velocity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>$\Delta xi$</td>
<td>Uncertainty of independent variable x</td>
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Abstract

Turbine airfoils cooling technology has been developing for more than 60 years to protect turbine airfoils from high temperature airflow. Rib-roughened cooling channel inside turbine airfoil is one of the most efficient way. This study investigates thermal behavior of a turbine airfoil cooling channel around a rib-roughened 180-degree turn for two different rib arrangements. Numerical and experimental methods are used to obtain heat transfer coefficients for different Reynolds numbers.

The test rig is made up of two rectangular channels of aspect ratio 1/6 connected together with a U-bent. This two-legged channel is roughened with 45° ribs in two arrangements. In the Baseline arrangement, the ribs are pointing away from the flow direction, while in the second arrangement, the ribs point towards flow direction. The numerical model is identical to the test rig in geometry and in boundary conditions.

A total of 15 million hexahedral structured meshes are used in both numerical models. For turbulence, the realizable $k - \varepsilon$ model is selected with enhanced wall treatment. Experimental tests are done using steady state liquid crystal thermography for a range of Reynolds number from 5000 to 40000. The results of numerical models and experimental data are compared and discussed. Numerical simulations and experimental data show good agreement for flow field parameters such as friction factor and turn losses. The heat transfer results, however, show a 20 to 30 percent difference with the numerical results being higher than the test data. One major conclusion of this study is that the rib geometry and U turn have strong influence on the heat transfer coefficient distribution.

Key words: Turbine blade cooling, U-bend channel, Rib roughness.
Introduction

Gas turbine engines are high performance power plant for aircraft propulsion and in-land power generation or industrial applications. They are going through a cycle that is modeled by Brayton cycle. That means the thermal efficiency and power output increase with increasing turbine rotor inlet temperature (RIT). [1] In advanced gas turbines, several cooling technologies are applied to allow turbine blades stand high-temperature outflow from combustors. Cooling technologies like film cooling, impingement cooling and transpiration cooling are developed and are combined to achieve the best cooling performance for gas turbines. Internal cooling, also known as convection cooling, which uses rib-roughened cooling channels in airfoils, is widely used as a major cooling method.

Figure 1. Turbine blade cooling technology development [1]
Turbulators in cooling channels can interupt the laminar sublayer and create local wall turbulence due to flow separation and reattachment between the ribs, greatly enhancing the heat transfer. [2] A lot of research work is focused on the rib influence on heat transfer in cooling channels. S V. Ekkad and J C. Han studied detailed heat transfer distributions in a two-pass square channel in 1996. [2] This is quite important because local heat transfer difference cause temperature difference on turbine airfoils, which is the reason for excessive thermal stresses that can cause thermal creep. H. Iacovdes and M. Raisee used computational method to learn cooling passage heat transfer with a U bend in 1999. [3] And their ribs arranged on left and right sides of a rectangular channel. In 2002, L. Al-Hadhrami and J C. Han studied effect of rotation on heat transfer. [4] In 2011, M. Schuler and H.M. Dreher used numerical methods to investigate rotational effect on heat transfer [5] and their results match the experimental results of Taslim et al. in 1991. [6] Investigation of different sides of ribbed wall was done by J. Gong, T. Gao and G. Li in 2012. [7] In 2001, R. Kiml, S. Mochizuki and A. Murata studied effects of rib arrangements on heat transfer. [8] In this research, they used different arranged rib angles to test their influence. With improvement computation methods and increasing computation speed, more and more numerical studies presented. And experimental methods researches were operated. T. Arts et al combined experimental and 2D numerical methods to investigate heat transfer in rib-roughened channels. [9] J. E. Dees, D. G. Bogard, performed experimental and computational investigation to study a cooling channel with 90-degree ribs in 2012. [10] M. E. Taslim and H. Liu studied a square channel with 45-degree ribs. [11] With high performance computer, numerical methods can get more accurate results. Numerical investigation of impingement cooling also achieved by fine enough mesh by M. E. Taslim and F. Xue in 2016 and their results while agreed their experiment data. [12]

Figure 2 shows a typical internal cooling system in a turbine airfoil. The internal cooling method is to route the air through turbulated serpentine passages within the airfoil and remove heat from the airfoil by convection. The coolant is then ejected either at the tip of the airfoil, through the cooling slots along the trailing edge or cooling holes along the airfoil surface. The vortices and other secondary flows introduced by turbulators increase the heat transfer from the turbine airfoil walls. Additional heat transfer is gained by increased extended surface area from the roughened surface. However, roughening the walls increases the pressure requirements of the compressor. [14]
Film cooling is a method to guide cooling air from high pressure compressor to turbine blade internal cooling channel. Then let the cooling air flow out though small holes on airfoil wall and eject to main stream. Due to main stream pressure and walls’ friction, ejected cooling air can form a thin cool layer to protect turbine airfoils from hot flow.

Figure 2. Cooling Channel of a Gas Turbine Blade [13]

In this work, we use both numerical and experimental methods to study a rib-roughened rectangular channels with a 180-degree rounded U-bend. This kind of cooling channel is widely used in turbine airfoil cooling systems. The test section is made up of two different aspect-ratio rectangular cooling passages and rib height-to-passage hydraulic diameter or blockage ratio \((e/D_h)\) is low in this test section. Ribs are arranged at 45 degrees and 135 degrees to the cooling air flow. This study will observe how different rib arrangements and round turn impact the heat transfer coefficient, friction factor of the channel, the enhancement factors at bottom surface and overall thermal performance of the test sections.
Experimental Method

1. Lab Setup and Equipments

All the tests were done in 165 Egan lab, Northeastern University, Boston, Massachusetts. The Lab setup is showed below.

Cooling air supply comes from a 100 psi JB #A10053 shop air compressor in Egan's first floor mechanical room. Compressed air is stored in air tank before transported to test section. Then the compressed air goes in to a Balston A60-BX filter to remove water, dirt and oil from it. Then the clean air enters one of several paralleled Venturis. Those sonic Venturis are used to measure mass flow rate of inlet cooling air from air tank. Cooling air reached critical state at Venturis’ throats, which helps mass flow rate measurement. Mass flow rate of choked flow is a function of Venturi’s inlet pressure and would not be influenced by pressure drop and fluctuations of upstream. To keep test section inlet flow at a constant temperature, a water cooling system is used to cool the air from Venturis to take heat generated by dissipation away and keep the air flow at a constant temperature.
After air is cooled through the cooling system, it enters a plenum with honey comb. This section is in between the pressure source and the actual test rig. The plenum is a six-sided enclosure composed of 6 plexi-glass see-thru walls. It is tightened by bolts at all interface and sealed up by silicon. The air is supplied equally by two same PVC pipes into plenum and straightened and filtered through a honey comb. After the air has been straightened and filter in plenum, it enters test section inlet.

A multi-channel power source is used to provide current to heaters of this test section. There are six heaters beneath liquid crystal and each of them connects to a single channel of power source separately. There are two different types of dial on the control plane, the large one is master dial, which control master voltage input. The other smaller type is “fine tuning” dial, which varied the voltage at much finer resolution, and only control a single channel. Each single channel is adjusted to supply same power to their heater before test, so only master dial need to be adjusted during test process to get different heat fluxes. Figure 4 shows a picture of this multi-channel power source.

Figure 4. Multi-Channel Power Source Used in Experiments
An Agilent 34970A Data Acquisition/switch Unit was used to read the temperature data from four temperature measurement points which located at Venturi, plenum and lab to get temperature data.

Venturi pressure was measured by Omega Engineering pressure gauge with one psi accuracy. Test section and plenum pressure were measured by a Dywer 1430 micromanometer. The ambient pressure was gotten from NOAA website for postal code 02115. Heater powers were measured indirectly by two Fluke 179 True RMS Multimeters. By acquiring voltage and current supplied to heater, the power or heat flux can be calculated.

Liquid crystal used in this experiment is R35C1W. R35C1W describes a TLC mixture with red start at 35 °F and a bandwidth of 1.8 °F. The reference green we used was calibrated to be 94 °F.

Photos of heated liquid crystal were taken by a Canon SX160 camera. All photos were taken from same height and angle to make sure a pixel represent same area. And a GE BBA 250 watts photography bulb was used as light source.

2. Test Geometry

To simulate the mid-chord cooling channel of a turbine blade, a two-legged test section with a 180-degree turn was built. The height of this channel is 12 inches and the width is 2 inches in first leg and 1.69 inches in the second leg. The all plexi-glass and polyurethane pieces were machined in Northeastern University Physics Machine Shop.

Figure 5 and Figure 6 shows those channels’ Solidworks models. Turning parts are not shown in those pictures.
This two-legged channel has two different aspect ratio rectangular passages. Passage with inlet surface is a 2 in by 12 in rectangular channel and passage with outlet is a 1.69 in by 12 in channel. Both of those passages are 38 in long and made of three Plexiglas. Left and right walls are made of 38 in by 12 in plates with 0.5 in thickness. The bottom wall is the heated wall with liquid crystal mounted on. This part is a 4-in-thick and 8-in-width polyurethane slab in order to mitigate heat loss from the heaters. All the interfaces of plates are sealed by silicone and Aluminium tape.
12 ribs are arranged by 45° and 135° to airflow on the bottom wall. There are also 12 ribs arranged on the top un-heated wall with same configuration. The first arrangement is called Baseline and the second is called Up-Point.

All the ribs used in this test section have same cross section. Difference in length is caused by width of passage. The rib used is designed to have a square cross section and a 0.164-in-rounded edge. As showed below:

![Figure 7. Rib Geometry Parameters](image)

Figure 7. Rib Geometry Parameters

![Figure 8. Picture of Mounted Rib in the Test Section](image)

Figure 8. Picture of Mounted Rib in the Test Section
The pitch of rib is 0.58 in, so does the cross-section width. Because ribs are arranged 45° or 135° to air flow, the normal width of ribs, which is 0.409 in, is different from the width. All the ribs are made of plastic and produced by Northeastern University Physics Machine Shop.

Figure 9. Middle Heat Cross Section of Test Section Channel

Figure 8 shows the configuration of test channel. A 180-degree turn is used in this test section. This U-bend turn is made by three parts. First is the Plexiglas-made channel. Three side walls consist a turn with sharp edges. By employing two rounded turn on two corners and a nose on middle wall, a 180-degree U-bend turn is built.

The final built baseline test section is showed below in figure 10. During heat transfer test, a hard foam coat would be applied to cover side walls of test section to reduce radiation and only the top wall would stay uncovered for photography.
The technique of the steady state liquid crystal thermography is employed to measure the heat transfer coefficients in these test sections. The liquid crystal sheet’s color changes depending on a specific range of temperatures; By this character, we can get temperature information during test. In these experiments, heaters are mounted under liquid crystal sheet. With generating constant heat flux, these heaters can heat liquid crystal, which changes color of liquid crystal. Green is chosen as reference color. During heat transfer test, reference color can move from one location to another one. By adjusting current and voltage carefully, we can let reference color cover the whole investigation area with different heat flux generated in that area. All those processes are record in series of pictures. Knowing heat flux and surface temperature, and air mixed mean temperature, we can get heat transfer coefficient. Those pictures of reference color in different location and covered different area can be transferred to local heat transfer coefficient of that area. By taking area-weighted average, we can get heat transfer coefficient of that whole area we are interested in.

Before testing, the liquid crystal sheet is calibrated as follows steps. A water bath is used to obtain uniform isochromes on a sample piece of the liquid crystal sheets is used throughout these studies. The temperature corresponding to each color is measured using a precision thermocouple and videos were taken at laboratory conditions.
simultaneously, which can simulate closely the actual experiment environment. Distilled water is heated to 100°F in a glass beaker using a hot plate and poured into an insulated cup where the test sample was secured. Along with the water cooling down, the test sample goes through its color bandwidth changing. The water is periodically stirred with a glass stick to make the temperature uniform in the cup. When the test sample turned green, the temperature showed on the data acquisition unit is assigned to this color. These videos could be played back to verify the temperature assignments. Reference colors along with their measured temperatures of 95.8°F is then chosen to be used throughout the experiments for the Baseline test section and the Up-Point test section, respectively. It should be noted that all possible shades of the selected reference color showed a temperature difference of no more than 0.5°F.

Figure 11. Liquid Crystal Calibration
3. Data Reduction

3.1 Flow Filed Data Reduction

Data reduction of experiments contains two different parts. The first one is about flow field like mass flow rates, Reynolds number and channel’s friction factor. The second part is about heat transfer performance. Nusselt number and mean flow temperature is acquired in this part.

In those experiments, mass flow rates are controlled by Venturi, so this parameter is calculated by a function provided by the manufacturer,

\[
\dot{m} = 0.5225 \cdot \frac{A_{throat} \cdot (P_{amb} + P_{ven})}{\sqrt{T_{ven}} + 460}
\]

\(A_{throat}\) is the cross section area of Venturi’s throat, \(P_{amb}\) is the ambient pressure, \(P_{ven}\) upstream pressure of the Venturi and \(T_{ven}\) is the upstream temperature of Venturi.

Then we can get Reynolds number.

\[
Re = \frac{4\dot{m}}{\mu P}
\]

Where \(\mu\) is the dynamic viscosity of cooling air and \(P\) is the perimeter of test section at the inlet.

Cooling air density at the inlet is calculated by following equation,

\[
\rho = \frac{144P_{amb} + P_{inlet}}{R_{gas}(T_{inlet} + 460)}
\]
Where $P_{inlet}$ is inlet pressure measured at inlet of test section, constant coefficient 144 is used to transfer ambient pressure unit to psf, $T_{inlet}$ is average of $T_{in1}$ and $T_{in2}$, which are temperature measured at two sites of inlet. $R_{gas}$ is gas constant and equals to 53.34.

The mean velocity of flow can be gained after gotten mass flow rate and density,

$$U_m = \frac{\dot{m}}{A_{cross} \cdot \rho} \quad (4)$$

Darcy friction factor, $f$ is a non-dimensional parameter to describe pressure drop and flow energy loss in a channel. This parameter is used in both experimental and numerical experiment to show the influence of ribs on flow friction,

$$f = \frac{\Delta p}{4 \left( \frac{L}{D} \right) \rho U_m^2} \quad (5)$$

where $\Delta p$ is pressure drop in the channel, $L$ is the channel's length, $D$ is hydraulic diameter which is,

$$D = \frac{4A_{cross}}{P} \quad (6)$$

where $P$ is cross-section's perimeter.

For pressure drop in this case, there are three different types. Pressure drop for the first part of the channel is,

$$\Delta p_1 = p_1 - p_2 \quad (7)$$
\[ \Delta p_2 = p_3 - p_{\text{amb}} \]  

(8)

Where \( p_1 \) is measured next to the channel inlet and considered as inlet pressure, \( p_2 \) is measured before the flow entering U-bend turn. Their positions are also showed in Figure 8. For the second type \( \Delta p_2 \), \( p_3 \) is the pressure measured after the flow exiting the U-bend turn.

Because of the U-bend turn, we need another friction factor to describe pressure loss at that turn. And this \( k \) is,

\[ k = \frac{\Delta p_{\text{turn}}}{\frac{1}{2} \rho U_m^2} \]  

(9)

where \( \Delta p_{\text{turn}} \) is,

\[ \Delta p_{\text{turn}} = p_2 - p_3 \]  

(10)

To compare those test sections with smooth channel, Blausis correlation is used to calculate smooth wall friction factor.

\[ f_s = \frac{0.316}{Re^{\frac{1}{4}}} \]  

(11)

3.2 Heat Transfer Data Reduction

All the heat transfer data reductions are done by a series of Fortran scripts written by Dr. M. E. Taslim.

The first step is building the test geometry. Inlet aspect ratio, number of heaters, heaters location and angle of ribs are setup in this part.
Form the inlet to the middle point of area we interested, the total heat added into the air flow by heaters is added up and this part is showed in Appendix II.

