Solar Turbines, Inc.
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Thermal Imaging Post Processing of a Turbine Blade

Prepared for

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1. Abstract

This report discusses the results of a thermal paint test performed on a 5x scaled turbine blade model. The primary test objective was to study blade cooling schemes, specifically in the leading edge, using transient liquid crystal paint. A secondary objective was to validate past blade tests by comparing heat transfer coefficient results. This blade model includes casting fillets on the swirl slots and leading edge trip as well as fully modeled trailing edge slot geometry and a full pin fin array.

Significant findings from this study include the following:

- The 5x scaled blade with an added trip strip and widened swirl cool slots shows an average 28% increase in Nusselt number (Nu) across the leading edge compared to the current blade.
- Adding realistic casting geometries had a small effect on heat transfer characteristics across the leading edge, showing a 3-4% drop in averaged Nu from an otherwise similar model.
- Application of the 5x scaled model results to an ANSYS thermal model shows a drop in leading edge temperature of approximately 23°F from the current blade.

2. Introduction

A turbine blade design experienced higher temperatures than expected in the leading edge region. It was hypothesized that the high temperatures were from low swirl cooling performance due to deviations from design intent during casting. Since this time, improving leading edge durability has been a principal concern. To this end, this thermal imaging test of a scaled blade model has been performed. In addition, a thermal model of the blade has been constructed in ANSYS Workbench with boundary condition application and processing performed in ANSYS Mechanical APDL. This document details the findings of the transient liquid crystal test performed on a 5x scaled stereolithography (SLA) model of the blade, and its application to the ANSYS thermal model. Discussion on the implications of the results of the test is presented.

3. Testing

3.1 Test Setup

A 5x scaled model of the turbine blade has been created. Liquid crystal paint was applied to the internal passages of the blade and thermocouples were installed. Solar’s thermal imaging rig for scaled turbine blades was used. Figure 1 shows the final test setup for the 5x model experiment.

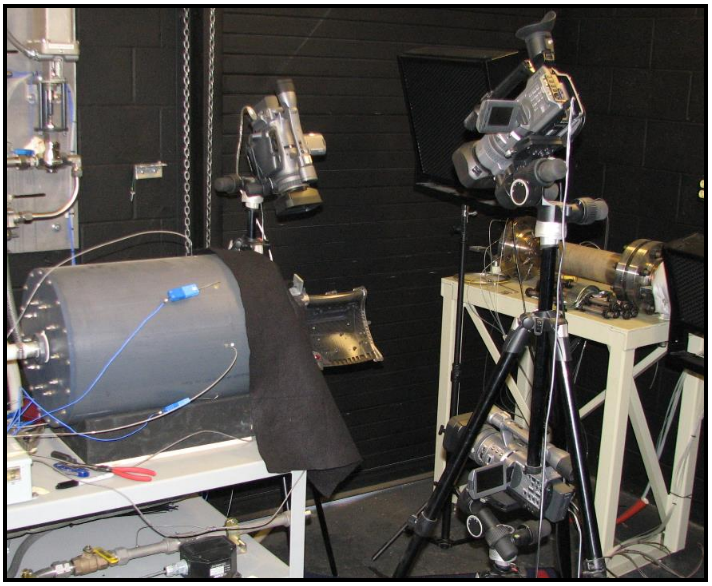

Figure 1. Final set-up for 5x liquid crystal paint test

3.2 Instrumentation

A total of fifteen .020" open-tip, T-type thermocouples were inserted from the pressure side of the blade and fixed in place using epoxy. Figure 2 displays the instrumentation tag names and locations of the installed thermocouples. Figures 3 and 4 show a cross section and side view of the blade highlighting the locations of thermocouples one through nine. Three Sony Handycam DCR-VX2100 cameras were used to film parts of the blade as shown in figure 5. Camera A captures the pressure side, camera B the leading edge, and camera C the suction side of the blade. Figure 6 shows the model fully instrumented and stationed for its test.

