Heat Transfer Analyses of Internal Cooling Passages of Turbine Blades and Nozzles

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1. Introduction
Two heat transfer experimental studies utilizing thermochromic liquid crystal (TLC) paints were conducted in the Aero, Thermal and Performance department at Solar Turbines, Inc. The first experiment study sought to determine the internal convective heat transfer coefficient (HTC) for three proposed modifications of a first stage turbine blade. Stereolithography (SLA) models of the three modified designs and a baseline model were scaled three times original size. The second experimental study looked at two proposed modifications to the first stage nozzle of a gas turbine. SLA models were also constructed, which were scaled two times original size with the baseline nozzle for a comparative analysis.

Typical heat transfer studies involving TLC’s record the transition color with a CCD (charged coupled device) camera as an airflow impinges on the surface coated with the TLC. Properties of the air flow and transition time are then used to calculate the HTC. The experiments conducted on the turbine blade and nozzles were conducted with known air flow conditions in the inner cooling passages with the TCL applied to the outer surface of the SLA model. Due to the air supply not contacting the TCL, the TCL transition was delayed by the conduction through the SLA material. This aspect of the test configuration required new software to analyze the time delay from conduction to determine the internal convective HTC. The software developed by the author will be discussed later in the paper.

Thermochromic liquid crystal paints are utilized by researchers due to their luminescence transition response to temperature variations. The transition process of a TLC is detailed in Figure 1, it begins at a colorless state, while the temperature is increased it progressively displays a visible spectrum in sequence red, yellow, green, blue, and violet (Handbook TLCT). The colors reverse themselves sequentialy as the TLC cools to original temperature conditions. The TLC used for the HTC studies was chosen to have a green start at 95°F with a 1.8 °F bandwidth.

![Figure 1 Typical reflected wavelength (color) and temperature response of a TLC (Handbook TLCT).](image)

2. Turbine Blade

2.1 Blade Re-design Options
The modified test blades proposed by Dr. Luzeng Zhang incorporated internal turning vanes, delta wings and extended wall geometries. These modifications sought to improve mass flow rate through the serpentine passage and decrease pressure loss while not affecting the current internal HTC. Stereolithography models three times original scale were manufactured for each modified design along with a baseline blade for use in a comparative analysis. The mass flow rate for each model was evaluated on an injector flow bench, which measures the flow rate with two sonic nozzles. Two flow rates were measured for each blade with a pressure differential of 1.7 and 1.29, the resulting flow rates can be seen in Figure 2. The results indicate a slight increase in flow rate in the mid-passage cooling channel of the modified blade designs compared to the baseline blade. Modified blade design three shows the highest flow rate which incorporates both delta wing and guide vane geometry. The delta wing in the leading passage of the modified blades decreased flow rate. The leading passage delta wing was considered a failure and was not pursued any further. A thermal analysis was then conducted to evaluate each design to quantify any improved or diminished internal heat transfer coefficients.

![Figure 2 Graph show flow rates of the baseline and modified blades.](image)

2.2 Experimental Setup
The thermal experimental setup for the 3X turbine blades can be seen in Figure 3. The test fixture contains a mixing chamber connected to a 2" silicone air supply hose with two plenums, which hold the test blades. Two perforated plates with an open area of 38 percent each are positioned in the mixing chamber between the inlet flow and plenums, with the second positioned mid-plenum. The perforated plates aid in decreasing any span wise variations in the
velocity field as the airflow travels to the blades. The test fixture was constructed out of PVC, which has a low thermal conductivity aiding in the reduction of heat loss and maintaining steady state conditions.

The test fixture was supplied by the facilities low-pressure air system. A diagram of the airflow through the system is detailed in Figure 4. The air supply from the compressor passes through a dome-loaded pressure regulator before entering through two turbine flow meters. The redundant flow meters measure a flow range of 5 to 12 ACMF. The flow enters a control valve, which enables an operator to adjust the flow rate as needed. The airflow temperature can be increased as it passes through a Watlow Immersion Heater. A pneumatic solenoid controls the flow direction to either the test fixture or out of the cell.