Then the total heat flux $Q$ created by heaters divides into two parts. One goes through the liquid crystal and added into air flow which is $Q_{heat}$. And another one loss into Plexiglas and polyurethane of test section which is $Q_{loss}$.

Then the mean temperature can be calculated as,

$$T_m = T_{inlet} + \frac{Q - Q_{loss}}{c_p \dot{m}} \quad (12)$$

And the heat transfer coefficient is,

$$h = \frac{Q - Q_{loss}}{(T_s - T_m) \cdot Area} \quad (13)$$

where $T_{surface}$ is surface temperature which can be acquired by color of liquid crystal.

The Nusselt number can be calculated,

$$Nu_{Tur} = \frac{hD}{k} \quad (14)$$

To compare the heat transfer performance of test section, enhancement factor is introduced to this test. Firstly, the Nusselt number of smooth channel is calculated by Dittus-Boelter correlation,

$$Nu_{smooth} = 0.023Re^{0.8}Pr^{0.4} \quad (15)$$
Then the enhancement factor is

\[ EF = \frac{Nu_{Tur}}{Nu_{smooth}} \] (16)

As this study needs figure out the are total Nusselt number, the area weighted average Nusselt number of each investigated area is calculated by,

\[ \overline{Nu} = \frac{\sum Nu_{Tur,i} \cdot Area_{ref,i}}{\sum Area_{ref,i}} \] (17)

The index \( i \) in this equation represents different experimental heat flux output. With increasing heat flux output, green color, which is reference liquid crystal color, travels and its shape’s trajectory covers all the investigated area. Then we can get this average Nusselt number.

Figure 10 shows typical measurement results of a certain area. The no fill symbols are the Nusselt number of each picture taken during the experiment, which is \( Nu_{Tur,i} \). And the solid fill is the area-weighted average Nusselt number of that area of different Reynolds number.
Figure 12. Nusselt Number of Area5 for Baseline

The uncertainty is calculated for each experiment with Kline and McClintock uncertainty analysis.

\[
\Delta F = \sum_{i=1}^{n} \left( \frac{\partial F}{\partial x_i} \Delta x_i \right)^2 \frac{1}{2} \tag{18}
\]

Thermal performance is evaluated by the area weighted number and friction factor of test section and smooth channel. The factor of thermal performance is,

\[
TP = \frac{Nu}{Nu_s} \left( \frac{f}{f_s} \right)^{-\frac{1}{3}} \tag{19}
\]
4. Test Procedure

4.1 Leakage Test

Leakage test is the first step of all the experiments of this study. When the whole test section is assembled and connected to gas supply system, leakage test can be done to make sure all compressed air is going through the test channel until it reaches outlet.

Leakage test is done by following steps. First step is setup cooling air supply. In this step, compressor should be switched on and Venturi should be set to the highest pressure which would be used in experiment. Then soap-suds is applied to all the locations where leakage may happen, which include interfaces of Plexiglas, pressure measurement holes and mounting holes etc. If leakage happened at those locations, a bubble would generate from soap-suds and get enlarged at each leakage location. When all the leaks were located and air supply was stopped, more silicone caulking is applied to these places. After 24 hours for silicone to get solid, another leak test would be operated until there is no leak from the whole test section.

4.2 Cold Test

Cold tests are carried out in order to get pressure drop in the test channel. Three pressure measurement points are showed in figure 9. The plenum pressure is also measured by manometer.

A micromanometer is used to get all the pressure data. After air supply started, this micromanometer is used to connected to pressure measurement holes to get pressure data. All data reading and recording are manually done by test operator.
4.3 Heat Transfer Test

To start a heat transfer test, cooling air supply should be stabilized to get a constant mass flow rate. After a certain Venturi pressure was stabilized, which means mass flow rate has been setup, heating section can be switched on. Then the multimeters are switched on to get voltage and current information to calculate accurate power.

In a typical data recording process, the thermocouple temperatures are recorded first. Then the multimeters take output power to get heat flux. The last step is photography taking. During the last stop, a BBA light bulb is employed to provide with illumination. For every ten different heat flux values, pressures are retaken. This loop will be ended until the green color is no longer visible in the investigating areas.
Numerical Study

1. Mesh

First step of CFD simulation is mesh building. The following two pictures are the meshes used in the CFD simulations.

Figure 13. Mesh of Baseline Geometry

Figure 14. Mesh of Up-Point Geometry
All the meshes used in CFD simulations are structured meshes. Thanks to Discovery Cluster at Northeastern University, we are able to use 15-million meshes in each simulation. Those fine meshes promise a high-level accuracy in the final results.

To make it easier to observe, the rest of the mesh images of this section are node-reduced version. By making the meshes coarser, more details of mesh configuration can be shown.

Using BiGeometric distribution, nodes are much more finer at near wall section than the mesh in the core. To calculate the first mesh height, we use the largest Reynolds number of all experiments and $y^+ \sim 1$. The first height of calculated result is 0.042mm and we set it as 0.01mm. And ratio of nodes increase is from 1.1 to 1.2.

O-grid method is employed for the U-bend turn and space around ribs. As following pictures showed, this method can increase mesh quality and make a finer resolution.

![Figure 15. O-Grid around 180° U-bend Turn](image.png)
Figure 16. O-Grid around Ribs

The final mesh quality is showed in the following pictures.

Figure 17. Determinant Meshes Quality of Baseline (up) and Up-Point (down)

Figure 18. Angle Meshes Quality of Baseline (up) and Up-Point (down)
The following picture shows the number of areas we are interested in. In Up-Point test section, the same rule of naming is employed to number the areas.

![Number of Investigated Area of Baseline](image)

Figure 19. Number of Investigated Area of Baseline

2. **Solver**

The CFD simulations are performed by using Fluent solver by Ansys, Inc., a pressure-correction based, multi-block, multi-grid, unstructured/adaptive 3D double precision solver. Realizable $k-\varepsilon$ turbulence model in combination with enhanced wall treatment approach for the near wall regions is used. The equation of state for an ideal gas is turned on to take the compressibility effects into consideration. For boundary conditions, the mass flow rate is employed at the test section inlet and atmospheric conditions are applied at the outlet. Mesh independence is tested by 5 million, 10 million 15 million and 20 million cells meshes. Meshes in all models are totally hexagonal, a preferred choice for CFD analysis, and are varied in size BiGeometrically from the boundaries to the center of the computational realm in order to have smaller cells close to the walls.

All the calculations are performed on Discovery Cluster. This platform allows 48 cores using for a single run.
Results and Analysis

1. Flow Field Parameters

Friction factor of test section has two different parts. The first is two legs' friction factor which shown by equation (5). Another factor to estimate flow energy loss is shown by equation (9).

First, figures 19 shows mass flow rate variation vs plenum pressure and inlet pressure to test section inlet.

Figure 19. Mass flow rate of Baseline (Up) and Up-Point (Down)
Then friction factors can be analyzed by equation (5). Results are shown in the following figures.

Figure 20. Friction Factors of Baseline (Up) and Up-Point (Down)
Overall, both of those two test sections show that friction factor trend to be stable with increasing Reynolds number. Both experimental and numerical results show that the first channel has lower friction factor than the second channel. An explanation for this behavior is that the blockage ration, which is $e/D_h$, is lower in the first channel because the hydraulic diameter is larger in that leg of test section. Although the turn of those tests has already rounded, it still can increase turbulence level of airflow to a large extend. This turbulence increase consumes more kinetic energy of airflow, which cause more pressure drop in the second channel.
2. Heat Transfer Performance

Following figures are results from the experimental data.
Figure 22. Nusselt Number and Enhancement Factor of Baseline Test Section

Figure 23. Nusselt Number and Enhancement Factor of Up-Point Test Section
Following part is results of CFD simulation.

Figure 24. Nusselt Number of Baseline Test Section, Upside Figure is Nusselt Number of All Areas, Lower Figure is Nusselt Number of Investigated Areas
From previous results we can see the relationship between heat transfer performance and Reynolds number. There is a stronger interaction between the airflow and turbulated surface as the Reynolds number increasing, which contributes to higher Nusselt number. Areas 6, 7 and 8 have the highest Nusselt number among all areas and their enhancement
factors are also the highest. We also can see that the enhancement factors go down with increasing Reynolds number. Similar results are seen from CFD models, although the CFD results of Up-Point simulation is behaving unreasonable. It’s speculated those numerical models don’t convergence properly. The Area 7 has much higher Nusselt number in CFD than the results from experimental for Baseline experiments data. But both experimental and numerical results show that U turn enhance the heat transfer coefficient. A possible explanation for this can be that U-bend turn increases turbulent level of air flow, which enhances the mixing of the cooler core flow with the warmer air close to rib-roughened surface. This also can explain why Area 8 can have high Nusselt number than the average. The flow after U turn has already added turbulent intensity by the turn, so it has stronger interaction with heated surface than the upstream which has not entered the U turn.

![Figure 25. Thermal Performance of Two Test Sections](image)

From the two sets of experimental results we can see that the Up-Point arrangement has better thermal performance than Baseline arrangement except for the second run at the Reynolds number is about 10400.
For detailed heat transfer performance of those areas, we will discuss heat transfer coefficients on each surface in this section both experimentally and numerically. And we will also discuss how flow field influence the heat transfer performance.

Figure 26. Experimental Nusselt number Distribution of Baseline Area4 with Re=20051

Figure 27. CFD Nusselt number Distribution of Baseline Area4 with Re=20381

From those two figures we can see the influence of angled ribs on heat transfer. The airflow comes from left side in both of those two figures. Compared with no angled ribs arrangement, the higher Nusselt number area moves to the up and left side of this area. As G. Rau and M.Cakan[15] found in 1998, the highest Nusselt number should be at the reattachment zone. By analyzing the flow field, we can find the answer.
Figure 28. Flow Vector of Area4 of Baseline with Re=20381, Up(Upside) to Central Line at 0.5 inch and Downside (Downside) to Central Line at 0.5 inch.

We can see that more air with higher velocity runs into upper part of Area4 and reattaches the heated surface on the upside part. This is caused by angled ribs which blocks the airflow first at upper side and let airflow tilt up, which increases airflow velocity and makes a stronger interaction between airflow and heated surface. This also happened in Up-Point experiments and the only difference is that airflow in Up-Point experiments tilts down in Area4.

And we can also see a velocity vector field made up by upside, central and downside cross sections surface in Figure 29.
In this heat transfer study, the U turn also plays an important role which should be discussed. Because of different rib arrangements, U turn areas of two experiments experience two different structures. We divided the turn area into two parts for clearer to analysis.
Figure 30. CFD Nusselt Distribution of Baseline on Area6& Area7

Figure 31. Experimental Nusselt Distribution of Baseline on Area6 & Area7
As shown in Figure 30, we can see there is an obvious strong heat transfer interaction area at the end of U turn. On the upper part of the U turn, which can be considered as U turn entry, heat transfer character is just the same as upstream areas. However, after rounded U turn, airflow hits the downside wall and mixes with airflow from inner U turn area. This causes the high Nusselt number in that area. The same situation happened in Up-Point experiments.

Figure 32. CFD Nusselt Distribution of Up-Point on Area6& Area7
Figure 33. Experimental Nusselt Distribution of Up-Point on Area6& Area7

Figure 34. CFD Turbulent Intensity Distribution of Baseline on Area6& Area7
As shown in figure above, turbulent level can nearly represent local heat transfer coefficient and local Nusselt number in the U turn, just like it is in straight channel. Angled ribs not only increase the turbulent level in the flow, but also tilt the airflow and move the reattachment zone to the area behind the first-blockage parts of ribs. The effect can be clearly shown in the following figures. As the reference temperature is set to 296K.

Figure 35. CFD Nusselt Distribution of Up-Point on Upside Channel

Figure 36. CFD Nusselt Distribution of Up-Point on Downside Channel
Figure 37. CFD Nusselt Distribution of Baseline on Upside Channel

Figure 38. CFD Nusselt Distribution of Baseline on Downside Channel
Conclusion

By performing both experimental and numerical studies, the heat transfer features of an angled rib-roughened channel in turbine airfoils with a 180-degree turn have been investigated. Two types of rib arrangements are studied both numerically and experimentally. It is found that rib arrangement can strongly affect inter-ribs heat transfer coefficient distribution and rounded U turn can strongly enhance heat transfer at the exit of the turn and also has influence on heat transfer distribution.

The main conclusions of this study are:

1. On the average, friction factors of Up-Point arrangement is lower than that of Baseline arrangement.

2. Friction factors do not show strong variation with Reynolds number.

3. The Up-Point arrangement has better thermal performance than Baseline arrangement.

4. angled ribs create a strong spanwisevariation on the aera between the period of ribscan tilt airflow which can move the highest Nusselt number area of inter-rib area to the corner of the first air blockage part of upstrea

5. U turn can strongly enhance heat transfer especially at its exit part of U turn.
Reference


Appendix I. Data Reduction Fortran Code

Baseline Experiment Heat Transfer Data Reduction Code

C  THIS PROGRAM WAS USED FOR AR=6 TESTS IN THE BASEMENT OF EGAN BUILDING. TEST SECTION WAS TWO-LEGGED 33 and 31" LONG, A 180-DEGREE TURN AND 7 HEATERS. SIX MAIN HEATERS (2" x 11") WERE CUSTOM-MADE BY BIRK. THE SMALL 7TH HEATER WAS A WATLOW HEATER

C  CONTROL PANEL ARANGEMENT FOR ONE HEATED WALL CASE

C  CHANNEL 1: FIRST HEATER IN LEG 1 AND LAST HEATER IN LEG 2 IN SERIES

C  CHANNEL 2: SECOND HEATER IN LEG 1

C  CHANNEL 3: THIRD HEATER IN LEG 1

C  CHANNEL 4: SMALL HEATER IN THE MIDDLE OF 180-DEGREE TURN

C  CHANNEL 5: FIRST HEATER IN LEG 2

C  CHANNEL 6: SECOND HEATER IN LEG 2

C  ALL HEATERS 5-mil thick

IMPLICIT REAL*8(A-H,O-Z)

CHARACTER*80 TITLE

REAL*8 Mv,Nut,Nus,Length,Kloss
COMMON Dh,AR,Width,Length,Hlength,P,Rgas,Mv,
&Tin,Tamb,Pamb,Tliquid,Pitch

\[ F(A,P,T) = 0.5215 \times A \times P / \sqrt{T} \]

\[ R_{gas} = 53.34 \]

\[ g_c = 32.2 \quad \text{! proportionality constant in Newton's 2nd law, \( \text{lbm} \cdot \text{ft} / (\text{lbf} \cdot \text{s}^2) \)} \]

\[ H_{gtopsi} = 0.49083935 \quad \text{! converts inches of Hg to psi} \]

\[ H_{2Otopsi} = H_{gtopsi} / 13.6 \quad \text{! converts inches of H2O to psi} \]

\[ O_{itopsi} = 0.827 \times H_{gtopsi} / 13.6 \quad \text{! converts inches of Oil to psi} \]

\[ \pi = 4 \times \tan(1) \]

\[ F_{AC1} = 3.413 \quad \text{! converts Watts to BTU/hr} \]

\[ g_c = 32.2 \quad \text{! \( \text{lbm} \cdot \text{ft} / (\text{lbf} \cdot \text{s}^2) \)} \]

---

**C**

**C** Rectangular Cross Sectional Area

**C**

height = 12. \quad \text{! inches} \n
height = height / 12. \quad \text{! ft} \n
width = 2. \quad \text{! inches} \quad \text{HEATED WALL} \n
width = width / 12. \quad \text{! ft} \n
\[ P = 2 \times \text{height} + 2 \times \text{width} \quad \text{! ft} \]

\[ \text{Across} = \text{height} \times \text{width} \quad \text{! ft}^2 \]
Dh=4.*Across/P         ! ft
RibbedL1=31            ! inches
RibbedL2=29            ! inches
TotalL=31+3+29;        ! inches, INLET PRESSURE TAP TO EXIT

C    AR : defined as top/side

AR=height/width

OPEN(UNIT=1,FILE='input.dat',STATUS='old')
OPEN(UNIT=21,FILE='fric1-plot-heat.out',STATUS='old')
OPEN(UNIT=22,FILE='fric2-plot-heat.out',STATUS='old')
OPEN(UNIT=23,FILE='fric12-plot-heat.out',STATUS='old')
OPEN(UNIT=24,FILE='Kloss-plot-heat.out',STATUS='old')
OPEN(UNIT=3,FILE='uncertainties.out',STATUS='old')
OPEN(UNIT=7,FILE='output.dat',STATUS='old')
OPEN(UNIT=8,FILE='nu-Area1.out',STATUS='old')
OPEN(UNIT=9,FILE='nu-Area2.out',STATUS='old')
OPEN(UNIT=10,FILE='nu-Area3.out',STATUS='old')
OPEN(UNIT=11,FILE='nu-Area4.out',STATUS='old')
OPEN(UNIT=12,FILE='nu-Area5.out',STATUS='old')
OPEN(UNIT=13,FILE='nu-Area6.out',STATUS='old')
READ(1,*)NP,Pitch,NRibs1,NRibs2,RibH,RibW,RibR,alpha1,alpha2,
&Tliquid

WRITE(7,402)NP

402 FORMAT(/,20x,'A total of',I5,2x,'pictures were taken',/)

poe=Pitch/Ribh

eoDh=Ribh/(12*Dh)

C HEAT TRANSFER AREA

Hlength=11.       ! heater length

Hlength=Hlength/12.