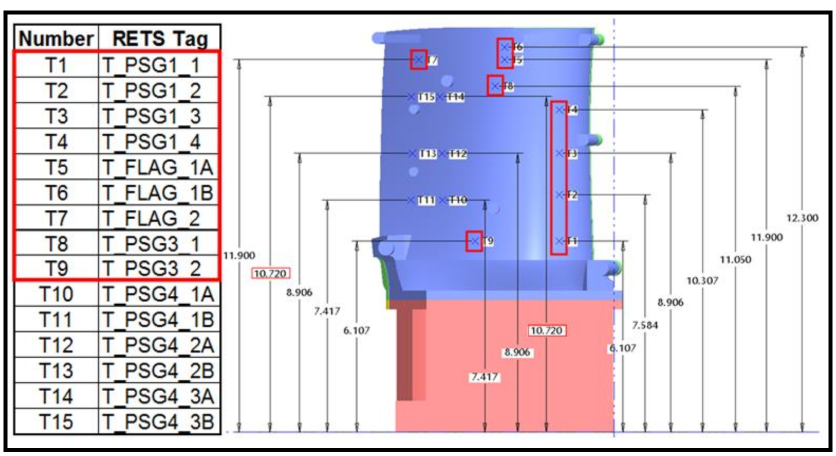

Figure 2. Instrumentation location and labels for Blade 5X SLA Model

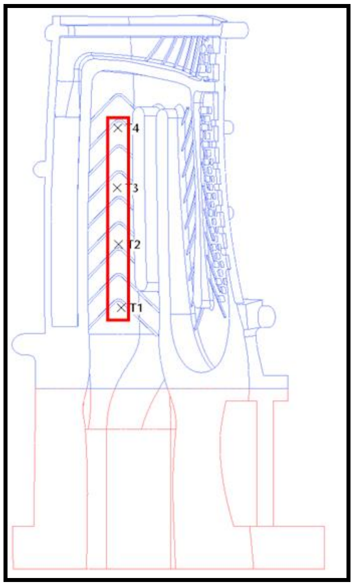

Figure 3. Cross section view showing TC locations 1-4

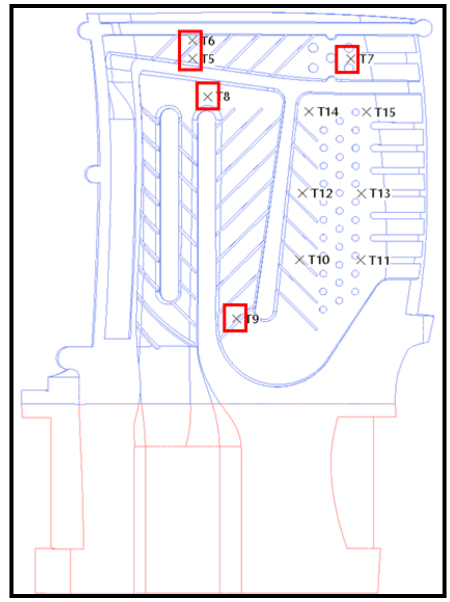

Figure 4. Side view showing TC locations 5-9

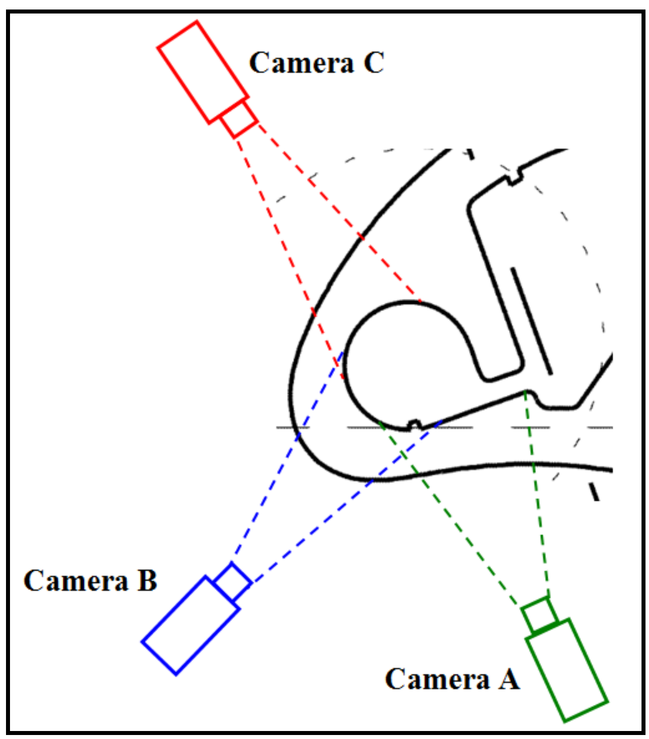

Figure 5. Three camera views

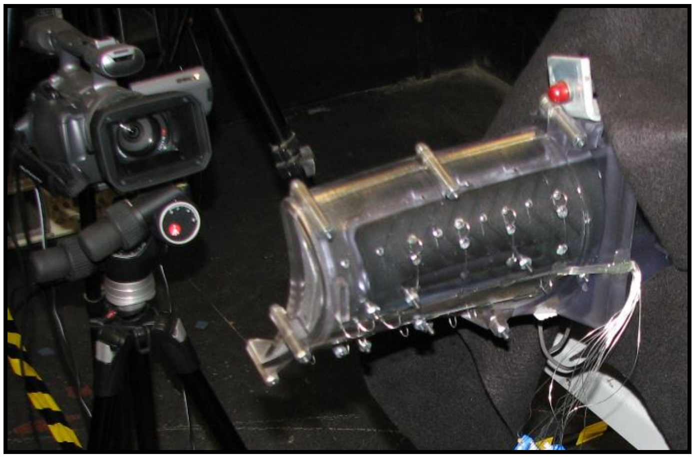

Figure 6. Fully instrumented model

3.3 Test conditions

The test conditions analyzed in this investigation are listed in table 1. For the 5x model, tests were performed at flow rates of .042, .060, and .077 lbm/s corresponding to Reynolds numbers of 27,510, 38,983 and 49,275 respectively.

Table 1. Test matrix detailing all data reduced in this investigation

Model	**Description**	**Flow Rate [pps]**	**Reynolds Number**	**Camera Views**
5X SLA w/ Trip Strip + Fillet Geometry	Low	0.042	27510	A, B, C
5X SLA w/ Trip Strip + Fillet Geometry	Nominal	0.060	38983	A, B, C
5X SLA w/ Trip Strip + Fillet Geometry	High	0.077	49275	A, B, C
6X SLA w/ Trip Strip	Nominal	0.072	38369	B
6x SLA As-Cast	Nominal	0.072	38369	B

4. Results

4.1 5x Scaled SLA Model: Local Nusselt Number Results

Figures 7-9 show local Nusselt number contour plots for each camera view based on liquid crystal test results for the 5x scaled model. The results for three mass flow rates are displayed. Figure 7 shows contour plots for the .042 lbm/s case corresponding to a Reynolds number of 27,510. The dashed box on the plots shows the area to be laterally averaged for further comparison between tests. Figure 8 shows contour plots for the same camera views at a mass flow rate of .060 lbm/s which corresponds to a Reynolds number of 38,983. Figure 9 shows the results with a mass flow rate of .072 lbm/s corresponding to a Reynolds number of 49,275. Figure 10 shows camera B results for each flow rate side by side for ease of comparison. A key trend is that the Nusselt number distributions along the leading edge in all three flow rates are uniform from one swirl cooling passage to another.