2.3 Instrumentation
Thermocouples (TC) with a diameter of .02” were placed around the thermal test fixture to acquire adequate temperature data for flow analysis. One TC was placed at the inlet of the mixing chamber, one before each plenum inlet, and two symmetrically around each plenum at five inches before the flow entrance to the blades. Each blade was instrumented with two TC’s, one for the forward cooling passage and the other for the mid-chord passage. Static pressure taps were also positioned in accordance to the TC’s but symmetrically opposing their locations.
Each SLA blade was first painted with a BB-G1 base black paint, which helped enhance the visibility of the TLC’s transition process. A clear coat of SPNR35C1W TLC was then airbrushed over the black base paint.

2.4 Testing and Data Acquisition
The test process evaluated a modified blade alongside a baseline blade. The transition of both blades was recorded by two Sony Handycam CCD-TRV608 cameras with one viewing the pressure side and the other the suction side. A LED light in view of each camera was illuminated when the 195 °F airflow was sent through the test fixture and out the blades. Data was collected using a Daytronics and PSI 8400 system. The data acquisition system began gathering data when a thermal couple serving as an indicator was triggered and the airflow was switched on. All flow rates and pressures recorded during testing were measured with the Esterline System 8400 pressure scanner. All temperature measurements were measured with a VTI VXI EX1048 temperature scanner.

2.5 Data Analysis
The captured video of the transition was then converted from a .wmv to .avi file, which is a format required by the Liquid Crystal Image Analyzer (LCIA) Program used to analyze the transition process. The liquid crystal program allows a user to select a domain of interest and enter a test start time. LCIA then analyzes the domain in the video pixel by pixel from the time the test begins to the time each pixel changes to a color green. The color green indicates a surface temperature of 95 °F. The program then assigns the pixel a time stamp, which is used to create a contour plot of transition time per pixel. An example of the contour plot is seen in Figure 5, with the blue color indicating a shorter transition time and the dark green to light green a long transition time. The program has many other features, which allow a user to evaluate convective heat transfer elements of the video. However, due to the heated flow not being applied to the TLC paint but inside the blade, the program could not be used to for determining the HTC. A new analysis program was needed to account for the transient convection and conduction process through the SLA material before the time data could be used.

Figure 5 An example of the time contour plot generated by the LCIA program with its color key to the right.

2.6.1 Transient Program Development
A program was written by the author in Visual Basic Studio, which accounted for transient convection and conduction through the SLA model. The program was then used to perform a
HTC analysis of the turbine blades with the use of the time data generated by LCIA. The results from the analysis were then compared to the baseline blade to verify whether the modifications had an adverse and positive effect on the HTC.

2.6.2 Transient Solution
Mathematically modeling the internal convective, conduction, and natural convection was accomplished by using an explicit discretized form of the heat equation as described below.

\[
E_{in} + E_g = E_{st}
\]

(1)

The heat equation can then be modified and applied to a system of nodes representing either conductive or convective elements. A system of six nodes seen in Figure 6, was chosen to represent the heat transfer scenario with one node dedicated to internal convection, four nodes representing conduction through the SLA, and the last node set at natural convection conditions. The discretized form of the heat equation representing conduction is shown by Equation 2, which was taken from Fundamentals of Heat and Mass Transfer.

\[
T_{m}^{n+1} = F_0 (T_{m-1}^n + T_{m+1}^n) + (1 - 2F_0) T_m^n
\]

(2)

Where the Fourier number is calculated by equation 3,

\[
F_0 = \frac{\alpha \Delta t}{\Delta x^2}
\]

(3)

The internal and external convection coefficients were model with equation 4,

\[
T_5^{n+1} = 2F_0 \left[ T_4^n + Bi \cdot T_4^n + \frac{Q(\Delta x)^2}{2k} \right] + (1 - 2F_0 - 2Bi F_0) T_5^n
\]

(4)

The Biot number is calculated with equation 5,

\[
Bi = \frac{h \Delta x}{k}
\]

(5)

Where the thermal diffusivity of the SLA is represented by \(\alpha\) and the time step for each iterative calculation is shown by \(\Delta t\). The length of each element containing one nodes is represented by \(\Delta x\).

Due to the inherent instability of the explicit discretized heat equation, a Fourier number less than or equal to .466 must be maintained for the resulting solution to be valid. The discretized solution was then used to solve for a range internal HTC’s, resulting in a range of transient times to reach transition temperature. Once the final solution was found, the number of nodes was doubled in order to verify whether more nodal points would change the solution and refinement was needed. The second solution showed no change; therefore, six nodes were determined to be sufficient.
A transient ANSYS solution was also performed to verify the discretized solution. The model seen in Figure 7 modeled twenty convective and conduction cases where the HTC was varied between .88 and 17.6 Btu/ft^2 hr °F. Each conduction thickness used a plane 77 element with eleven nodes. A constant internal bulk temperature was used for one set of solutions while actual test data was used for a ramped-up temperature solution. The number of nodes was doubled to verify the refinement of the mesh and an eleven node thickness was found sufficient for the solution.