Length=3*Hlength  ! Total heated length for radiation losses

Hwidth=2.         ! including the boaders

Hwidth=Hwidth/12.

Area=Hwidth*Hlength  ! sq.ft

DO 1=1,10

READ(1,10)TITLE

WRITE(7,10)TITLE

WRITE(3,10)TITLE
enddo

10 FORMAT(A80,/)  
11 FORMAT(5x,'Photos:',2F8.0)

WRITE(7,100) 12*Height,12*Width,12*Dh,AR,Pitch,
&NRibs1,NRibs2,RibH,RibW,RibR,poe,eoDh,Alpha1,Alpha2,
&TotalL,12*Hlength,12*Hwidth

100 FORMAT(/,
&3x,'Channel Height=' f6.2, ' inches',/, 
&3x,'Channel Width=' f6.2, ' inches',/, 
&3x,'Channel Hydraulic Diameter=' f8.3, ' inches',/, 
&3x,'Channel Aspect Ratio=' f7.3,/, 
&3x,'Rib Pitch=' f7.3, ' inches',/, 
&3x,'No. of Ribs in LEG 1: ',i2,/, 
&3x,'No. of Ribs in LEG 2: ',i2,/, 
&3x,'Rib Height=' f7.3, ' inches',/, 
&3x,'Rib Width=' f7.3, ' inches',/, 
&3x,'Rib Top Corner Radius=' f7.3, ' inches',/, 
&3x,'Rib Pitch to Height=' f7.3,/, 
&3x,'Rib Height to Channel Dh=' f7.3,/, 
&3x,'Rib Angle to Flow direction in LEG 1: ',f5.0,' deg'/, 
&3x,'Rib Angle to Flow direction in LEG 2: ',f5.0,' deg'/, 
&3x,'Rib-Roughened Length=' f7.3, ' inches',/,
&3x,'Heater Length=',f7.3,' inches',/
&3x,'Heater Width=',f7.3,' inches',/)

WRITE(8,450)

450 FORMAT(' PHOTOS     RE         NUT        EF    UNCER ',//)

DO 1 I=1,NP

READ(1,*)Photo1,Photo2,Dthroat,Pven,Tven,Tin1,Tin2,Tamb,
&Pplen,Pinlet,Pup,Pdown,SG,Pamb,V1,A1,V2,A2,V3,A3,V4,A4,
&V5,A5,V6,A6

WRITE(7,*)' ' WRITE(7,11)Photo1,Photo2 WRITE(7,*)' '

WRITE(7,200)V1,A1,V2,A2,V3,A3,V4,A4,V5,A5,V6,A6,
&Dthroat,Pven,Tven,Tin1,Tin2,Tamb,Pplen,Pinlet,Pup,
&Pdown,Pamb,SG
Tin=0.5*(Tin1+Tin2)
TinR=Tin+460.
CALL AIRPROP(TinR,GAMMA,CON,VIS,PR,CP)
VISin=VISin/3600

Pamb=Pamb*Hgtopsi ! psi
Pplenum=2*Pplenum*H2Otopsi
DeltaP1=2*(Pinlet-Pup)*H2Otopsi
DeltaP2=2*Pdown*H2Otopsi
DeltaP12=2*Pinlet*H2Otopsi
DeltaPTurn=2*(Pup-Pdown)*H2Otopsi

! AIR MASS FLOW RATE FROM THE CRITICAL VENTURI

Athroat=PI*(Dthroat**2)/4.

Mv=F(Athroat,Pven+Pamb,Tven+460)

DO 17 kk=1,6
Write(7,*) '  
Write(7,*)' ON AREA',kk  
Write(7,*)'  

! TOTAL HEAT ADDED TO THE AIR BY THE HEATERS FROM THE 
! INLET TO THE POINT IN QUESTION

IF(kk.EQ.1)Q=0.5*V1*A1+V2*A2*((7.769/12)/Hlength) 
IF(kk.EQ.2)Q=0.5*V1*A1+V2*A2+V3*A3*((2.123/12)/Hlength) 
IF(kk.EQ.3)Q=0.5*V1*A1+V2*A2+V3*A3*((8.02/12)/Hlength) 

IF(kk.EQ.4)Q=0.5*V1*A1+V2*A2+V3*A3+V4*A4+V5*A5*((2.98/12)/Hlength) 

IF(kk.EQ.5)Q=0.5*V1*A1+V2*A2+V3*A3+V4*A4+ 
&V5*A5*((8.977/12)/Hlength) 

IF(kk.EQ.6)Q=0.5*V1*A1+V2*A2+V3*A3+V4*A4+V5*A5+ 
&V6*A6*((3.33/12)/Hlength) 

Q=Q*FAC1

! HEAT FLUX, BTU/(sqft.Sec)

IF(kk.LE.1)Flux=V2*A2*FAC1/(Area);
IF (kk.GT.1.AND.kk.LE.3) Flux=V3*A3*FAC1/(Area);
IF (kk.GT.3.AND.kk.LE.5) Flux=V5*A5*FAC1/(Area);
IF (kk.GT.5) Flux=V6*A6*FAC1/(Area);

C write(6,*)'kk,Q,Flux',kk,Q,Flux
CALL COEFFICIENT(Q,Flux,Tm,Tback,hturb,Floss,kk)

! FILM TEMPERATURE

TF=(Tback+Tm)/2.

! DENSITY AT FILM TEMPERATURE

RHO=((Pamb+0.5*DeltaP)*144)/(Rgas*(TF+460.))

! OTHER PROPERTIES AT FILM TEMPERATURE

TfR=TF+460.
CALL AIRPROP(TfR,GAMMA,CON,VIS,PR,CP)
VIS=VIS/3600

! REYNOLDS NUMBER

Re=4.*Mv/(P*VIS)
SMOOTH CHANNEL NUSSELT NUMBER FROM DITTUS-BOELTER CORRELATION

Nus = 0.023*(RE**0.8)*(PR**0.4)

NUSELT NUMBER

Nut = Hturb*Dh/Con

ENHANCEMENT FACTOR = Nut/Nus

EF = Nut/Nus

AVERAGE VELOCITY, Um, ft/Sec.

UM = MV/(Across*RHO)

FRICTION FACTORS AND TURN LOSSES

FRIC1 = 2*gc*144*DeltaP1*(12*Dh/RibbedL1)/(RHO*Um*Um)
FRIC2 = 2*gc*144*DeltaP2*(12*Dh/RibbedL2)/(RHO*Um*Um)
FRIC12 = 2*gc*144*DeltaP12*(12*Dh/TotalL)/(RHO*Um*Um)
Kloss = 2*gc*144*DeltaPturn/(RHO*Um*Um)
IF(kk.eq.4)Write(21,405)Re,FRIC1
IF(kk.eq.4)Write(22,405)Re,FRIC2
IF(kk.eq.4)Write(23,405)Re,FRIC12
IF(kk.eq.4)Write(24,405)Re,Kloss

!  UNCERTAINTY ANALYSIS

IF(kk.eq.4)CALL UNCERTAIN(Pamb,Pven,Tven,a1,V1,a2,V2,a3,
    &V3,Dthroat,Area,Tback,Tin,Floss,Uncer)

IF(kk.eq.4)WRITE(7,300)TM,MV,UM,RE,FRIC12
IF(kk.eq.4)WRITE(7,401)NUS,NUT,EF,UNCER
IF(kk.ne.4)WRITE(7,407)NUS,NUT,EF

IF(kk.eq.1)WRITE(8,403)Photo1,Photo2,RE,NUT,EF
IF(kk.eq.2)WRITE(9,403)Photo1,Photo2,RE,NUT,EF
IF(kk.eq.3)WRITE(10,403)Photo1,Photo2,RE,NUT,EF
IF(kk.eq.4)WRITE(11,404)Photo1,Photo2,RE,NUT,EF,UNCER
IF(kk.eq.5)WRITE(12,403)Photo1,Photo2,RE,NUT,EF
IF(kk.eq.6)WRITE(13,403)Photo1,Photo2,RE,NUT,EF

17 ENDDO

1 CONTINUE
405 FORMAT(10X,E12.5,10X,E12.5)
406 FORMAT(10X,'Friction Factor= ',E10.4)
403 FORMAT(1X,2F7.0,1X,E11.6,1X,E11.6,1X,E11.6)
404 FORMAT(1X,2F7.0,1X,E11.6,1X,E11.6,1X,E11.6,1X,E9.3)

300 FORMAT(/,X,'Tm=',F6.2,1X,' Mv=',E9.3,1X,
       &' Um=',F6.2,1X,'Re=',F8.2,1X,'f (darcy)=',F8.4)
401 FORMAT(X,'NUs=',F8.3,2X,'NUt=',F8.3,2X,' EF=',F7.4,2X,
       &'% UNCER (in h) =',F7.2)
407 FORMAT(X,'NUs=',F8.3,2X,'NUt=',F8.3,2X,' EF=',F7.4)

REWIND 1
READ(1,*),dum
DO i=1,10
   READ(1,10),TITLE
   WRITE(8,10),TITLE
enddo

STOP
END

C**********************************************************************C
SUBROUTINE UNCERTAIN(Pamb,Pven,Tven,i1,V1,i2,V2,i3,V3,Dth,
&Harea,Tsurf,Tin,Losses,Uncer)

IMPLICIT REAL*8(A-H,O-Z)
REAL*8 i1,i2,i3,Losses,M1,M2

PI=4.*ATAN(1.E00)

FAC1=3.413 ! converts Watts to BTU/hr

C=0.24*0.5215*3600

P1=Pven+Pamb
T1=Tven+460.0
TI=Tin
TS=Tsurf
a=Harea
f=0.729

ATH=PI*(Dth**2)/4.
DATH=PI*((Dth+0.001)**2)/4. -ATH

h=((FAC1*(V3*i3)/a)-Losses)/
&(TS-TI-(SQRT(T1)*(FAC1*(0.5*V1*i1+V2*i2+f*V3*i3)))/(C*P1*ATH))
WRITE(3,*) '  '  
WRITE(3,*) ' h =\,h,\, BUT/hr.sq.ft'  
  
H2=h*h  
  
C  
C       i3 v3  
C       ------ - Floss  
C       a3  
C       ---------------------------------------------  
C       sqrt(T1)(0.5 i1 v1 + i2 v2 + f i3 v3)  
C       Ts-Ti - --------------------------------------  
C       C P1 A_throat  
C  
  
DLOSS=0.1*Losses  
  
dv1=0.1  
dv2=0.1  
dv3=0.1  
  
di1=0.01  
di2=0.01  
di3=0.01
\[da = \frac{1}{(32.32.144)}\]
\[dts = 0.5\]
\[dti = 0.5\]
\[dt1 = 0.5\]
\[dp1 = 0.5\]
\[Df = 0.1\]
\[C1 = FAC1 \times (V3 \times i3/a) - \text{Losses}\]
\[Q1 = C \times P1 \times \text{Ath}\]
\[Q2 = Q1 \times \sqrt{T1}\]
\[M1 = (Ts-Ti) \times Q1\]
\[A = FAC1 \times (0.5 \times i1 \times v1 + i2 \times v2)\]
\[B = FAC1 \times i3 \times v3\]
\[M2 = M1 - \sqrt{T1} \times (A + f \times B)\]

\[DHDF = B \times Q1 \times C1 \times \sqrt{T1} / (M2^2)\]
\[DHDTI = C1 \times (Q1^2) / (M2^2)\]
\[DHDTS = -C1 \times (Q1^2) / (M2^2)\]
\[DHDA = -(FAC1 \times i3 \times v3) \times Q1 / (M2^2)\]
\[DHDLOSS = -Q1 / M2\]

\[DHDI1 = 0.5 \times FAC1 \times v1 \times Q1 \times C1 \times \sqrt{T1} / (M2^2)\]
\[DHDV1 = 0.5 \times FAC1 \times i1 \times Q1 \times C1 \times \sqrt{T1} / (M2^2)\]
\[
\begin{align*}
DHDI2 &= FAC1 \cdot v2 \cdot Q1 \cdot C1 \cdot \sqrt{T1} / (M2^{2}) \\
DHDV2 &= FAC1 \cdot i2 \cdot Q1 \cdot C1 \cdot \sqrt{T1} / (M2^{2}) \\
DHDI3 &= FAC1 \cdot v3 \cdot Q1 \cdot (M2 + C1 \cdot f \cdot a \cdot \sqrt{T1}) / (a \cdot (M2^{2})) \\
DHDV3 &= FAC1 \cdot i3 \cdot Q1 \cdot (M2 + C1 \cdot f \cdot a \cdot \sqrt{T1}) / (a \cdot (M2^{2})) \\
\end{align*}
\]

\[
\begin{align*}
DHDATH &= C1 \cdot C \cdot P1 \cdot (M2 - M1) / (M2^{2}) \\
DHDP1 &= C1 \cdot C \cdot \text{Ath} \cdot (M2 - M1) / (M2^{2}) \\
DHDT1 &= 0.5 \cdot C1 \cdot Q1 / (T1 \cdot (\sqrt{T1} \cdot (A + f \cdot B))) \\
\end{align*}
\]

\[
\begin{align*}
ZF &= (DF \cdot DHDF)^{2} \\
ZA &= (DA \cdot DHDA)^{2} \\
\end{align*}
\]

\[
\begin{align*}
ZI1 &= (DI1 \cdot DHDI1)^{2} \\
ZV1 &= (DV1 \cdot DHDV1)^{2} \\
\end{align*}
\]

\[
\begin{align*}
ZI2 &= (DI2 \cdot DHDI2)^{2} \\
ZV2 &= (DV2 \cdot DHDV2)^{2} \\
\end{align*}
\]

\[
\begin{align*}
ZI3 &= (DI3 \cdot DHDI3)^{2} \\
ZV3 &= (DV3 \cdot DHDV3)^{2} \\
\end{align*}
\]

\[
\begin{align*}
ZTS &= (DTS \cdot DHDTS)^{2} \\
ZTI &= (DTI \cdot DHDTI)^{2} \\
\end{align*}
\]
ZATH = (DATH * DHDATH)**2
ZP1 = (DP1 * DHDP1)**2
ZT1 = (DT1 * DHDT1)**2
ZFLOSS = (DLOSS * DHDLOSS)**2