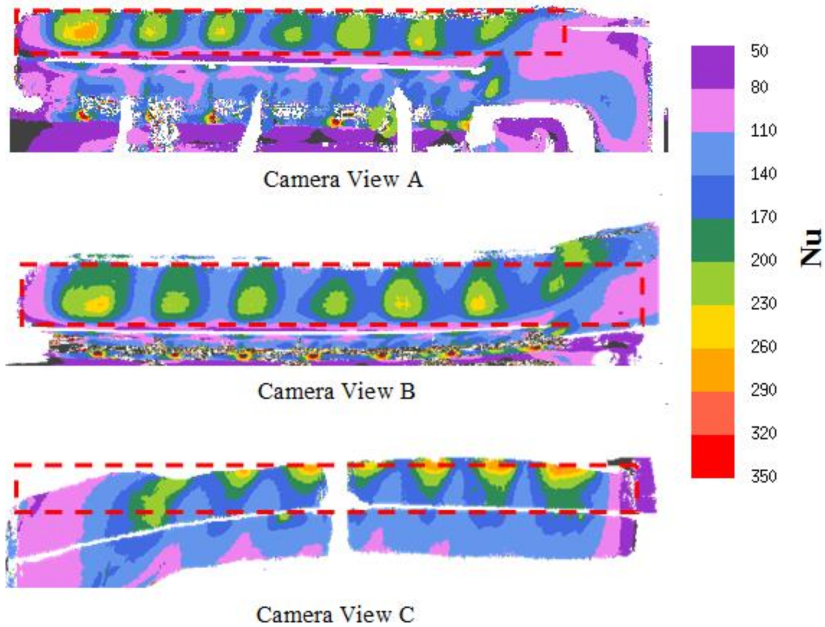

Figure 7. Local Nu plot for 5X SLA w/ TripStrip + Fillets for .042 pps @ Re = 27510

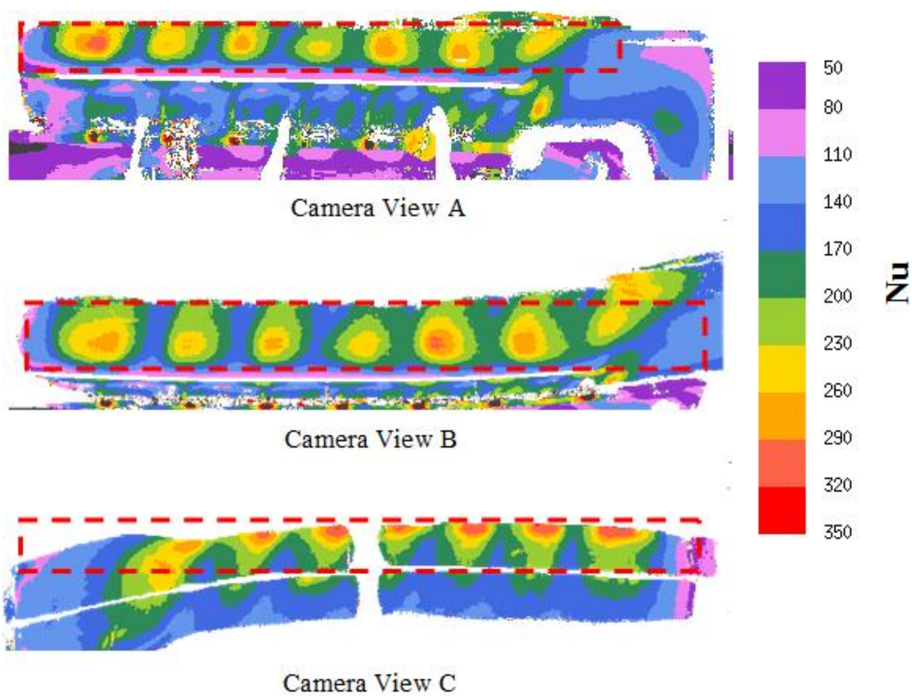

Figure 8. Local Nu plot for 5X SLA w/ TripStrip + Fillets for .060 pps @ Re = 38983

