University Turbine Systems Research (UTSR) Fellowship Program 2017

Turbine Aerodynamics

Prepared for:

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Due to the nature of the projects, many critical details have been left out due to proprietary information and property infringement.

1. Introduction

The goal for this project was to better understand the effects of different trailing edge parameters on the efficiency of gas turbine airfoils. Two main categories of trailing edge design were investigated. The first being the shape, and the second were the cooling characteristics of the airfoil. The trailing edge shapes used were generated using a MATLAB script, that systematically produced shapes with different degrees of roundness. The script used two factors to produce the trailing edge points; the factors were named the "roundness" and "flatness" factors. The different shapes were run both steady and unsteady and then analyzed for changes in stage efficiency.

For the trailing edge cooling the temperature and hole spacing were changed for one study. The round trailing edge shape was chosen to be used for the cooing studies because it was the baseline for the shape study. The other study changed the film hole size along with the hole spacing. In all cases the total added flow was held constant. Similarly, the efficiencies would be analyzed for those studies.

2. Generating Trailing Edge Shapes

A MATLAB script was created to produce trailing edge shapes in a standardized manner. The method consisted of two parameters used as inputs into the script. The first input was named the "roundness" factor. The factor is a fraction between 0 and 1, and is used to determine at what percentage of the trailing edge radius the new trailing edge begins. The squarest shape means it has a roundness factor of 0, and the round case has a roundness factor of 1. The second parameter is called the "flatness" parameter. It was used to determine the height of the new trailing edge. (See Figure 1). The cases primarily depended on the roundness factor as separation would occur near that point, which simplified analyzing the shapes because the study focused on one factor instead of two. Further studies involving the flatness parameter would be useful in the future.

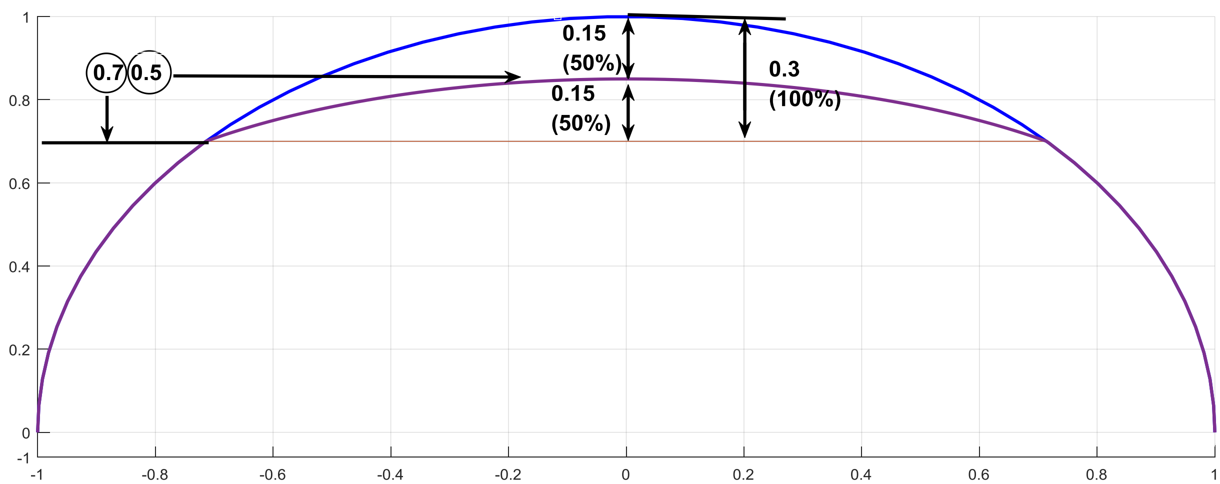


Figure 1. This is a figure of the round trailing edge from which the other cases were inscribed from, and the 0.7_0.5 case is shown as an example. The first parameter (roundness factor) gives the percent length of the trailing edge. The second parameter (flatness) gives how flat the edge is. (0 being square and 1 being round).

3. Steady vs. Unsteady Results for Roundness Study

All five cases shown in Figure 2 were run both steady and unsteady on a single stage (stage 1 nozzle and blade). The roundness factor was plotted against the stage 1 delta efficiency. The baseline for the delta efficiency were the steady and unsteady round cases. As seen in Figure 3, the results for the steady cases had a general trend of decreasing as the shape moved from round to square, which was expected. However, there was a point at which the loss leveled out. This was unexpected especially when compared to the unsteady cases, which never leveled off. Instead the unsteady cases showed more losses. While running these cases, it was also noted that even small deformities could cause a sizeable jump in efficiency. The code is thus sensitive to small trailing edge changes and it is important to get the airfoil shape correct. Further investigation is needed to understand the trends occurring in the steady and unsteady results.