Uncer = 100 * SQRT((ZI1 + ZI2 + ZI3 + ZV1 + ZV2 + ZV3 +
& ZA + ZTS + ZTI + ZATH + ZP1 + ZT1 + ZFLOSS + ZF) / (H2))

WRITE(3, *) 'TOTAL UNCER. %:', Uncer
WRITE(3, *)
WRITE(3, *)' % Uncer. assoc. with f', 100. * sqrt(ZF) / h
WRITE(3, *)' % Uncer. assoc. with I1', 100. * sqrt(ZI1) / h
WRITE(3, *)' % Uncer. assoc. with V1', 100. * sqrt(ZV1) / h
WRITE(3, *)' % Uncer. assoc. with I2', 100. * sqrt(ZI2) / h
WRITE(3, *)' % Uncer. assoc. with V2', 100. * sqrt(ZV2) / h
WRITE(3, *)' % Uncer. assoc. with I3', 100. * sqrt(ZI3) / h
WRITE(3, *)' % Uncer. assoc. with V3', 100. * sqrt(ZV3) / h
WRITE(3, *)' % Uncer. assoc. with Tin', 100. * sqrt(ZTI) / h
WRITE(3, *)' % Uncer. assoc. with Ts', 100. * sqrt(ZTS) / h
WRITE(3, *)' % Uncer. assoc. with Tven', 100. * sqrt(ZT1) / h
WRITE(3, *)' % Uncer. assoc. with Pven', 100. * sqrt(ZP1) / h
WRITE(3, *)' % Uncer. assoc. with Aheater', 100. * sqrt(ZA) / h
WRITE(3, *)' % Uncer. assoc. with Floss', 100. * sqrt(ZFLOSS) / h
WRITE(3, *)' % Uncer. assoc. with Athroat', 100. * sqrt(ZATH) / h
SUBROUTINE EQSOLVE(A,B,NA,NDIM,NB)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION A(NDIM,NDIM),B(NDIM,NB)
DO 291 J1=1,NA
C FIND REMAINING ROW CONTAINING LARGEST ABSOLUTE
C VALUE IN PIVOTAL COLUMN.
101 TEMP=0.
   DO 121 J2=J1,NA
      IF(ABS(A(J2,J1))-TEMP) 121,111,111
111 TEMP=ABS(A(J2,J1))
   IBIG=J2
121 CONTINUE
IF(IBIG-J1)5001,201,131
C REARRANGING ROWS TO PLACE LARGEST ABSOLUTE
C VALUE IN PIVOT POSITION.

131 DO 141 J2=J1,NA
   TEMP=A(J1,J2)
   A(J1,J2)=A(IBIG,J2)
141 A(IBIG,J2)=TEMP
   DO 161 J2=1,NB
   TEMP=B(J1,J2)
   B(J1,J2)=B(IBIG,J2)
161 B(IBIG,J2)=TEMP

C COMPUTE COEFFICIENTS IN PIVOTAL ROW.

201 TEMP=A(J1,J1)
   DO 221 J2=J1,NA
221 A(J1,J2)=A(J1,J2)/TEMP
   DO 231 J2=1,NB
231 B(J1,J2)=B(J1,J2)/TEMP
   IF(J1-NA)236,301,5001

C COMPUTE NEW COEFFICIENTS IN REMAINING ROWS.

236 N1=J1+1
   DO 281 J2=N1,NA
   TEMP=A(J2,J1)
   DO 241 J3=N1,NA
241 A(J2,J3)=A(J2,J3)-TEMP*A(J1,J3)
   DO 251 J3=1,NB
251 \[ B(J2,J3) = B(J2,J3) - \text{TEMP} \cdot B(J1,J3) \]

281 CONTINUE

291 CONTINUE

C OBTAINING SOLUTIONS BY BACK SUBSTITUTION.

301 IF(NA-1)5001,5001,311

311 DO 391 J1=1,NB

\[ N1 = NA \]

321 DO 341 J2=N1,NA

341 \[ B(N1-1,J1) = B(N1-1,J1) - B(J2,J1) \cdot A(N1-1,J2) \]

\[ N1 = N1 - 1 \]

391 CONTINUE

5001 CONTINUE

RETURN

END

SUBROUTINE COEFFICIENT(Q,Fluxb,Tm,Tback,hback,Floss,kk)

IMPLICIT REAL*8(A-H,O-Z)

CHARACTER*8 PHOTOS

REAL*8 kinc,kadh,kkap,kmyl,kpoly,ksty,kblack,kliq,kplex,
&Length,Mv

COMMON Dh,AR,Width,Length,Hlength,P,Rgas,Mv,
&Tin,Tamb,Pamb,Tliquid,Pitch
C BACK WALL (LIQUID CRYSTAL WALL)

C FROM THE CENTER OF HEATING ELEMENT TO THE AMBIENT AIR

C 0.75 mil INCONEL HEATING ELEMENT ----- 0.5 mil ADHESIVE ----- 1 mil KAPTON ---- 2 mil DOUBLE-SIDED TAPE ----- 4 inches

C POLYURETHANE ---- AMBIENT

C tinc/kinc -- tadh1/kadh -- tkap/kkap -- tadh2/kadh --

C tpoly/kpoly -- 1/ho

C FROM THE CENTER OF HEATING ELEMENT TO THE AIR INSIDE THE TEST SECTION

C 0.75 mil INCONEL HEATING ELEMENT ----- 0.5 mil ADHESIVE

C ----- 1.0 mil ---- KAPTON ---- 3.5 mil ADHESIVE ----

C 3.0 mil ---- ABSORPTIVE BLACK BACKGROUND ---- 2.0 mil

C LIQUID CRYSTAL ---- 5.0 mil ---- MYLAR ---- AIR INSIDE THE

C TEST SECTION

C tinc/kinc -- tadh1/kadh -- tkap/kkap -- tadh3/kadh --

C -- tblack/kblack -- tliq/kliq -- tmyl/kmyl -- 1/hi

C TOP, FRONT AND BOTTOM WALLS
FROM THE INSIDE AIR TO THE AMBIENT AIR

AIR INSIDE ---- 0.5 inches PLEXIGLAS ---- 1.375 inches

STYROFOAM ---- AMBIENT AIR

1/hi -- tplex/kplex -- tsty/ksty -- 1/ho

Heat transfer coefficient on the outer surface

De=9./12.        ! ft, Average test section side with insulation
TambR=Tamb+460

CALL AIRPROP(TambR,GAMMA,CON,VIS,PR,CP)

VIS=VIS/3600

ho=0.36*con/De    ! Ozisik, Page 443

tinc = 2.0e-03/12. ! BIRK

tadh1 = 0.5e-03/12. ! BIRK

tadh2 = 2.0e-03/12.

tadh3 = 3.5e-03/12. ! double-stck tape used on top of L.C. glue

tkap = 1.0e-03/12. ! MINCO's fact sheet
tpoly = 4./12.

tplex = 0.5/12.

tsty = 2./12.

tblack = 3.0e-03/12.  ! absorptive black background (from DAVIS)

tliq = 2.0e-03/12.   ! liquid crystal thickness (from DAVIS)

tmyl = 5.0e-03/12.  ! MYLAR thickness (from DAVIS)

kkap = 0.0942        ! BTU/hr.ft.F  MINCO (0.163 W/m.K)
ksty = 0.02          ! BTU/hr.ft.F

kpoly = 0.543        ! BTU/hr.ft.F from GOLDENWEST INC. BTU/(ft.hr.F)
kplex = 0.11         ! BTU/hr.ft.F  AIN Plastics k=1.3 BTU/hr.F.sqft/in,

kadh = 0.1272        ! BTU/hr.ft.F  MINCO  (0.220 W/m.K)
kinc = 9.0152        ! BTU/hr.ft.F  MINCO (inconel 600  K=15.6 W/m.K)
kblack = 0.165       ! BTU/hr.ft.F  Glycerin

tliq = 0.165         ! BTU/hr.ft.F  Glycerin
\[ R_{\text{inc}} = \frac{t_{\text{inc}}}{k_{\text{inc}}} \]

\[ R_{\text{adh1}} = \frac{t_{\text{adh1}}}{k_{\text{adh}}} \]
\[ R_{\text{adh2}} = \frac{t_{\text{adh2}}}{k_{\text{adh}}} \]
\[ R_{\text{adh3}} = \frac{t_{\text{adh3}}}{k_{\text{adh}}} \]

\[ R_{\text{kap}} = \frac{t_{\text{kap}}}{k_{\text{kap}}} \]

\[ R_{\text{poly}} = \frac{t_{\text{poly}}}{k_{\text{poly}}} \]

\[ R_{\text{sty}} = \frac{t_{\text{sty}}}{k_{\text{sty}}} \]

\[ R_{\text{plex}} = \frac{t_{\text{plex}}}{k_{\text{plex}}} \]

\[ R_{\text{black}} = \frac{t_{\text{black}}}{k_{\text{black}}} \]

\[ R_{\text{liq}} = \frac{t_{\text{liq}}}{k_{\text{liq}}} \]

\[ R_{\text{myl}} = \frac{t_{\text{myl}}}{k_{\text{myl}}} \]

\[ R_{\text{conv}} = \frac{1}{\alpha} \]

\[ R_{\text{back}} = 0.5R_{\text{inc}} + R_{\text{adh1}} + R_{\text{kap}} + R_{\text{adh2}} + R_{\text{poly}} + R_{\text{conv}} \]
\[ R_{\text{front}} = 0.5 \cdot R_{\text{inc}} + R_{\text{adh1}} + R_{\text{kap}} + R_{\text{adh3}} + R_{\text{black}} + R_{\text{liq}} \]

\[ \text{Theater} = \frac{\text{fluxb} + \frac{T_{\text{amb}}}{R_{\text{back}}} + \frac{T_{\text{liquid}}}{R_{\text{front}}}}{(1./R_{\text{back}} + 1./R_{\text{front}})} \]

\[ \text{flback} = \frac{\text{Theater} - T_{\text{amb}}}{R_{\text{back}}} \quad \text{! loss from the back side} \]

\[ \text{ffront} = \frac{\text{Theater} - T_{\text{liquid}}}{R_{\text{front}}} \]

\[ T_{\text{back}} = T_{\text{liquid}} - \text{ffront} \cdot R_{\text{myl}} \quad \text{! Surface temperature, } T_s \]

\[ \text{perloss} = 100. \cdot (\text{flback} / \text{fluxb}) \]

\[ \text{WRITE}(7,*)' ' \]
\[ \text{WRITE}(7,*)' LIQUID CRYSTAL SIDE' \]
\[ \text{WRITE}(7,*)' ' \]
\[ \text{WRITE}(7,101) \text{Theater, fluxb, flback, ffront, perloss, } T_{\text{liquid}}, T_{\text{back}}, T_{\text{amb}}, \text{ho} \]

100 FORMAT(/,5X,'HEATER TEMPERATURE = ',F8.3,' F',/,
&5X,'TOTAL HEAT FLUX = ',F8.3,' BTU/hr.sqft',/,
&5X,'HEAT FLUX TO THE BACK = ',F8.3,' BTU/hr.sqft',/,
&5X,'HEAT FLUX TO THE FRONT = ',F8.3,' BTU/hr.sqft',/,
&5X,'% OF HEAT LOST FROM THE BACK SIDE = ',F8.3,/,
&5X,'LIQUID CRYSTAL TEMPERATURE = ',F8.3,' F',/,
&5X,'SURFACE TEMPERATURE = ',F8.3,' F',/,
&5X,'AMBIENT TEMPERATURE = ',F8.3,' F',/,
&5X,'U_{\text{inf}} where camera is located = ',F8.3,' ft/s',/,
&5X,'Re based on the test section outer dimension = ',E13.6,/,
&5X,'Outer heat transfer coefficient= ',F8.3,
&' BTU/hr.sqft.F')

101 FORMAT(/,5X,'HEATER TEMPERATURE = ',F8.3,'  F',/, 
&5X,'TOTAL HEAT FLUX = ',F8.3,'  BTU/hr.sqft',/, 
&5X,'HEAT FLUX TO THE BACK = ',F8.3,'  BTU/hr.sqft',/, 
&5X,'HEAT FLUX TO THE FRONT = ',F8.3,'  BTU/hr.sqft',/, 
&5X,'% OF HEAT LOST FROM THE BACK SIDE = ',F8.3,/, 
&5X,'LIQUID CRYSTAL TEMPERATURE = ',F8.3,'  F',/, 
&5X,'SURFACE TEMPERATURE = ',F8.3,'  F',/, 
&5X,'AMBIENT TEMPERATURE = ',F8.3,'  F',/, 
&5X,'Outer heat transfer coefficient= ',F8.3,
&' BTU/hr.sqft.F')

IF(kk.EQ.1)Atop=AR*Width*Hlength*(1+((7.769/12)/Hlength))
IF(kk.EQ.2)Atop=AR*Width*Hlength*(2+((2.123/12)/Hlength))
IF(kk.EQ.3)Atop=AR*Width*Hlength*(2+((8.02/12)/Hlength))
IF(kk.EQ.4)Atop=AR*Width*Hlength*(3+((2/12)/Hlength))
IF(kk.EQ.5)Atop=AR*Width*Hlength*(3+((8.977/12)/Hlength))
IF(kk.EQ.6)Atop=AR*Width*Hlength*(4+((3.33/12)/Hlength))

IF(kk.EQ.1)Aback=Width*Hlength*(1+((7.769/12)/Hlength))
IF(kk.EQ.2)Aback=Width*Hlength*(2+((2.123/12)/Hlength))
IF(kk.EQ.3)Aback=Width*Hlength*(2+((8.02/12)/Hlength))
IF(kk.EQ.4)Aback=Width*Hlength*(3+((2/12)/Hlength))
IF(kk.EQ.5) Aback = Width*Hlength*(3+((8.977/12)/Hlength))
IF(kk.EQ.6) Aback = Width*Hlength*(4+((3.33/12)/Hlength))

Abot = Atop
Afront = Aback

C write(6,*)'Atop,Abot,Aback,Afront',Atop,Abot,Aback,Afront

! AIR INLET ENTHALPY

TinR = Tin + 460
CALL AIRPROP(TinR,GAMMA,CON,VIS,PR,CP)
VIS = VIS/3600
Hin = CP*TinR

! ITERATIONS STARTS HERE

! INITIAL GUESSES

Hout = Hin + (Q/(3600.*Mv))
TmR = Hout/CP
Tm = TmR - 460

hback = (Fluxb-Flback)/(Tback-Tm)
hfront = hback
htop = 0.8*hback
hbot = htop

Ttop = Tm
Tfront = Tm
Tbot = Tm

DO l = 1, 20

! RADIATIONAL LOSSES

call rad(AR, Width, Length, Tback, Ttop, Tfront, Tbot,
& Frback, Frtop, Frfront, Frbot)

C write(6, *)'Frback', Frback
C write(6, *)'Frtop', Frtop
C write(6, *)'Frfront', Frfront
C write(6, *)'Frbot', Frbot

C FLUX LOSSES FROM TOP, BOTTOM AND FRONT WALLS

R1 = Rplex + Rsty + Rconv ! from surface to ambient
! TOP WALL

R3 = 1./htop

Ttop = (((1./R3)*Tm + (1./R1)*Tamb - Frtop) / ((1./R1) + (1./R3)))

Fltop = (Ttop - Tamb) / R1

! BOTTOM WALL

R3 = 1./hbot

Tbot = (((1./R3)*Tm + (1./R1)*Tamb - Frbot) / ((1./R1) + (1./R3)))

Flbot = (Tbot - Tamb) / R1

! FRONT WALL

R3 = 1./hfront

Tfront = (((1./R3)*Tm + (1./R1)*Tamb - Frfront) / ((1./R1) + (1./R3)))

Fflfront = (Tfront - Tamb) / R1

! TOTAL HEAT LOSS TO THE AMBIENT

Qwaste = Fltop*Atop + Flbot*Abot + Flfront*Afront + Flback*Aback

! NET HEAT ADDED TO THE AIR FROM THE INLET TO THE POINT IN QUESTION
\[ \text{Qadd} = Q - Q_{\text{waste}} \]

\[ \text{Hout} = \text{Hin} + \frac{\text{Qadd}}{(3600 \cdot Mv)} \]

\[ \text{TmR} = \frac{\text{Hout}}{\text{CP}} \]
\[ \text{Tm} = \text{TmR} - 460. \]
\[ \text{CALL AIRPROP(TmR,GAMMA,CON,VIS,PR,CP)} \]
\[ \text{VIS} = \text{VIS} / 3600 \]

\[ \text{Floss} = \text{Flback} + \text{Frback} \]
\[ \text{hback} = \frac{\text{Fluxb - Flback - Frback}}{(\text{Tback} - \text{Tm})} \]
\[ \text{hfront} = \text{hback} \]

\[ \text{CALL AIRPROP(TmR,GAMMA,CON,VIS,PR,CP)} \]
\[ \text{VIS} = \text{VIS} / 3600 \]

\[ \text{Floss} = \text{Flback} + \text{Frback} \]
\[ \text{hback} = \frac{\text{Fluxb - Flback - Frback}}{(\text{Tback} - \text{Tm})} \]
\[ \text{hfront} = \text{hback} \]

\[ \text{CALL AIRPROP(TmR,GAMMA,CON,VIS,PR,CP)} \]
\[ \text{VIS} = \text{VIS} / 3600 \]
Tf=(Tback+Tm)/2.