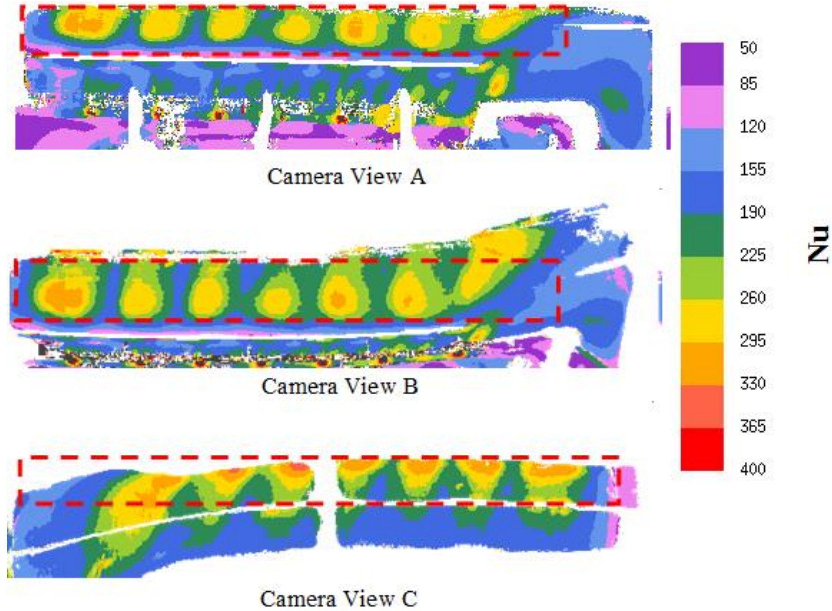

Figure 9. Local Nu plot for 5X SLA w/ TripStrip + Fillets for .072 pps @ Re = 49275

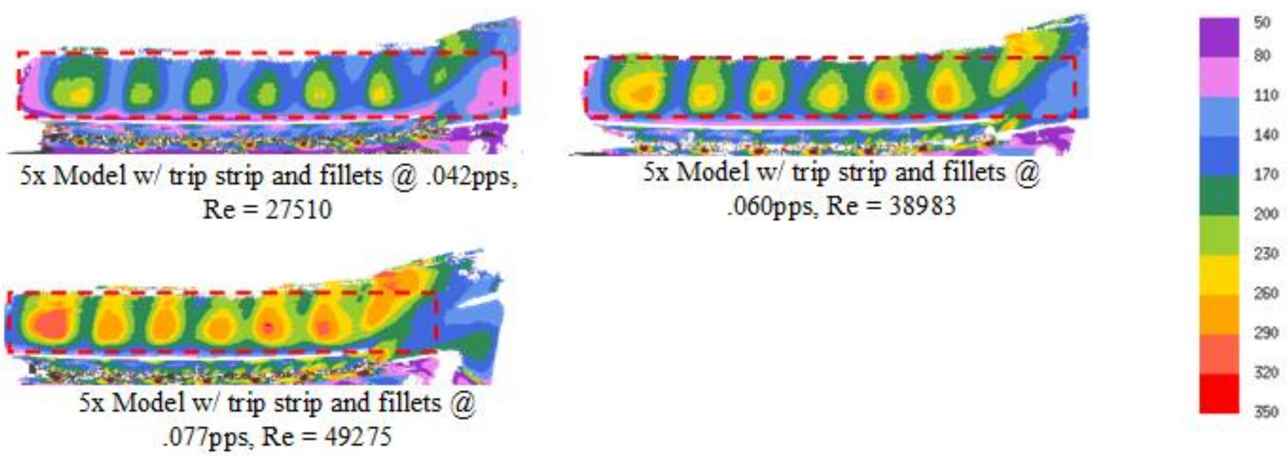

Figure 10. 5x Model local Nu results

4.2 5x Scaled SLA Model: Laterally Averaged Nusselt Number Results

For direct comparison between flow rates, laterally averaged Nusselt number data is plotted against a non-dimensional axial length. This non-dimensional axial length used as the horizontal scale in all time plots represents the beginning (0) and end (1) of the leading edge passage as shown in figure 11. Figure 12 compares the laterally averaged Nu at the three different mass flow rates. Again, the Nu distribution between the swirl cool passages is even. The difference in Nu from peak to peak is minimal, implying an even cooling distribution across the leading edge.