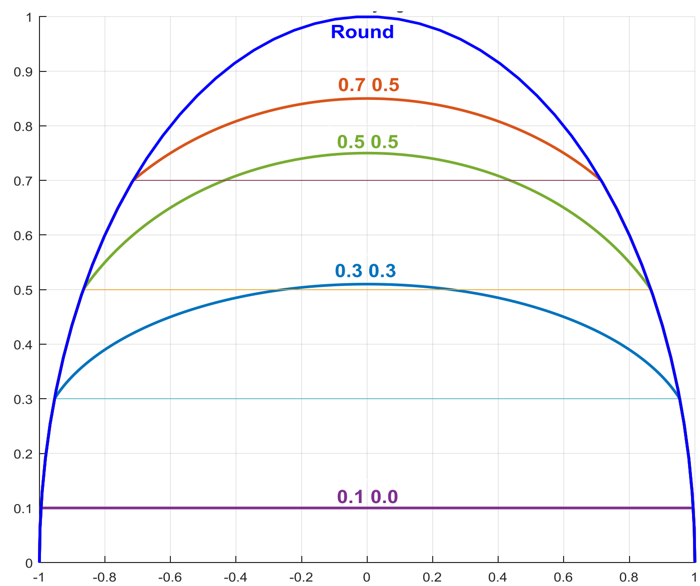


Figure 2. The five non-dimensional cases used to understand the effects of changing a TE shape. These cases were chosen to obtain an even distribution of round to square cases.

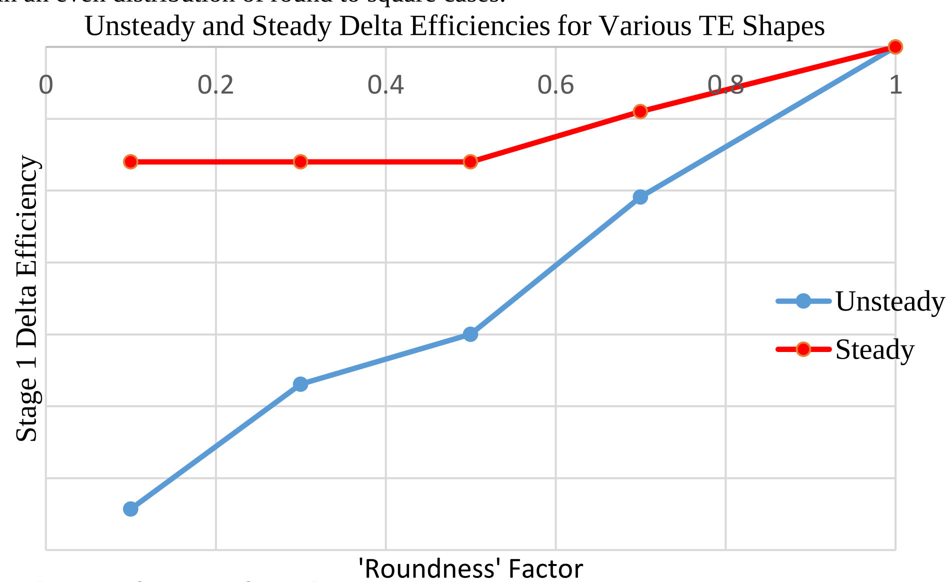


Figure 3. Stage 1 loss as a function of roundness.

In order to better understand where the losses were coming from, the nozzle 1 delta losses were plotted in Figure 4 as a function of roundness. However, more investigation is needed to understand the plot. The nozzle 1 delta efficiency displays that the 0.1 case does not fit the trends for either the steady or unsteady. The unsteady curve shows a steep slope between the 0.3 and 0.1 cases, and the steady curve shows less loss coming from the 0.1 case than the 0.3 or 0.5 case. This could be due to uncertainties, but most likely it was some deformity in the trailing edge that occurred due to the method of adding new trailing edges to original airfoil geometry. The TP3 point is taken to be what the true value should be for a nozzle 1 loss, because it is based on test data. The steady is relatively close, but again having an untrustworthy data point makes it hard to make any conclusions with confidence.