! DENSITY AT FILM TEMPERATURE

RH0=Pamb/(Rgas*(Tf+460.))

! OTHER PROPERTIES AT FILM TEMPERATURE

TfR=Tf+460.

CALL AIRPROP(TfR,GAMMA,CON,VIS,PR,CP)

VIS=VIS/3600

Re=4.*Mv/(P*vis)

! HEAT TRANSFER COEFFICIENT ON THE NON-TURBULATED WALL

htop=0.8*hback
hbot=htop

FNETTOP=htop*(Ttop-Tm)+Fltop+Frtop
FNETBOT=hbot*(Tbot-Tm)+Flbot+Frbot
FNETFRONT=hfront*(Tfront-Tm)+Flfront+Frfront
IF(abs(FNETTOP).le.0.001.AND.abs(FNETFRONT).le.0.001)
&go to 34

enddo

write(7,400)
400 FORMAT(/,20x,'***** Did not converge after 20 iterations',
   &'*****',/)

WRITE(9,410)Re,PHOTOS,FNETTOP,FNETFRONT,FNETBOT
410 FORMAT(5X,'Re=',E12.5,5X,'PHOTOS',A8,5X,
   &'FNETTOP,FNETFRONT & FNETBOT=',3E15.5,/)  
   GO TO 503

34 WRITE(7,500)I,FNETTOP,FNETFRONT,FNETBOT
500 FORMAT(/,5x,'Convergence after',i4,' iterations ',/,5X,
   &'FNETTOP,FNETFRONT & FNETBOT =',3E15.5,/)  

503 continue
   write(7,110)Tback,Ttop,Tfront,Tbot
110 FORMAT(5x,'Back, Top, Front and Botom Wall Temperatures: ',
   &/,10x,4F10.2,' F')
   write(7,115)Tm,Tf
115 FORMAT(5X,'Air Mixed Mean and Film Temperatures',2F9.3,' F')
write(7,120) hback,htop
120 FORMAT(5x,'hturb=',F8.3,5X,'hunt=',F8.3,
&'  BTU/hr.sqft.F')
write(7,170) Q
170 format(5x,'Total Elect. Power=',F8.3,'  BTU/hr')
write(7,116) Qwaste
116 FORMAT(5X,'Total Heat Loss to Ambient=',F8.3,' BTU/hr')
write(7,190) Fluxb,Fluxtop,Fluxf,Fluxbot
190 FORMAT(5X,'Heat Fluxes Generated by Back, Top, Front and'
&' Bottom Heaters:',/,10x,4F10.3,'  BTU/sqft.hr')
write(7,180) Flback,Fltop,Flfront,Flbot
180 FORMAT(5X,'Flux Losses from Back, Top, Front and'
&' Bottom Surfaces:',/,10x,4F10.3,'  BTU/sqft.hr')
write(7,150) Frback,Frtop,Frfront,Frbot
150 FORMAT(5X,'Radiative Fluxes from Back, Top, Front and'
&' Bottom Surfaces:',/,10x,4F10.3,'  BTU/sqft.hr')
RETURN
END

SUBROUTINE RAD(AR,Width,Length,Tback,Ttop,Tfront,Tbot,
&Frback,Frtop,Frfront,Frbot)
IMPLICIT REAL*8(A-H,O-Z)
REAL*8 Length
DIMENSION A(4,4),B(4,1),E(4),T(4),Q(4)
W = Width
H = AR * Width
H = H / Length
W = W / Length
T(1) = T_{back} + 460.
T(2) = T_{top} + 460.
T(3) = T_{front} + 460.
T(4) = T_{bot} + 460.

C Emissivities

E(1) = 0.85 ! Liquid Crystal Foil
E(2) = 0.9 ! PLEXIGLAS
E(3) = 0.9 ! PLEXIGLAS
E(4) = 0.9 ! PLEXIGLAS

N = 4
PI = 4. * ATAN(1.E00)
SIGMA = 0.1712E-08

C WRITE(7,150)
150 FORMAT(//,20X,'SHAPE FACTORS',//)

C Shape Factors SIEGAL AND HOWELL
\[ W2 = W^2 \]
\[ H2 = H^2 \]
\[ Z1 = \frac{1}{\pi W} \]
\[ Z2 = W \times \text{ATAN}(1/W) \]
\[ Z3 = H \times \text{ATAN}(1/H) \]
\[ Z = \sqrt{H^2 + W^2} \]
\[ Z4 = -Z \times \text{ATAN}(1/Z) \]
\[ Z = (1+W^2)(1+H^2) \]
\[ ZZ = 1+W^2+H^2 \]
\[ Z5 = Z/ZZ \]
\[ Z = W^2 ZZ / ((1+W^2)(W^2+H^2)) \]
\[ Z6 = Z^2 W^2 \]
\[ Z = H^2 ZZ / ((1+H^2)(W^2+H^2)) \]
\[ Z7 = Z^2 H^2 \]
\[ Z8 = 0.25 \times \log(Z5 Z6 Z7) \]
\[ F12 = Z1 (Z2 + Z3 + Z4 + 0.25 \times \log(Z5 Z6 Z7)) \]
\[ F11 = 0. \]
\[ F14 = F12 \]
\[ F13 = 1.-F11-F12-F14 \]
F21 = (W/H) * F12
F22 = 0.
F23 = F21
F24 = 1. - F21 - F22 - F23
F31 = F13
F32 = F12
F33 = 0.
F34 = F14
F41 = F21
F42 = F24
F43 = F23
F44 = 0.

C WRITE (6, 110) F11, F12, F13, F14
C WRITE (6, 120) F21, F22, F23, F24
C WRITE (6, 130) F31, F32, F33, F34
C WRITE (6, 140) F41, F42, F43, F44

110 FORMAT (5X, 'F11=', F6.4, 5X, 'F12=', F6.4, 5X, 'F13=', F6.4,\
           &5X, 'F14=', F6.4, /)
120 FORMAT (5X, 'F21=', F6.4, 5X, 'F22=', F6.4, 5X, 'F23=', F6.4,\
&5X,'F24=','F6.4,/

130 FORMAT(5X,'F31=','F6.4,5X,'F32=','F6.4,5X,'F33=','F6.4,
&5X,'F34=','F6.4,/

140 FORMAT(5X,'F41=','F6.4,5X,'F42=','F6.4,5X,'F43=','F6.4,
&5X,'F44=','F6.4,/

C WRITE(7,160)

160 FORMAT(/,20X,'EMISSIVITIES',//)

C WRITE(7,100)(I,E(I),I=1,N)

C WRITE(7,170)

170 FORMAT(/,20X,'TEMPERATURES IN R',//)

C WRITE(7,100)(I,T(I),I=1,N)

A(1,1)=F11-1./(1.-E(1))
A(1,2)=F12
A(1,3)=F13
A(1,4)=F14

A(2,1)=F21
A(2,2)=F22-1./(1.-E(2))
A(2,3)=F23
A(2,4)=F24

A(3,1)=F31
A(3,2)=F32
A(3,3)=F33-1./(1.-E(3))
\[ A(3,4) = F_{34} \]

\[ A(4,1) = F_{41} \]

\[ A(4,2) = F_{42} \]

\[ A(4,3) = F_{43} \]

\[ A(4,4) = F_{44} \frac{1}{1 - E(4)} \]

C WRITE(7,180)

180 FORMAT(//,20X,'COEFFICIENT MATRIX',/)

C WRITE(7,200)((A(I,J),J=1,N),I=1,N)

DO I=1,N

\[ B(I,1) = -E(I) \times \sigma(T(I)^2) \times (T(I)^2)/(1 - E(I)) \]

ENDDO

C WRITE(7,250)

C WRITE(7,100)(I,B(I,1),I=1,N)

200 FORMAT(1X,4E15.6)

250 FORMAT(/,20X,'RIGHT HAND SIDE ',/)

C WRITE(7,55)

55 FORMAT(//,20X,'GAUSSIAN ELIMINATION METHOD',/)

CALL EQSOLVE(A,B,N,N,1)

C WRITE(7,50)

C WRITE(7,100)(I,B(I,1),I=1,N)

DO I=1,N

\[ Q(I) = E(I) \times (\sigma(T(I)^2) \times (T(I)^2) - B(I,1))/(1 - E(I)) \]

)
ENDDO

Frback= q(1)
Frtop= q(2)
Frfront=q(3)
Frbot= q(4)

C WRITE(7,350)
C WRITE(7,100)(I,Q(I),I=1,N)
100 FORMAT(4(I3,E15.6))
50 FORMAT(/,20X,'RADIOCITIES',/)
350 FORMAT(/,20X,'HEAT FLUXES IN BTU/hr.sqft',/)
RETURN
END

C**********************************************************************C
SUBROUTINE AIRPROP(t,gamx,kx,mux,prx,cpx)
IMPLICIT REAL*8(A-H,O-Z)

c physical properties of dry air at one atmosphere

c ref: GE heat transfer handbook

c

c temperature range: 160 to 3960 deg. rankine

c -300 to 3500 deg. fahrenheit
c
t  - temperature, R
gamx - ratios of specific heats
kx  - thermal conductivity, BTU/hr.ft.R
mux - viscosity, lbm/hr.ft
prx - prandtl no.
cpx - specific heat, BTU/lbm.R
c
dimension tab(34),gam(34),pr(34),cp(34)
real*8 k(34),mu(34),kx,mux
data nent/34/
data tab/ 160., 260.,
& 1160., 1260., 1360., 1460., 1560., 1660., 1760., 1860.,
& 2760., 2860., 2960., 3160., 3360., 3560., 3760., 3960./
data gam/ 1.417, 1.411,
& 1.406, 1.403, 1.401, 1.398, 1.395, 1.390, 1.385, 1.378,
& 1.372, 1.366, 1.360, 1.355, 1.350, 1.345, 1.340, 1.336,
& 1.332, 1.328, 1.325, 1.321, 1.318, 1.315, 1.312, 1.309,
& 1.306, 1.303, 1.299, 1.293, 1.287, 1.281, 1.275, 1.269/
data k/ 0.0063,0.0086,
& 0.0108,0.0130,0.0154,0.0176,0.0198,0.0220,0.0243,0.0265,
& 0.0282, 0.0301, 0.0320, 0.0338, 0.0355, 0.0370, 0.0386, 0.0405, 
& 0.0422, 0.0439, 0.0455, 0.0473, 0.0490, 0.0507, 0.0525, 0.0542, 
& 0.0560, 0.0578, 0.0595, 0.0632, 0.0666, 0.0702, 0.0740, 0.0780/
data mu/ 0.0130, 0.0240, 
& 0.0326, 0.0394, 0.0461, 0.0519, 0.0576, 0.0627, 0.0679, 0.0721, 
& 0.0766, 0.0807, 0.0847, 0.0882, 0.0920, 0.0950, 0.0980, 0.1015, 
& 0.1045, 0.1075, 0.1101, 0.1110, 0.1170, 0.1200, 0.1230, 0.1265, 
& 0.1300, 0.1330, 0.1360, 0.1420, 0.1480, 0.1535, 0.1595, 0.1655/
data pr/ 0.7710, 0.7590, 
& 0.7390, 0.7180, 0.7030, 0.6940, 0.6860, 0.6820, 0.6790, 0.6788, 
& 0.6793, 0.6811, 0.6865, 0.6880, 0.6882, 0.6885, 0.6887, 0.6890, 
& 0.6891, 0.6893, 0.6895, 0.6897, 0.6899, 0.6900, 0.6902, 0.6905, 
& 0.6907, 0.6909, 0.6910, 0.6913, 0.6917, 0.6921, 0.6925, 0.6929/
data cp/ 0.247, 0.242, 
& 0.241, 0.240, 0.241, 0.242, 0.244, 0.246, 0.248, 0.251, 
& 0.254, 0.257, 0.260, 0.264, 0.267, 0.270, 0.272, 0.275, 
& 0.277, 0.279, 0.282, 0.284, 0.286, 0.288, 0.291, 0.293, 
& 0.296, 0.298, 0.300, 0.305, 0.311, 0.318, 0.326, 0.338/
c
if(t.lt.tab(1)) print 510,t,tab(1)
510 format(" in airprop --- temp=",f8.1," is less than min temp",
&" of ",f8.1)
if(t.gt.tab(nent)) print 520, t,tab(nent)
520 format(" in airprop --- temp=",f8.1," is greater than max",

if(t-tab(1)) 120, 120, 100
if(tab(nent)-t) 130, 130, 110
m = 2
go to 140
j = 1
go to 180
j = nent
go to 180
if(t-tab(m)) 160, 170, 150
m = m + 1
go to 140

c

-- Linear Interpolation ---
c

slp = (t-tab(m-1))/(tab(m)-tab(m-1))
mux = mu(m-1)+(mu(m)-mu(m-1))*slp
prx = pr(m-1)+(pr(m)-pr(m-1))*slp
cpx = cp(m-1)+(cp(m)-cp(m-1))*slp
kx = k(m-1)+(k(m)-k(m-1))*slp
gamx = gam(m-1)+(gam(m)-gam(m-1))*slp
go to 190
j = m
go to 180
mux=mu(j)
prx=pr(j)
cpx=cp(j)
kx=k(j)
gamx=gam(j)

return
end

C**********************************************************************C
Up-Point Experiment Heat Transfer Data Reduction Code

C   THIS PROGRAM WAS USED FOR AR=6 TESTS IN THE BASEMENT OF EGAN BUILDING. TEST SECTION WAS TWO-LEGGED 33 and 31" LONG, A 180-DEGREE TURN AND 7 HEATERS. SIX MAIN HEATERS (2" x 11") WERE CUSTOM-MADE BY BIRK. THE SMALL 7TH HEATER WAS A WATLOW HEATER. RIBS ARE POINTING UP (TOWARDS THE 180-DEGREE BENT)

C   CONTROL PANEL ARANGEMENT FOR ONE HEATED WALL CASE

C   CHANNEL 1: FIRST HEATER IN LEG 1 AND LAST HEATER IN LEG 2 IN SERIES
C   CHANNEL 2: SECOND HEATER IN LEG 1
C   CHANNEL 3: THIRD HEATER IN LEG 1
C   CHANNEL 4: SMALL HEATER IN THE MIDDLE OF 180-DEGREE TURN
C   CHANNEL 5: FIRST HEATER IN LEG 2
C   CHANNEL 6: SECOND HEATER IN LEG 2