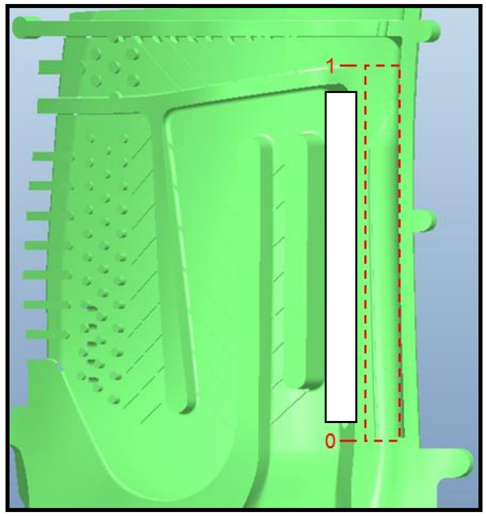

Figure 11. Non-dimensional axial length reference diagram

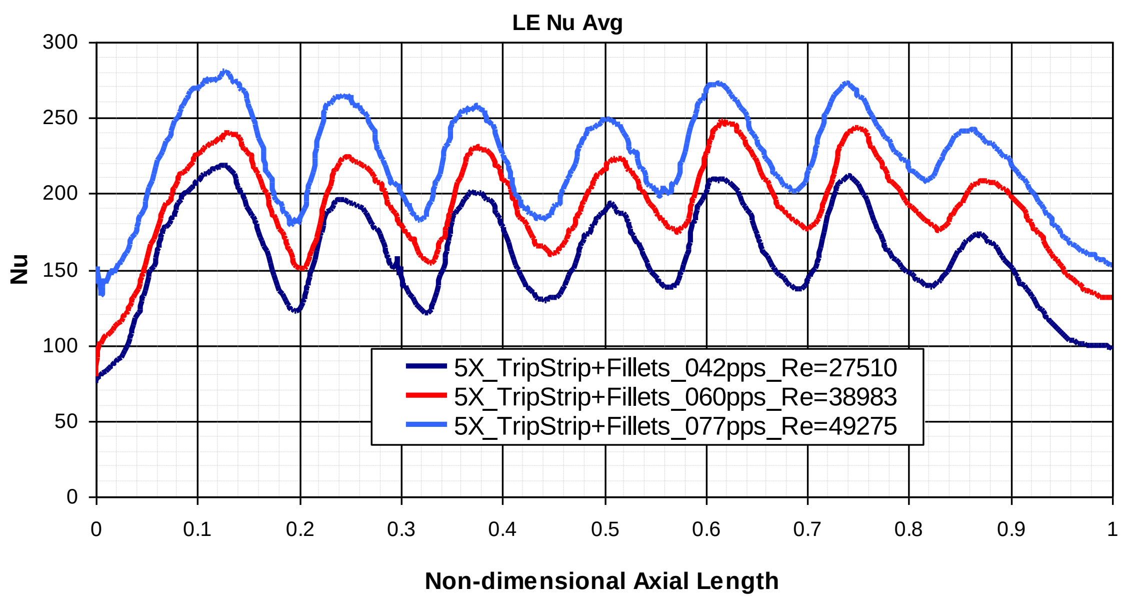

Figure 12. 5x Model Laterally Averaged Nu Results

4.3 5x and 6x Scaled SLA Model Comparison: Local Nusselt Number Results

One of the objectives of this investigation was to compare the current production blade (or "as-cast") 6x model with the 5x and model. Figure 13 shows the local Nusselt number contour plots of the 6x as-cast SLA model (representing the current production blade) compared to the 5x modified SLA model (with widened swirl cool slots and an added trip strip in addition to the geometry changes previously referenced). The contours compare each model's respective nominal flow rate. The 5x model with the trip strip has a uniform Nu distributions along the leading edge. In addition to a much lower magnitude, the 6x as-cast model's Nu distribution has a very different pattern. The cooling distribution is not as uniform as the 5x model with the added trip strip, specifically from the last three swirl slots in the passage.