An exact analytical solution which negates the natural convection was solved to put into perspective how much natural convection influenced the final results. Equation 6 was used in the exact solution of convection and conduction through a plane wall.

$$\theta'(x', t') = C_1 \exp\left(-\frac{x'}{L_1} \right) \cos\left(\frac{x'}{L_1} \right)$$

With a Biot number greater than point one, the Fourier number could be assumed to be greater than point two. This condition made a one term solution acceptable, by assuming the maximum temperature occurred at the mid-plane, Equation 8 became the resulting equation used to evaluate the model.
\[ x^* = \frac{x}{l} = 0 \rightarrow \theta^*(x^*, t^*) = C_1 \exp(-\zeta_1^2 \text{Fo}) \cos(0) \quad (7) \]

\[ \theta^*(x^*, t^*) = C_1 \exp(-\zeta_1^2 \text{Fo}) \quad (8) \]

Where the Fourier number could be calculated by Equation 9, and the dimensionless mid-plane temperature as Equation 10.

\[ \text{Fo} = -\frac{\ln(\theta_0^*/C_1)}{\zeta_1^2} \quad (9) \]

\[ \theta^* = \frac{T(x, t) - T_x}{T_f - T_x} \quad (10) \]

The final time to transition temperature can then be calculated by Equation 11,

\[ \text{Fo} = \frac{\alpha t_f}{L^2} \rightarrow t_f = \frac{L^2 \text{Fo}}{\alpha} \quad (11) \]

The final solutions for all three methods of calculating the transient times to transition temperature of 95 °F over a range of HTC are plotted in Figure 8. The curve on the left represents a constant internal bulk temperature used for all three methods. The exact solution is slightly more conservative than the solutions using natural convection. The solutions using a ramped bulk temperature, taken from actual test data, are nearly identical. The results from these three solutions indicate the discretized explicit method was satisfactory and could be used in a data analysis program.

![Figure 8 The explicit, ANSYS, and exact solutions to the transient convection and conduction HT model.](image-url)
2.6.3 User Interface
The main user interface seen in Figure 9, encompasses three main categories used to perform a transient convection and conduction analysis. Test conditions and properties enable the user to input material properties such as thickness, thermal conductivity, diffusivity, and specific heat. Atmospheric conditions during the test are then used to calculate natural convection. The internal conditions of the test article are also needed such as the hydraulic diameter, constant or variable bulk temperature, and range of HTC the program should solve. The image file generated from LCIA can then be opened, which is then read into the analysis program. The program can then convert the time information in the file to HTC or Nusselt number values.

The calculations option allows the user to specify the output units as either English or metric. The solution to the input parameters is then fitted to a best fit power curve with the HTC variable being a function of time as seen in Equation 12,

$$h(t) = at^b$$  \hspace{1cm} (12)

An R squared value is displayed to indicate the reliability of the best fit curve to the solution. Once the coefficients for the power curve are found, HTC and Nusselt number can be calculated for each pixel in the .tim file generated by LCIA.

Figure 9 A screen shot of the transient conduction analysis program main user interface.

The image analyses category enables the user to display the time, HTC, and Nusselt number image. The color display can be refined to reveal more contours on the image by changing the minimum and maximum values on the color key. By positioning the curser over the image, like Figure 5, pixel numerical values and colors are displayed along with their X and Y position. An analysis of the HTC and Nusselt number can be calculated in the Pixel Domain frame.
Figure 10 A HTC image of the pressure and suction side of the turbine blade divided up into domains and zones for analysis.

The images in the far left of Figure 10, show how the pressure and suction surfaces of the turbine blade has been divided up into five domains with three zones within each domain. The cooling flow passage of the SLA baseline model, visible in the middle of Figure 10, is where the domains are positioned. The domain areas are described and specified in the domain analyzer interface, right image Figure 10, by setting a range of pixels in the X plane and the Y plane. Pixel locations for both pressure and suction surfaces were written in the code which could be easily displayed by pressing their individual load button. The accuracy of the analysis was dependant on the geometry in the image having the same size for each modified blade. Therefore, a comparison could be easily made between the baseline and modified blades. The domain analysis averaged each pixel value in the specified zone which could then be copied into a spread sheet for comparative ratios to be created.