C   ALL HEATERS 5-mil thick

IMPLICIT REAL*8(A-H,O-Z)

CHARACTER*80 TITLE

REAL*8 Mv,Nut,Nus,Length,Kloss

COMMON Dh,AR,Width,Length,Hlength,P,Rgas,Mv,
&Tin,Tamb,Pamb,Tliquid,Pitch
F(A,P,T)=0.5215*A*P/SQRT(T)

Rgas=53.34

gc=32.2 ! proportionality constant in Newton’s 2nd law, lbm.ft/(lbf.s^2)

Hgttopsi= 0.49083935 ! converts inches of Hg to psi

H2Otopsi=Hgttopsi/13.6 ! converts inches of H2O to psi

Oiltopsi=0.827*Hgttopsi/13.6 ! converts inches of Oil to psi

Pi=4.*ATAN(1.E00)

FAC1=3.413 ! converts Watts to BTU/hr

gc=32.2 ! lbm.ft/(lbf.s^2)

C

C Rectangular Cross Sectional Area

C

height=12. ! inches

height=height/12. ! ft

width=2. ! inches HEATED WALL

width=width/12. ! ft

P=2.*height+2.*width ! ft

Across=height*width ! ft^2

Dh=4.*Across/P ! ft

RibbedL1=31 ! inches
RibbedL2=29 ! inches

TotalL=31+3+29; ! inches, INLET PRESSURE TAP TO EXIT

C AR : defined as top/side

AR=height/width

OPEN(UNIT=1,FILE='input.dat',STATUS='old')
OPEN(UNIT=21,FILE='fric1-plot-heat.out',STATUS='old')
OPEN(UNIT=22,FILE='fric2-plot-heat.out',STATUS='old')
OPEN(UNIT=23,FILE='fric12-plot-heat.out',STATUS='old')
OPEN(UNIT=24,FILE='Kloss-plot-heat.out',STATUS='old')
OPEN(UNIT=3,FILE='uncertainties.out',STATUS='old')
OPEN(UNIT=7,FILE='output.dat',STATUS='old')
OPEN(UNIT=8,FILE='nu-Area1.out',STATUS='old')
OPEN(UNIT=9,FILE='nu-Area2.out',STATUS='old')
OPEN(UNIT=10,FILE='nu-Area3.out',STATUS='old')
OPEN(UNIT=11,FILE='nu-Area4.out',STATUS='old')
OPEN(UNIT=12,FILE='nu-Area5.out',STATUS='old')
OPEN(UNIT=13,FILE='nu-Area6.out',STATUS='old')

C

READ(1,*)NP,Pitch,NRibs1,NRibs2,RibH,RibW,RibR,alpha1,alpha2,
&Tliquid
WRITE(7,402)NP

402 FORMAT(/,20x,'A total of',I5,2x,'pictures were taken',/)
11 FORMAT(5x,'Photos:',2F8.0)

WRITE(7,100) 12*Height, 12*Width, 12*Dh, AR, Pitch,
&NRibs1, NRibs2, RibH, RibW, RibR, poe, eoDh, Alpha1, Alpha2,
&TotalL, 12*Hlength, 12*Hwidth

100 FORMAT(/,
&3x,'Channel Height=' ,f6.2,' inches',/,
&3x,'Channel Width=' ,f6.2,' inches',/,
&3x,'Channel Hydraulic Diameter=' ,f8.3,' inches',/,
&3x,'Channel Aspect Ratio=' ,f7.3,/,
&3x,'Rib Pitch=' ,f7.3,' inches',/,
&3x,'No. of Ribs in LEG 1: ' ,i2,/,
&3x,'No. of Ribs in LEG 2: ' ,i2,/,
&3x,'Rib Height=' ,f7.3,' inches',/,
&3x,'Rib Width=' ,f7.3,' inches',/,
&3x,'Rib Top Corner Radius=' ,f7.3,' inches',/,
&3x,'Rib Pitch to Height=' ,f7.3,/,
&3x,'Rib Height to Channel Dh=' ,f7.3,/,
&3x,'Rib Angle to Flow direction in LEG 1: ' ,f5.0,' deg',/,
&3x,'Rib Angle to Flow direction in LEG 2: ' ,f5.0,' deg',/,
&3x,'Rib-Roughened Length=' ,f7.3,' inches',/,
&3x,'Heater Length=' ,f7.3,' inches',/,
&3x,'Heater Width=' ,f7.3,' inches' /)
WRITE(8,450)

450 FORMAT(' PHOTOS RE Nu,t EF UNCER ',//)

DO 1 I=1,NP

READ(1,*)Photo1,Photo2,Dthroat,Pven,Tven,Tin1,Tin2,Tamb, &Pplen,Pinlet,Pup,Pdown,SG,Pamb,V1,A1,V2,A2,V3,A3,V4,A4, &V5,A5,V6,A6

WRITE(7,*)' 'WRITE(7,11)Photo1,Photo2

WRITE(7,*)' 'WRITE(7,*)' Collected Data: V1,I1,V2,I2,V3,I3'

WRITE(7,*)' Collected Data: V4,I4,V5,I5,V6,I6'

WRITE(7,*)' Dthroat,Pven,Tven,Tin1,Tin2,Tamb'

WRITE(7,*)' Pplen,Pinlet,Pamb,SG'

WRITE(7,*)' 'WRITE(7,200)V1,A1,V2,A2,V3,A3,V4,A4,V5,A5,V6,A6, &Dthroat,Pven,Tven,Tin1,Tin2,Tamb,Pplen,Pinlet,Pup, &Pdown,Pamb,SG

200 FORMAT(4X,F5.1,',''F4.3,'',F5.1,',''F4.3,'', &F5.1,',''F4.3,/,4X,F5.1,',''F4.3,'',F5.1,',''F4.3,'',
Tin = 0.5 * (Tin1 + Tin2)

TinR = Tin + 460.

CALL AIRPROP(TinR, GAMMA, CON, VIS, PR, CP)

VISin = VISin / 3600

Pamb = Pamb * Hgtopsi ! psi

Pplenum = 2 * Pplenum * H2Otopsi

DeltaP1 = 2 * (Pinlet - Pup) * H2Otopsi

DeltaP2 = 2 * Pdown * H2Otopsi

DeltaP12 = 2 * Pinlet * H2Otopsi

DeltaPTurn = 2 * (Pup - Pdown) * H2Otopsi

! AIR MASS FLOW RATE FROM THE CRITICAL VENTURI

Athroat = PI * (Dthroat**2) / 4.

Mv = F(Athroat, Pven + Pamb, Tven + 460)

DO 17 kk = 1, 6

Write(7, *)' ON AREA', kk
Write(7,*),

!  TOTAL HEAT ADDED TO THE AIR BY THE HEATERS FROM THE
!  INLET TO THE POINT IN QUESTION

IF(kk.EQ.1) Q = 0.5*V1*A1 + V2*A2*((9.7188/12)/Hlength)
IF(kk.EQ.2) Q = 0.5*V1*A1 + V2*A2 + V3*A3*((4.1/12)/Hlength)
IF(kk.EQ.3) Q = 0.5*V1*A1 + V2*A2 + V3*A3*((9.1157/12)/Hlength)

IF(kk.EQ.4) Q = 0.5*V1*A1 + V2*A2 + V3*A3 + V4*A4 + V5*A5* &((1.978/12)/Hlength)

IF(kk.EQ.5) Q = 0.5*V1*A1 + V2*A2 + V3*A3 + V4*A4 + &V5*A5*((6.9578/12)/Hlength)

IF(kk.EQ.6) Q = 0.5*V1*A1 + V2*A2 + V3*A3 + V4*A4 + V5*A5 + &V6*A6*((1.3118/12)/Hlength)

Q = Q*FAC1

!  HEAT FLUX, BTU/(sqft.Sec)

IF(kk.LE.1) Flux = V2*A2*FAC1/(Area);
IF(kk.GT.1.AND.kk.LE.3) Flux = V3*A3*FAC1/(Area);
IF(kk.GT.3.AND.kk.LE.5) Flux=V5*A5*FAC1/(Area);
IF(kk.GT.5) Flux=V6*A6*FAC1/(Area);

C   write(6,*)'kk,Q,Flux',kk,Q,Flux
    CALL COEFFICIENT(Q,Flux,Tm,Tback,hturb,Floss,kk)

!   FILM TEMPERATURE

TF=(Tback+Tm)/2.

!   DENSITY AT FILM TEMPERATURE

RHO=((Pamb+0.5*DeltaP)*144)/(Rgas*(TF+460.))

!   OTHER PROPERTIES AT FILM TEMPERATURE

TfR=TF+460.
    CALL AIRPROP(TfR,GAMMA,CON,VIS,PR,CP)
    VIS=VIS/3600

!   REYNOLDS NUMBER

Re=4.*Mv/(P*VIS)
! SMOOTH CHANNEL NUSSELT NUMBER FROM DITTUS-BOELTER CORRELATION

\[ N_{\text{us}} = 0.023 \cdot (\text{Re}^{0.8}) \cdot (\text{Pr}^{0.4}) \]

! NUSSELT NUMBER

\[ N_{\text{ut}} = \frac{H_{\text{turb}} \cdot D_{h}}{C_{\text{on}}} \]

! ENHANCEMENT FACTOR = \( N_{\text{ut}} \)/\( N_{\text{us}} \)

\[ E_{\text{F}} = \frac{N_{\text{ut}}}{N_{\text{us}}} \]

! AVERAGE VELOCITY, \( U_{m} \), ft/Sec.

\[ U_{\text{M}} = \frac{M_{V}}{(A_{\text{cross}} \cdot \rho)} \]

! FRICTION FACTORS AND TURN LOSSES

\[ F_{\text{R1}} = 2 \cdot g \cdot c \cdot 144 \cdot \Delta P_{1} \cdot (12 \cdot D_{h} / \text{RibbedL1}) / (\rho \cdot U_{m} \cdot U_{m}) \]
\[ F_{\text{R2}} = 2 \cdot g \cdot c \cdot 144 \cdot \Delta P_{2} \cdot (12 \cdot D_{h} / \text{RibbedL2}) / (\rho \cdot U_{m} \cdot U_{m}) \]
\[ F_{\text{R12}} = 2 \cdot g \cdot c \cdot 144 \cdot \Delta P_{12} \cdot (12 \cdot D_{h} / \text{TotalL}) / (\rho \cdot U_{m} \cdot U_{m}) \]
\[ K_{\text{loss}} = 2 \cdot g \cdot c \cdot 144 \cdot \Delta P_{\text{turn}} / (\rho \cdot U_{m} \cdot U_{m}) \]

IF(kk.eq.4)Write(21,405)Re,FRIC1
IF(kk.eq.4)Write(22,405)Re,FRIC2
IF(kk.eq.4)Write(23,405)Re,FRIC12
IF(kk.eq.4)Write(24,405)Re,Kloss

! UNCERTAINTY ANALYSIS

IF(kk.eq.4)CALL UNCERTAIN(Pamb,Pven,Tven,a1,V1,a2,V2,a3,
&V3,Dthroat,Area,Tback,Tin,Floss,Uncer)

IF(kk.eq.4)WRITE(7,300)TM,MV,UM,RE,FRIC12
IF(kk.eq.4)WRITE(7,401)Nus,Nut,EF,UNCER
IF(kk.ne.4)WRITE(7,407)Nus,Nut,EF

IF(kk.eq.1)WRITE(8,403)Photo1,Photo2,RE,Nut,EF
IF(kk.eq.2)WRITE(9,403)Photo1,Photo2,RE,Nut,EF
IF(kk.eq.3)WRITE(10,403)Photo1,Photo2,RE,Nut,EF
IF(kk.eq.4)WRITE(11,404)Photo1,Photo2,RE,Nut,EF,UNCER
IF(kk.eq.5)WRITE(12,403)Photo1,Photo2,RE,Nut,EF
IF(kk.eq.6)WRITE(13,403)Photo1,Photo2,RE,Nut,EF

17 ENDDO
1 CONTINUE

405 FORMAT(10X,E12.5,10X,E12.5)
REWIND 1
READ(1,*) dum
DO I=1,10
READ(1,10) TITLE
WRITE(8,10) TITLE
endo
dostop
end

C**********************************************************************C
SUBROUTINE UNCERTAIN(Pamb,Pven,Tven,i1,V1,i2,V2,i3,V3,Dth,
&Harea,Tsurf,Tin,Losses,Uncer)
IMPLICIT REAL*8(A-H,O-Z)

REAL*8 i1,i2,i3,Losses,M1,M2

PI=4.*ATAN(1.E00)

FAC1=3.413 ! converts Watts to BTU/hr

C=0.24*0.5215*3600

P1=Pven+Pamb
T1=Tven+460.0
T1=Tin
TS=Tsurf
a=Harea
f=0.729

ATH=PI*(Dth**2)/4.
DATH=PI*((Dth+0.001)**2)/4.-ATH

h=((FAC1*(V3*i3)/a)-Losses)/
&(TS-TI-(SQRT(T1)*(FAC1*(0.5*V1*i1+V2*i2+f*V3*i3)))/(C*P1*ATH))
WRITE(3,*) '  
WRITE(3,*)  h =',h,' BUT/hr.sqft.F'

H2=h*h

C

C   i3 v3

C     -------  - Floss

C   a3

C  ---------------------------------------------

C   sqrt(T1)(0.5 i1 v1 + i2 v2 + f i3 v3)

C  Ts-Ti - --------------------------------------

C   C P1 A_throat

C

DLOSS=0.1*Losses

dv1=0.1

dv2=0.1

dv3=0.1

di1=0.01

di2=0.01

di3=0.01
da=1./(32.*32.*144)
dts=0.5
dti=0.5
dt1=0.5
dp1=0.5
Df=0.1
C1=FAC1*(V3*i3/a)-Losses
Q1=C*P1*Ath
Q2=Q1*sqrt(T1)
M1=(Ts-Ti)*Q1
A=FAC1*(0.5*i1*v1+i2*v2)
B=FAC1*(i3*v3)
M2=M1-sqrt(T1)*(A+f*B)

DHDF=B*Q1*C1*sqrt(T1)/(M2**2)
DHDTI= C1*(Q1**2)/(M2**2)
DHDTS=-C1*(Q1**2)/(M2**2)
DHDA=-(FAC1*i3*v3)*Q1/(M2*(a**2))
DHDLOSS=-Q1/M2

DHDI1=0.5*FAC1*v1*Q1*C1*sqrt(T1)/(M2**2)
DHDV1=0.5*FAC1*i1*Q1*C1*sqrt(T1)/(M2**2)

DHDI2=FAC1*v2*Q1*C1*sqrt(T1)/(M2**2)
DHDV2 = FAC1*i2*Q1*C1*sqrt(T1)/(M2**2)

DHDI3 = FAC1*v3*Q1*(M2+C1*f*a*sqrt(T1))/(a*(M2**2))
DHDV3 = FAC1*i3*Q1*(M2+C1*f*a*sqrt(T1))/(a*(M2**2))

DHDATH = C1*C*P1*(M2-M1)/(M2**2)
DHDP1 = C1*C*Ath*(M2-M1)/(M2**2)
DHDT1 = 0.5*C1*Q1/(T1*(sqrt(T1)*(A+f*B)))

ZF = (DF*DHDF)**2
ZA = (DA*DHDA)**2

ZI1 = (DI1*DHDI1)**2
ZV1 = (DV1*DHDV1)**2

ZI2 = (DI2*DHDI2)**2
ZV2 = (DV2*DHDV2)**2

ZI3 = (DI3*DHDI3)**2
ZV3 = (DV3*DHDV3)**2

ZTS = (DTS*DHDTS)**2
ZTI = (DTI*DHDTI)**2
ZATH = (DATH*DHDATH)**2
ZP1 = (DP1 * DHDP1)**2 
ZT1 = (DT1 * DHDT1)**2 
ZFLOSS = (DLOSS * DHDLOSS)**2 