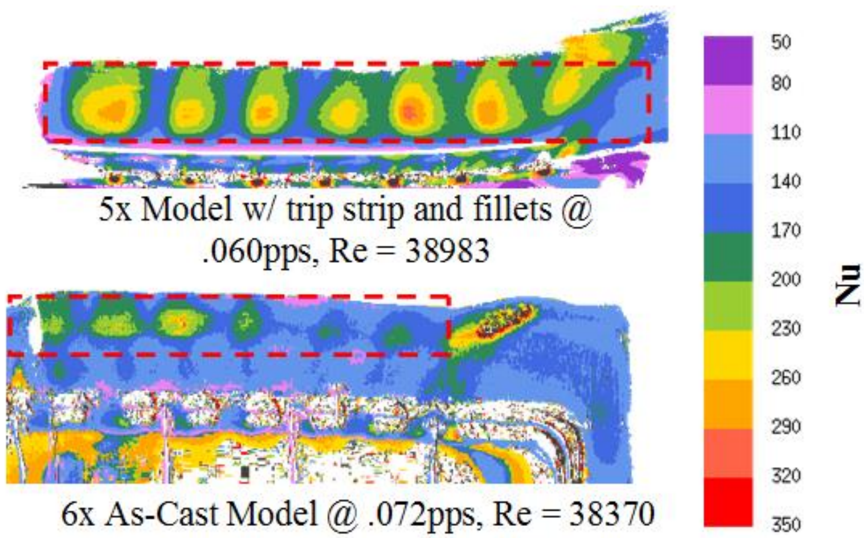

Figure 13. Local Nu comparison between models

4.4 5x and 6x Scaled SLA Model Comparison: Laterally Averaged Nusselt Number Results

Figure 14 shows the laterally averaged Nusselt number data plotted against a non-dimensional axial length. The 6x as-cast model is being compared to the 5x modified model. Results show that adding a trip strip and widening the swirl cool slots gave an increase in Nusselt number over the regular as-cast design. For the 5x modified SLA model, averaging the Nu values across the leading edge shows an averaged increased Nu of 28% across the leading edge over the as-cast.