2.7 Analysis Results
The graphical results from the Transient Convection and Conduction program included in Appendix A, Figures 13 through 15, where the averaged ratios found through the pixel analyzer are tabulated in Table 1. The HTC improvement for each modified blade is clearly visible in each image for both suction and pressure sides of the blade. Table 1 shows a total improvement ratio for modification design 2 as 1.21 and 1.28 on the pressure and suction surfaces. Blade modification design three has a 1.22 and 1.21 ratio improvement on the pressure and suction surface. The greatest ratio was that of modification design four with a total ratio of 1.25 and 1.27 improvement on the pressure and suction surface.
Table 1 Averaged heat transfer values of each domain on the pressure and suction surface of the turbine blade.

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3. Turbine Nozzles
3.1 Nozzle Re-Design Options
A thermal TLC test was performed on the turbine nozzles in a similar fashion to that of the turbine blades. Two modifications were proposed by Dr. Luzeng Zhang to improve cooling to the trailing edge of the pressure surface. The first modified nozzle design had the two ribs which separated the cooling path into partitions removed. The second design incorporated pin fin geometries on the ribs, which created bumpy partitioned ribs. Two SLA models were created from these two designs, an baseline nozzle was included so a comparative analysis could be performed from a single test. An example of the baseline nozzle and modified nozzle can be seen in Figure 11. The SLA model was first painted with a black base paint to enhance the visibility of the transition colors with the TLC painted over it.

![Figure 11 Turbine nozzle 2X scaled SLA model.](image)

3.2 Experimental Setup
The test fixture seen in Figure 12 was constructed from a 14" schedule 80 PVC pipe to mitigate heat loss and to maintain steady state conditions. A baffle plate 9" diameter was placed inside the cylinder and positioned three inches from the flow entrance. The baffle plate served to dampen inlet flow velocity while enhancing flow uniformity. The nozzle test plenum was supplied with heated air in the same fashion as the turbine blade plenums were. The flow diagram and description for this process can be seen in Figure 4.
3.3 Instrumentation
The test fixture plenum was instrumented at the mid-length of the plenum chamber with four symmetric static pressure taps and four TC’s. The base of the SLA model was instrumented with two static pressure taps and two TC’s opposing each another. The TC’s and static pressure taps were position in-line with the leading edge of the nozzles and at mid-height of the base. Each tip of the SLA model was instrumented with a TC, which was used to measure the flow temperature.

3.4 Testing and Data Acquisition
Both nozzles were originally going to be tested simultaneously; however, during a trial run, induced and impinged flow adversely affected the transition process of the TLC paint. The induced flow was created as a low pressure zone formed at the trailing edge of the nozzle, due to the heated flow exiting the air channels. The impinged flow was caused by the exit channel flow from the nozzle positioned forward of the other nozzle. A decision was made to only run air through one nozzle for each test. Two blocker plates were fashioned to inhibit air flow to one nozzle and the other to prevent induced flow between the two nozzles.

Testing of each nozzle design was performed for two inlet flow pressures of 1.8 and 3.6 psig. Each flow rate was heated to 150°F before entering the plenum and out the nozzles. The transitions of the nozzles were recorded by two Sony Handycam CCD-TRV608 cameras, which viewed the pressure and suction surfaces. The TC data was measured by the VTI VXI EX1048 temperature scanner and the pressure data was recorded by PSI 8400 system.

3.5 Data Analysis
The video was first analyzed with the LCIA program which produced a contoured image with pixel transition time. The custom conduction transient analyzer was then used to generate a solution curve to a range of HTC, which was then used to convert the time data to HTC’s. The images for this analysis can be found in Appendix B, Figures 16 through 17.

3.6 Analysis results
The final results of the thermal analysis with the transient convection and conduction program indicate a visual improvement of the HTC for the no rib and modified rib to the baseline nozzle.
With an inlet flow pressure of 3.6 psig, the no rib design showed the greatest HTC on the pressure side, while the modified rib design showed better uniformity. At an inlet pressure of 1.8 psig the results showed an improvement in HTC for both no rib and modified rib designs compared against the baseline nozzle. The HTC distribution appears to be more uniform for both modified designs on both pressure and suction sides.