Uncer = 100 * SQRT((ZI1 + ZI2 + ZI3 + ZV1 + ZV2 + ZV3 + ZA + ZTS + ZTI + ZATH + ZP1 + ZT1 + ZFLOSS + ZF) / (H2)) 

WRITE(3, *) 'TOTAL UNCER.%:', Uncer 
WRITE(3, '*')'' 
WRITE(3, '*') % Uncer. assoc. with f', 100 * sqrt(ZF) / h 
WRITE(3, '*') % Uncer. assoc. with I1', 100 * sqrt(ZI1) / h 
WRITE(3, '*') % Uncer. assoc. with V1', 100 * sqrt(ZV1) / h 
WRITE(3, '*') % Uncer. assoc. with I2', 100 * sqrt(ZI2) / h 
WRITE(3, '*') % Uncer. assoc. with V2', 100 * sqrt(ZV2) / h 
WRITE(3, '*') % Uncer. assoc. with I3', 100 * sqrt(ZI3) / h 
WRITE(3, '*') % Uncer. assoc. with V3', 100 * sqrt(ZV3) / h 
WRITE(3, '*') % Uncer. assoc. with Tin', 100 * sqrt(ZTI) / h 
WRITE(3, '*') % Uncer. assoc. with Ts', 100 * sqrt(ZTS) / h 
WRITE(3, '*') % Uncer. assoc. with Tven', 100 * sqrt(ZT1) / h 
WRITE(3, '*') % Uncer. assoc. with Pven', 100 * sqrt(ZP1) / h 
WRITE(3, '*') % Uncer. assoc. with Aheater', 100 * sqrt(ZA) / h 
WRITE(3, '*') % Uncer. assoc. with Floss', 100 * sqrt(ZFLOSS) / h 
WRITE(3, '*') % Uncer. assoc. with Athroat', 100 * sqrt(ZATH) / h
C*******************************************************************

SUBROUTINE EQSOLVE(A,B,NA,NDIM,NB)
IMPLICIT REAL*8(A-H,O-Z)
DIMENSION  A(NDIM,NDIM),B(NDIM,NB)
DO 291 J1=1,NA
C FIND REMAINING ROW CONTAINING LARGEST ABSOLUTE
C VALUE IN PIVOTAL COLUMN.
101  TEMP=0.
   DO 121 J2=J1,NA
      IF(ABS(A(J2,J1))-TEMP) 121,111,111
111  TEMP=ABS(A(J2,J1))
   IBIG=J2
121  CONTINUE
   IF(IBIG-J1)5001,201,131
C REARRANGING ROWS TO PLACE LARGEST ABSOLUTE
C VALUE IN PIVOT POSITION.

131 DO 141 J2=J1,NA
    TEMP=A(J1,J2)
    A(J1,J2)=A(IBIG,J2)
141 A(IBIG,J2)=TEMP
    DO 161 J2=1,NB
    TEMP=B(J1,J2)
    B(J1,J2)=B(IBIG,J2)
161 B(IBIG,J2)=TEMP

C COMPUTE COEFFICIENTS IN PIVOTAL ROW.

201 TEMP=A(J1,J1)
    DO 221 J2=J1,NA
221 A(J1,J2)=A(J1,J2)/TEMP
    DO 231 J2=1,NB
231 B(J1,J2)=B(J1,J2)/TEMP
    IF(J1-NA)236,301,5001

C COMPUTE NEW COEFFICIENTS IN REMAINING ROWS.

236 N1=J1+1
    DO 281 J2=N1,NA
    TEMP=A(J2,J1)
    DO 241 J3=N1,NA
241 A(J2,J3)=A(J2,J3)-TEMP*A(J1,J3)
    DO 251 J3=1,NB
251 B(J2,J3)=B(J2,J3)-TEMP*B(J1,J3)
CONTINUE

C OBTAINING SOLUTIONS BY BACK SUBSTITUTION.

IF(NA-1)5001,5001,311
311 DO 391 J1=1,NB
     N1=NA
321 DO 341 J2=N1,NA
341 B(N1-1,J1)=B(N1-1,J1)-B(J2,J1)*A(N1-1,J2)
     N1=N1-1
391 CONTINUE
5001 CONTINUE
RETURN
END

SUBROUTINE COEFFICIENT(Q,Fluxb,Tm,Tback,hback,Floss,kk)
IMPLICIT REAL*8(A-H,O-Z)
CHARACTER*8 PHOTOS
REAL*8 kinc,kadh,kkap,kmyl,kpoly,ksty,kblack,kliq,kplex,
&Length,Mv
COMMON Dh,AR,Width,Length,Hlength,P,Rgas,Mv,
&Tin,Tamb,Pamb,Tliquid,Pitch

C BACK WALL (LIQUID CRYSTAL WALL)
FROM THE CENTER OF HEATING ELEMENT TO THE AMBIENT AIR

0.75 mil INCONEL HEATING ELEMENT ----- 0.5 mil ADHESIVE ----- 1 mil KAPTON ---- 2 mil DOUBLE-SIDED TAPE ----- 4 inches

POLYURETHANE ---- AMBIENT

tinc/kinc -- tadh1/kadh -- tkap/kkap -- tadh2/kadh --
tpoly/kpoly -- 1/ho

FROM THE CENTER OF HEATING ELEMENT TO THE AIR INSIDE THE TEST SECTION

0.75 mil INCONEL HEATING ELEMENT ----- 0.5 mil ADHESIVE

----- 1.0 mil ---- KAPTON ---- 3.5 mil ADHESIVE ----

3.0 mil ---- ABSORBITIVE BLACK BACKGROUND ---- 2.0 mil

LIQUID CRYSTAL ---- 5.0 mil ---- MYLAR ---- AIR INSIDE THE

TEST SECTION

tinc/kinc -- tadh1/kadh -- tkap/kkap -- tadh3/kadh --
tblack/kblack -- tliq/kliq -- tmyl/kmyl -- 1/hi

TOP, FRONT AND BOTTOM WALLS
FROM THE INSIDE AIR TO THE AMBIENT AIR

AIR INSIDE ---- 0.5 inches PLEXIGLAS ---- 1.375 inches

STYROFOAM ---- AMBIENT AIR

1/hi -- tplex/kplex -- tsty/ksty -- 1/ho

Heat transfer coefficient on the outer surface

\[ \text{De} = \frac{9}{12} \text{ ft}, \text{ Average test section side with insulation} \]

\[ \text{TambR} = \text{Tamb} + 460 \]

\[ \text{CALL AIRPROP}(\text{TambR}, \text{GAMMA,CON,VIS,PR,CP}) \]

\[ \text{VIS} = \frac{\text{VIS}}{3600} \]

\[ \text{ho} = 0.36 \times \text{con/De} \quad \text{! Ozisik, Page 443} \]

c
tinc = 2.0e-03/12. \quad \text{! BIRK} \]

tadh1 = 0.5e-03/12. \quad \text{! BIRK} \]

tadh2 = 2.0e-03/12. \]

tadh3 = 3.5e-03/12. \quad \text{! double-stck tape used on top of L.C. glue} \]

tkap = 1.0e-03/12. \quad \text{! MINCO's fact sheet} \]
tpoly = 4./12.

tplex = 0.5/12.

tsty = 2./12.

tblack = 3.0e-03/12.  ! absorptive black background (from DAVIS)

tliq = 2.0e-03/12.    ! liquid crystal thickness (from DAVIS)

tmyl = 5.0e-03/12.   ! MYLAR thickness (from DAVIS)

kkap = 0.0942        ! BTU/hr.ft.F MINCO (0.163 W/m.K)

ksty = 0.02          ! BTU/hr.ft.F

kpoly= 0.543         ! BTU/hr.ft.F from GOLDENWEST INC. BTU/(ft.hr.F)

kplex= 0.11          ! BTU/hr.ft.F AIN Plastics k=1.3 BTU/hr.F.sqft/in,

! same given by 1-800-523-7500

kmyl = 0.085         ! BTU/hr.ft.F Abauf's serpentine report, page 19

kadh = 0.1272        ! BTU/hr.ft.F MINCO (0.220 W/m.K)

kinc = 9.0152        ! BTU/hr.ft.F MINCO (inconel 600 K=15.6 W/m.K)

kblack = 0.165       ! BTU/hr.ft.F Glycerin

kliq = 0.165         ! BTU/hr.ft.F Glycerin
\[ R_{\text{inc}} = \frac{t_{\text{inc}}}{k_{\text{inc}}} \]

\[ R_{\text{adh1}} = \frac{t_{\text{adh1}}}{k_{\text{adh}}} \]
\[ R_{\text{adh2}} = \frac{t_{\text{adh2}}}{k_{\text{adh}}} \]
\[ R_{\text{adh3}} = \frac{t_{\text{adh3}}}{k_{\text{adh}}} \]

\[ R_{\text{kap}} = \frac{t_{\text{kap}}}{k_{\text{kap}}} \]

\[ R_{\text{poly}} = \frac{t_{\text{poly}}}{k_{\text{poly}}} \]

\[ R_{\text{sty}} = \frac{t_{\text{sty}}}{k_{\text{sty}}} \]

\[ R_{\text{plex}} = \frac{t_{\text{plex}}}{k_{\text{plex}}} \]

\[ R_{\text{black}} = \frac{t_{\text{black}}}{k_{\text{black}}} \]

\[ R_{\text{liq}} = \frac{t_{\text{liq}}}{k_{\text{liq}}} \]

\[ R_{\text{myl}} = \frac{t_{\text{myl}}}{k_{\text{myl}}} \]

\[ R_{\text{conv}} = \frac{1}{h_{\text{o}}} \]

\[ R_{\text{back}} = 0.5 R_{\text{inc}} + R_{\text{adh1}} + R_{\text{kap}} + R_{\text{adh2}} + R_{\text{poly}} + R_{\text{conv}} \]
\[ R_{\text{front}} = 0.5 \times R_{\text{inc}} + R_{\text{adh1}} + R_{\text{kap}} + R_{\text{adh3}} + R_{\text{black}} + R_{\text{liq}} \]

\[ \text{Theater} = (\text{fluxb} + \frac{T_{\text{amb}}}{R_{\text{back}}} + \frac{T_{\text{liquid}}}{R_{\text{front}}}) / (1.0/R_{\text{back}} + 1.0/R_{\text{front}}) \]

\[ f_{\text{back}} = \frac{\text{Theater} - T_{\text{amb}}}{R_{\text{back}}} \quad \text{! loss from the back side} \]

\[ f_{\text{front}} = \frac{\text{Theater} - T_{\text{liquid}}}{R_{\text{front}}} \]

\[ T_{\text{back}} = T_{\text{liquid}} - f_{\text{front}} \times R_{\text{myl}} \quad \text{! Surface temperature, Ts} \]

\[ \text{perloss} = 100.0 \times (f_{\text{back}} / \text{fluxb}) \]

\[ \text{WRITE(7,*)}'' \]

\[ \text{WRITE(7,*)} \quad \text{LIQUID CRYSTAL SIDE'} \]

\[ \text{WRITE(7,*)}'' \]

\[ \text{WRITE(7,101)} \text{Theater, fluxb, fback, ffront,} \]

\[ & \text{perloss, Tliquid, Tback, Tamb, ho} \]

100 FORMAT(/,5X,'HEATER TEMPERATURE = ',F8.3,' F',/,

\&5X,'TOTAL HEAT FLUX = ',F8.3,' BTU/hr.sqft',/,

\&5X,'HEAT FLUX TO THE BACK = ',F8.3,' BTU/hr.sqft',/,

\&5X,'HEAT FLUX TO THE FRONT = ',F8.3,' BTU/hr.sqft',/,

\&5X,'% OF HEAT LOST FROM THE BACK SIDE = ',F8.3,/

\&5X,'LIQUID CRYSTAL TEMPERATURE = ',F8.3,' F',/,

\&5X,'SURFACE TEMPERATURE = ',F8.3,' F',/,

\&5X,'AMBIENT TEMPERATURE = ',F8.3,' F',/,

\&5X,'U_{\text{inf where camera is located}} = ',F8.3,' ft/s',/,

\&5X,'Re based on the test section outer dimension = ',E13.6,/

\&5X,'Outer heat transfer coefficient = ',F8.3,/)
HEATER TEMPERATURE = ',F8.3,' F',/
TOTAL HEAT FLUX = ',F8.3,' BTU/hr.sqft',/
HEAT FLUX TO THE BACK = ',F8.3,' BTU/hr.sqft',/
HEAT FLUX TO THE FRONT = ',F8.3,' BTU/hr.sqft',/
% OF HEAT LOST FROM THE BACK SIDE = ',F8.3,/
LIQUID CRYSTAL TEMPERATURE = ',F8.3,' F',/
SURFACE TEMPERATURE = ',F8.3,' F',/
AMBIENT TEMPERATURE = ',F8.3,' F',/
Outer heat transfer coefficient= ',F8.3,

IF(kk.EQ.1)Atop=AR*Width*Hlength*(1+((9.7188/12)/Hlength))
IF(kk.EQ.2)Atop=AR*Width*Hlength*(2+((4.1/12)/Hlength))
IF(kk.EQ.3)Atop=AR*Width*Hlength*(2+((9.1157/12)/Hlength))
IF(kk.EQ.4)Atop=AR*Width*Hlength*(3+((2/12)/Hlength))
IF(kk.EQ.5)Atop=AR*Width*Hlength*(3+((6.9578/12)/Hlength))
IF(kk.EQ.6)Atop=AR*Width*Hlength*(4+((1.3118/12)/Hlength))

IF(kk.EQ.1)Aback=Width*Hlength*(1+((9.7188/12)/Hlength))
IF(kk.EQ.2)Aback=Width*Hlength*(2+((4.1/12)/Hlength))
IF(kk.EQ.3)Aback=Width*Hlength*(2+((9.1157/12)/Hlength))
IF(kk.EQ.4)Aback=Width*Hlength*(3+((2/12)/Hlength))
IF(kk.EQ.5)Aback=Width*Hlength*(3+((6.9578/12)/Hlength))
IF(kk.EQ.6)Aback=Width*Hlength*(4+((1.3118/12)/Hlength))

Abot=Atop
Afront=Aback

C write(6,*)'Atop,Abot,Aback,Afront',Atop,Abot,Aback,Afront

! AIR INLET ENTHALPY

TinR=Tin+460
CALL AIRPROP(TinR,GAMMA,CON,VIS,PR,CP)
VIS=VIS/3600
Hin=CP*TinR

! ITERATIONS STARTS HERE

! INITIAL GUESSES

Hout=Hin + (Q/(3600.*Mv))
TmR=Hout/CP
Tm=TmR-460

hback=(Fluxb-Flback)/(Tback-Tm)
hfront=hback
htop = 0.8 * hback
hbot = htop

Ttop = Tm
Tfront = Tm
Tbot = Tm

DO I = 1, 20

! RADIATIONAL LOSSES

call rad(AR, Width, Length, Tback, Ttop, Tfront, Tbot,
& Frback, Frtop, Frfront, Frbot)

C write(6, *) 'Frback', Frback
C write(6, *) 'Frtop', Frtop
C write(6, *) 'Frfront', Frfront
C write(6, *) 'Frbot', Frbot

C FLUX LOSSES FROM TOP, BOTTOM AND FRONT WALLS

R1 = Rplex + Rsty + Rconv ! from surface to ambient
! TOP WALL

\[ R_3 = \frac{1}{h_{top}} \]
\[ T_{top} = \frac{(1/R_3)T_m + (1/R_1)T_{amb} - F_{rtop}}{(1/R_1) + (1/R_3)} \]
\[ F_{ltop} = \frac{T_{top} - T_{amb}}{R_1} \]

! BOTTOM WALL

\[ R_3 = \frac{1}{h_{bot}} \]
\[ T_{bot} = \frac{(1/R_3)T_m + (1/R_1)T_{amb} - F_{rbot}}{(1/R_1) + (1/R_3)} \]
\[ F_{lbot} = \frac{T_{bot} - T_{amb}}{R_1} \]

! FRONT WALL

\[ R_3 = \frac{1}{h_{front}} \]
\[ T_{front} = \frac{(1/R_3)T_m + (1/R_1)T_{amb} - F_{rfront}}{(1/R_1) + (1/R_3)} \]
\[ F_{lfront} = \frac{T_{front} - T_{amb}}{R_1} \]

! TOTAL HEAT LOSS TO THE AMBIENT

\[ Q_{waste} = F_{ltop}A_{top} + F_{lbot}A_{bot} + F_{lfront}A_{front} + F_{lback}A_{back} \]

! NET HEAT ADDED TO THE AIR FROM THE INLET TO THE POINT IN QUESTION
Qadd = Q-Qwaste

! AIR MIXED MEAN ENTHALPY AT THE POINT WHERE THE HEAT TRANSFER
! COEFFICIENT IS BEING MEASURED

Hout=Hin + Qadd/(3600.*Mv)

! AIR MIXED MEAN TEMPERATURE AT THE POINT WHERE THE HEAT TRANSFER
! COEFFICIENT IS BEING MEASURED

TmR=Hout/CP

Tm=TmR-460.