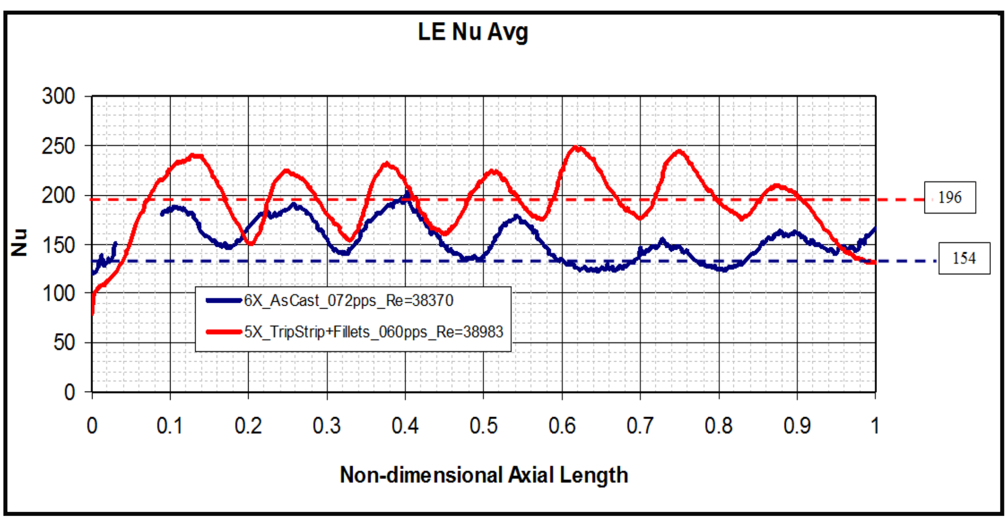

Figure 14. Laterally averaged Nu comparison between models

5.5 Application of Findings to The Blade Thermal Model

The purpose of the thermal model is to simulate engine conditions experienced by the blade in order to predict temperatures at full heat load. The transient liquid crystal test results for the 5x scaled model show an average increase in Nu of 27.7% across the leading edge over the as-cast design with the addition of the trip strip. An increase in Nu along the interior of the blade leading edge implies a drop in temperature. In order to approximate this temperature drop from the current-production durability update blade (p/n: 380245-1), the increase in Nu along the leading edge has been applied to the thermal model. A temperature difference plot between the original thermal model and the model with 27.7% increased Nu is presented in figure 15. A temperature drop of approximately 25°F can be seen across the leading edge with the application of the 5x scaled model liquid crystal test results. The localized increase in temperature on the pressure side of the blade is due to the drop in HTC as a result of widening the swirl cool slots and the redistribution of flow through the slots.

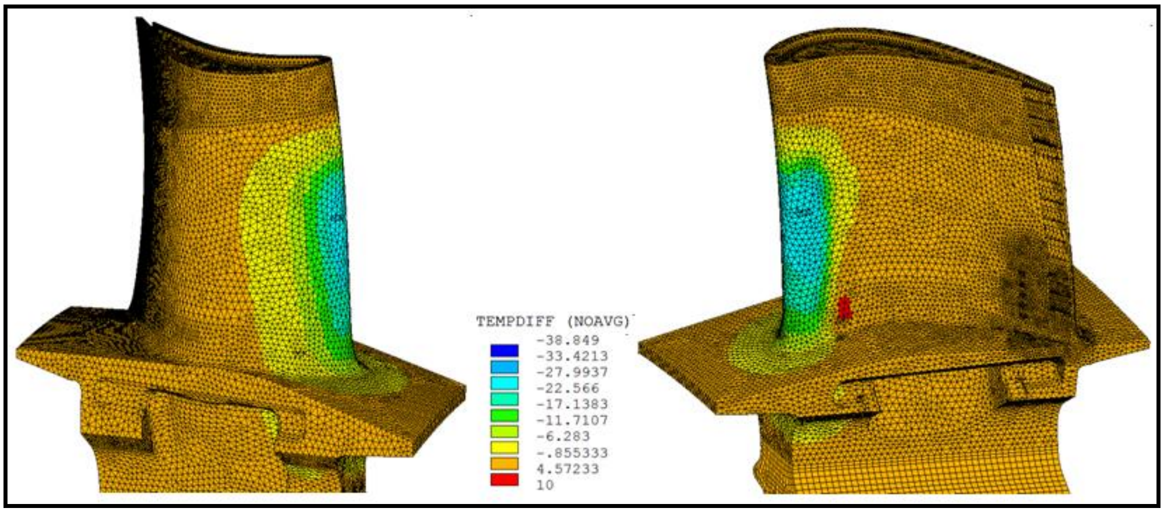

Figure 15. ANSYS temperature difference plot between original as-cast design and 5x scaled model results

6. Conclusion

- The blade has been experiencing higher temperatures than expected in the leading edge. An experiment was performed on a 5x scaled SLA model of the blade using the thermal imaging rig and liquid crystal paint.
- Results show that adding a trip strip and widening swirl cool slots give an average of 27.7% increase in Nusselt number across the leading edge compared to the original as-cast blade.
- Findings significant because they validate the 6x SLA model test, which now shows an averaged increase in Nusselt number of 31.6% with the thermal conductivity and data file error issues being resolved.
- Adding realistic casting geometries had a small but noticeable effect on heat transfer characteristics across the leading edge (about a 3-4% drop in average Nu).

- Application of the 5x scaled model results to the ANSYS thermal model show a drop in leading edge temperature of approximately 23°F from the as-cast design.

7. Acknowledgements

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