Further analysis is required to obtain quantitative result in order to show actual improvement for each nozzle designs. This analysis would involve partitioning each nozzle surface into domains and dividing the domain into sections. The Transient Convection and Conduction Analyzer program could then be used to generate averages for these domains and finally ratios of improvements from the baseline nozzle.

4.1 Conclusion
Two heat transfer tests, studying the turbine blade and nozzle were successfully conducted by Developmental Testing at Solar Turbines. A new analysis program was developed and written in order to evaluate the data of these tests. The new program can calculate the HTC and Nusselt number of TLC paint tests where the heat flow and TLC paint are separated by a material thickness.

The Transient Convection and Conduction Analyzer program produced HTC result for three inner cooling passage re-design option of the turbine blade. Averaged HTC were then calculated for five domains on both the pressure and suction surfaces of the blades. These averages were then used to compare against the baseline model where ratios were calculated. The ratios indicated an improvement for all three proposed re-designs. These augmentation values can be used to modify 3D blade models for life assessment of the blade.

The results of the thermal TLC test of the two proposed re-designs for the turbine nozzle were analyzed with the Transient Convection and Conduction Analyzer program. Visually, the proposed designs improved HTC for the two different inlet pressures tested. Though the modified rib design did not appear to have the highest HTC at the trailing edge of the pressure-side, it was more uniform than the no rib design. Further analysis is needed to quantify these results and calculate improvement ratios against the baseline nozzle.

Acknowledgments
The experience I gained while working at Solar Turbines has been extremely rewarding to my understand of the gas turbine industry. The insight I was given from engineering to manufacturing and the needs of the customer also helped in my overall appreciation the industries dynamics. Being able to work with in such a diversified environment has definitely improved my skills in engineering.

The guidance I received during my time at Solar Turbines greatly benefited the enjoyment I had while working on my project. I acquired a great amount of information from the many tours I was given of the facility and would like to thank the engineers, technicians, and management who took their time to show me around. I would like to thank especially Dr. Luzeng Zhang for his mentorship and giving me a great perspective on blade and nozzle heat transfer. Thank you John Mason and Dr. Hee-Koo Moon for acquainting me to the Aero, Thermal and Performance department and with refining my work. I would like to thank Gail Doore and Mike Austin for performing excellent tests and patience they showed while working with me.
I would like to thank Dr. Forrest Ames, for being a great advisor, who provided me with insights and opportunities in the gas turbine industry. His experience and knowledge has aided in my decision to pursue a career in gas turbines.

Finally, I would like to thank the University Turbine Systems Research Fellowship Program, and the Southwest Research Institute for providing me with this great opportunity to work in the gas turbine industry.
Works Cited


Handbook of Thermochromic Liquid Crystal Technology. 1991 Hallcrest: Glenview, Illinois
Figure 13 Thermal analysis of the turbine baseline blade on the left and the proposed design 2 on the right. A color scale of 0 to 25 Btu/hr ft\(^2\) °F is provide on the far right.

Figure 14 Thermal analysis of the turbine baseline blade on the left and the proposed design 3 on the right. A color scale of 0 to 25 Btu/hr ft\(^2\) °F is provide on the far right.
Figure 15 Thermal analysis of the turbine baseline blade on the left and the proposed design 4 on the right. A color scale of 0 to 25 Btu/hr ft$^2$ °F is provide on the far right.
Appendix B

<table>
<thead>
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<th>Pressure-Side</th>
<th>Turbine Nozzle 2X SLA Flow Pressure of 3.6 PSIG</th>
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<tr>
<td>No Rib Nozzle</td>
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<tr>
<td>Modified Rib Nozzle</td>
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<th>Color Key</th>
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- **Units:** Btu/hr ft^2 °F

Figure 16 Thermal analysis of the turbine nozzle with a flow rate pressure of 3.6 psig. The baseline nozzle is located on the left, no rib middle, and modified rib on the right. A color scale of 0 to 15 Btu/hr ft^2 °F is provide on the far left.
Figure 17 Thermal analysis of the turbine nozzle with a flow rate pressure of 1.8 psig. The baseline nozzle is located on the left, no rib middle, and modified rib on the right. A color scale of 0 to 15 Btu/hr ft^2 °F is provide on the far left.