CALL AIRPROP(TmR,GAMMA,CON,VIS,PR,CP)

VIS=VIS/3600

! HEAT TRANSFER COEFFICIENT FROM THE NEWTON LAW OF COOLING

Floss=Flback+Frback

hback=(Fluxb-Flback-Frback)/(Tback-Tm)

hfront=hback

! FILM TEMPERATURE
Tf=(Tback+Tm)/2.

! DENSITY AT FILM TEMPERATURE

RHO=Pamb/(Rgas*(Tf+460.))

! OTHER PROPERTIES AT FILM TEMPERATURE

TfR=Tf+460.

CALL AIRPROP(TfR,GAMMA,CON,VIS,PR,CP)

VIS=VIS/3600

Re=4.*Mv/(P*vis)

! HEAT TRANSFER COEFFICIENT ON THE NON-TURBULATED WALL

htop=0.8*hback

hbot=htop

FNETTOP=htop*(Ttop-Tm)+Fltop+Frtop

FNETBOT=hbot*(Tbot-Tm)+Flbot+Frbot

FNETFRONT=hfront*(Tfront-Tm)+Flfront+Frfront

IF(abs(FNETTOP).le.0.001.AND.abs(FNETFRONT).le.0.001)
&go to 34

endo

write(7,400)

400 FORMAT(/,20x,'***** Did not converge after 20 iterations',
  &' *****',/)

WRITE(9,410)Re,PHOTOS,FNETTOP,FNETFRONT,FNETBOT

410 FORMAT(5X,'Re=',E12.5X,'PHOTOS',A8.5X,
  &'FNETTOP,FNETFRONT & FNETBOT=',3E15.5,/)  
GO TO 503

34 WRITE(7,500)I,FNETTOP,FNETFRONT,FNETBOT

500 FORMAT(/,5x,'Convergence after',i4,' iterations ',/,5X,
  &'FNETTOP,FNETFRONT & FNETBOT =',3E15.5,/)  

503 continue
  write(7,110)Tback,Ttop,Tfront,Tbot

110 FORMAT(5x,'Back, Top, Front and Bottom Wall Temperatures: ',
  &/,10x,4F10.2,' F')

write(7,115)Tm,Tf

115 FORMAT(5X,'Air Mixed Mean and Film Temperatures',2F9.3,' F')

write(7,120)hback,htop
SUBROUTINE RAD(AR, Width, Length, Tback, Ttop, Tfront, Tbot,
& Frback, Frtop, Frfront, Frbot)
IMPLICIT REAL*8(A-H,O-Z)
REAL*8 Length
DIMENSION A(4,4), B(4,1), E(4), T(4), Q(4)
W=Width

120 FORMAT(5x,'hturb=',F8.3,5X,'hunt=',F8.3, & ' BTU/hr.sqft.F')
write(7,170)Q
170 format(5x,'Total Elect. Power=',F8.3,' BTU/hr')
write(7,116)Qwaste
116 FORMAT(5X,'Total Heat Loss to Ambient=',F8.3,' BTU/hr')
write(7,190)Fluxb,Fluxtop,Fluxf,Fluxbot
190 FORMAT(5X,'Heat Fluxes Generated by Back, Top, Front and' & ' Bottom Heaters:',/,10x,4F10.3,' BTU/sqft.hr')
write(7,180)Flback,Fltop,Flfront,Flbot
180 FORMAT(5X,'Flux Losses from Back, Top, Front and' & ' Bottom Surfaces:',/,10x,4F10.3,' BTU/sqft.hr')
write(7,150)Frback,Frtop,Frfront,Frbot
150 FORMAT(5X,'Radiative Fluxes from Back, Top, Front and' & ' Bottom Surfaces:',/,10x,4F10.3,' BTU/sqft.hr')
RETURN
END
H = AR*Width
H = H/Length
W = W/Length

T(1) = Tback + 460.
T(2) = Ttop + 460.
T(3) = Tfront + 460.
T(4) = Tbot + 460.

C Emissivities

E(1) = 0.85 ! Liquid Crystal Foil
E(2) = 0.9 ! PLEXIGLAS
E(3) = 0.9 ! PLEXIGLAS
E(4) = 0.9 ! PLEXIGLAS

N = 4
PI = 4.*ATAN(1.E00)
SIGMA = 0.1712E-08

C WRITE(7,150)
150 FORMAT(//,20X,'SHAPE FACTORS',//)

C Shape Factors SIEGAL AND HOWELL

W2 = W^W
H2 = H*H

Z1 = 1./(PI*W)

Z2 = W*ATAN(1./W)
Z3 = H*ATAN(1./H)
Z = SQRT(H2+W2)
Z4 = -Z*ATAN(1./Z)

Z = (1.+W2)*(1.+H2)
ZZ = 1.+W2+H2
Z5 = Z/ZZ

Z = W2*ZZ/((1.+W2)*(W2+H2))
Z6 = Z**W2

Z = H2*ZZ/((1.+H2)*(W2+H2))
Z7 = Z**H2

Z8 = .25*LOG(Z5*Z6*Z7)
F12 = Z1*(Z2+Z3+Z4+0.25*LOG(Z5*Z6*Z7))
F11 = 0.
F14 = F12
F13 = 1.-F11-F12-F14
\[ F_{21} = (W/H) \times F_{12} \]

\[ F_{22} = 0. \]

\[ F_{23} = F_{21} \]

\[ F_{24} = 1. \times F_{21} - F_{22} - F_{23} \]

\[ F_{31} = F_{13} \]

\[ F_{32} = F_{12} \]

\[ F_{33} = 0. \]

\[ F_{34} = F_{14} \]

\[ F_{41} = F_{21} \]

\[ F_{42} = F_{24} \]

\[ F_{43} = F_{23} \]

\[ F_{44} = 0. \]

C      WRITE(6,110)F11,F12,F13,F14
C      WRITE(6,120)F21,F22,F23,F24
C      WRITE(6,130)F31,F32,F33,F34
C      WRITE(6,140)F41,F42,F43,F44

110 FORMAT(5X,'F11=',F6.4,5X,'F12=',F6.4,5X,'F13=',F6.4,
\&5X,'F14=',F6.4,/)  
120 FORMAT(5X,'F21=',F6.4,5X,'F22=',F6.4,5X,'F23=',F6.4,
\&5X,'F24=',F6.4,/)
130 FORMAT(5X,'F31=',F6.4,5X,'F32=',F6.4,5X,'F33=',F6.4,5X,'F34=',F6.4,/) 
140 FORMAT(5X,'F41=',F6.4,5X,'F42=',F6.4,5X,'F43=',F6.4,5X,'F44=',F6.4,/) 
C WRITE(7,160) 
160 FORMAT(/,20X,'EMISSIVITIES',//) 
C WRITE(7,100)(I,E(I),I=1,N) 
C WRITE(7,170) 
170 FORMAT(/,20X,'TEMPERATURES IN R',//) 
C WRITE(7,100)(I,T(I),I=1,N) 
A(1,1)=F11-1./(1.-E(1)) 
A(1,2)=F12 
A(1,3)=F13 
A(1,4)=F14 
A(2,1)=F21 
A(2,2)=F22-1./(1.-E(2)) 
A(2,3)=F23 
A(2,4)=F24 
A(3,1)=F31 
A(3,2)=F32 
A(3,3)=F33-1./(1.-E(3)) 
A(3,4)=F34
A(4,1) = F41
A(4,2) = F42
A(4,3) = F43
A(4,4) = F44 - 1./(1.-E(4))

C  WRITE(7,180)
180 FORMAT(/,20X,'COEFFICIENT MATRIX',/)

C  WRITE(7,200)((A(I,J), J=1,N), I=1,N)

DO I=1,N
    B(I,1) = -E(I)*SIGMA*(T(I)**2.)*(T(I)**2.)/(1.-E(I))
ENDDO

C  WRITE(7,250)

C  WRITE(7,100)(I,B(I,1), I=1,N)
200 FORMAT(1X,4E15.6)
250 FORMAT(/,20X,'RIGHT HAND SIDE ',/)

C  WRITE(7,55)
55 FORMAT(/,20X,'GAUSSIAN ELIMINATION METHOD',/)
    CALL EQSOLVE(A,B,N,N,1)

C  WRITE(7,50)

C  WRITE(7,100)(I,B(I,1), I=1,N)

DO I=1,N
    Q(I) = E(I)*(SIGMA*(T(I)**2.)*(T(I)**2.)*B(I,1))/(1.-E(I))
ENDDO
Frback= q(1)
Frtop= q(2)
Frfront=q(3)
Frbot= q(4)

C   WRITE(7,350)
C   WRITE(7,100)(I,Q(I),I=1,N)
100 FORMAT(4(I3,E15.6))
50  FORMAT(/,20X,'RADIOCITIES',/)
350 FORMAT(/,20X,'HEAT FLUXES IN  BTU/hr.sqft',/)
   RETURN
   END

C**********************************************************************C
SUBROUTINE AIRPROP(t,gamx,kx,mux,prx,cpx)
IMPLICIT REAL*8(A-H,O-Z)

c  physical properties of dry air at one atmosphere

c      ref: GE heat transfer handbook

c

c  temperature range:  160 to 3960 deg. rankine

c         -300 to 3500 deg. fahrenheit

c
c t - temperature, R

c gamx - ratios of specific heats

c kx - thermal conductivity, BTU/hr.ft.R

c mux - viscosity, lbm/hr.ft

c prx - prandtl no.

c cpx - specific heat, BTU/lbm.R

c
dimension tab(34),gam(34),pr(34),cp(34)
real*8 k(34),mu(34),kx,mux
data nent/34/
data tab/ 160., 260.,
& 1160., 1260., 1360., 1460., 1560., 1660., 1760., 1860.,
& 2760., 2860., 2960., 3160., 3360., 3560., 3760., 3960./
data gam/ 1.417, 1.411,
& 1.406, 1.403, 1.401, 1.398, 1.395, 1.390, 1.385, 1.378,
& 1.372, 1.366, 1.360, 1.355, 1.350, 1.345, 1.340, 1.336,
& 1.332, 1.328, 1.325, 1.321, 1.318, 1.315, 1.312, 1.309,
& 1.306, 1.303, 1.299, 1.293, 1.287, 1.281, 1.275, 1.269/
data k/ 0.0063,0.0086,
& 0.0108,0.0130,0.0154,0.0176,0.0198,0.0220,0.0243,0.0265,
& 0.0282,0.0301,0.0320,0.0338,0.0355,0.0370,0.0386,0.0405,
& 0.0422, 0.0439, 0.0455, 0.0473, 0.0490, 0.0507, 0.0525, 0.0542,
& 0.0560, 0.0578, 0.0595, 0.0632, 0.0666, 0.0702, 0.0740, 0.0780/
data mu/ 0.0130, 0.0240,
& 0.0326, 0.0394, 0.0461, 0.0519, 0.0576, 0.0627, 0.0679, 0.0721,
& 0.0766, 0.0807, 0.0847, 0.0882, 0.0920, 0.0950, 0.0980, 0.1015,
& 0.1045, 0.1075, 0.1101, 0.1110, 0.1170, 0.1200, 0.1230, 0.1265,
& 0.1300, 0.1330, 0.1360, 0.1420, 0.1480, 0.1535, 0.1595, 0.1655/
data pr/ 0.7710, 0.7590,
& 0.7390, 0.7180, 0.7030, 0.6940, 0.6860, 0.6820, 0.6790, 0.6788,
& 0.6793, 0.6811, 0.6865, 0.6880, 0.6882, 0.6885, 0.6887, 0.6890,
& 0.6891, 0.6893, 0.6895, 0.6897, 0.6899, 0.6900, 0.6902, 0.6905,
& 0.6907, 0.6909, 0.6910, 0.6913, 0.6917, 0.6921, 0.6925, 0.6929/
data cp/ 0.247, 0.242,
& 0.241, 0.240, 0.242, 0.244, 0.246, 0.248, 0.251,
& 0.254, 0.257, 0.260, 0.264, 0.267, 0.270, 0.272, 0.275,
& 0.277, 0.279, 0.282, 0.284, 0.286, 0.288, 0.291, 0.293,
& 0.296, 0.298, 0.300, 0.305, 0.311, 0.318, 0.326, 0.338/
c
   if(t.lt.tab(1)) print 510,t,tab(1)
510 format(" in airprop --- temp=",f8.1," is less than min temp",
   &" of ",f8.1)
   if(t.gt.tab(nent)) print 520, t,tab(nent)
520 format(" in airprop --- temp=",f8.1," is greater than max",
   &" temp of ",f8.1)
if(t-tab(1))120,120,100
100 if(tab(nent)-t)130,130,110
110 m=2
    go to 140
120 j=1
    go to 180
130 j=nent
    go to 180
140 if(t-tab(m))160,170,150
150 m=m+1
    go to 140

c

-- Linear Interpolation ---

c
160 slp=(t-tab(m-1))/(tab(m)-tab(m-1))
    mux= mu(m-1)+(mu(m)-mu(m-1))*slp
    prx= pr(m-1)+(pr(m)-pr(m-1))*slp
    cpx=cp(m-1)+(cp(m)-cp(m-1))*slp
    kx=k(m-1)+(k(m)-k(m-1))*slp
    gamx=gam(m-1)+(gam(m)-gam(m-1))*slp
    go to 190
170 j=m
    go to 180
180  mux=mu(j)
prx=pr(j)
cpx=cp(j)
kx=k(j)
gamx=gam(j)

190 return

end

C*****************************************************************************C
Appendix II. Visualized Heat Transfer Data

Baseline Experiment, Run4

Area 4

Area 4

Area 6
Area 7

Area 8

Area 9
Up-Point Experiment, Run 4

Area 4

Area 5

Area 6

Area 7
# Appendix III. Experiments Data

## Baseline Experiment Data

<table>
<thead>
<tr>
<th>Tve</th>
<th>Tin1</th>
<th>Tin2</th>
<th>Tamb</th>
<th>Ppl</th>
<th>en</th>
<th>Pinlet</th>
<th>Pup</th>
<th>Down</th>
<th>S.G.</th>
<th>Pamb</th>
<th>V1</th>
<th>I1</th>
<th>V2</th>
<th>I2</th>
<th>V3</th>
<th>I3</th>
<th>V4</th>
<th>I4</th>
<th>V5</th>
<th>I5</th>
<th>V6</th>
<th>I6</th>
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<td>69.4</td>
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(Numerical values represent Nusselt numbers vs. Reynolds number for different areas.)