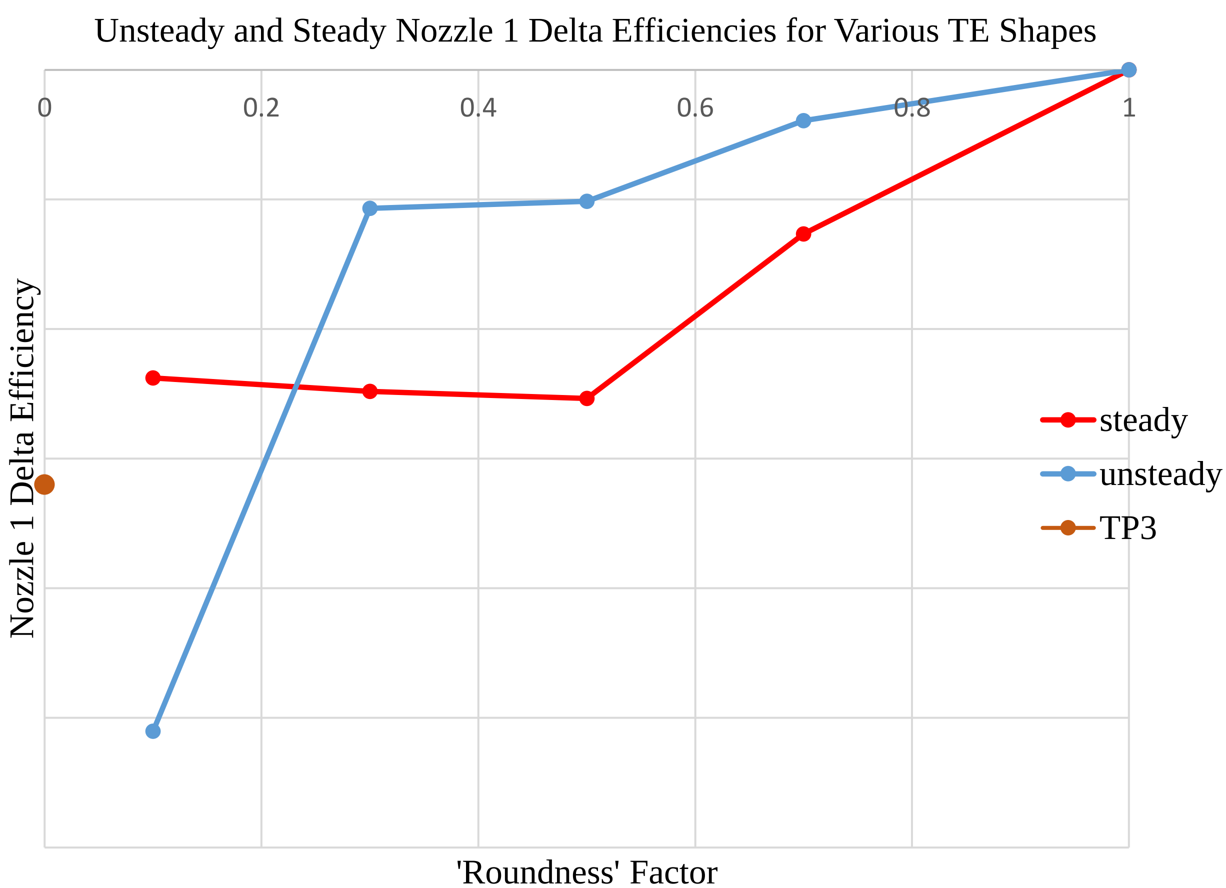


Figure 4. Nozzle 1 loss as a function of roundness.

Instantaneous entropy contour plots shown in Figure 5, display how the wake changes based on the trailing edge shape. As the trailing edge becomes more round there is more vortex shedding for the unsteady cases. Wakes produced by the squarer cases will cause greater loss to occur in the blades downstream. The steady cases on the other hand have a smooth wake and there are no apparent changes as the shape changes.

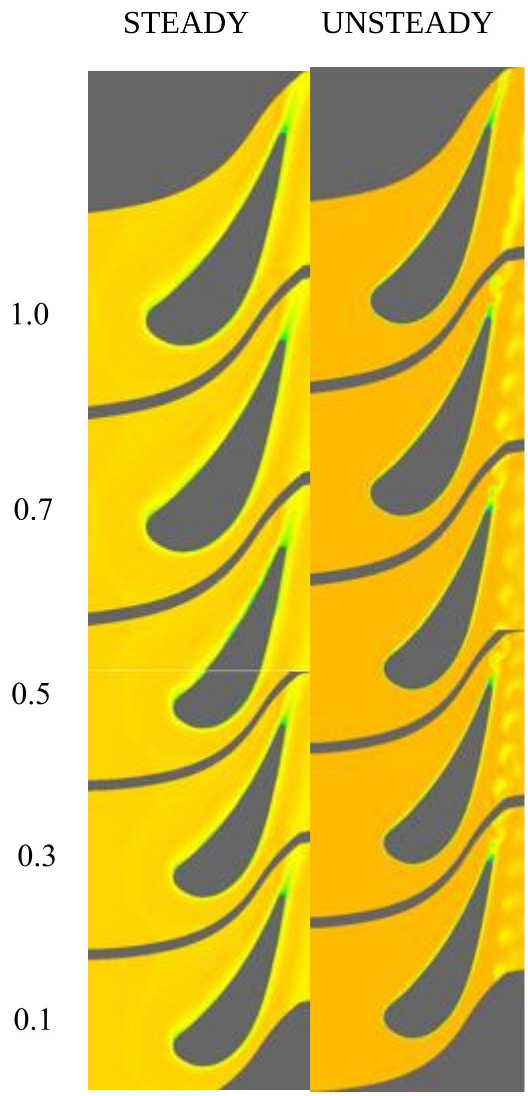
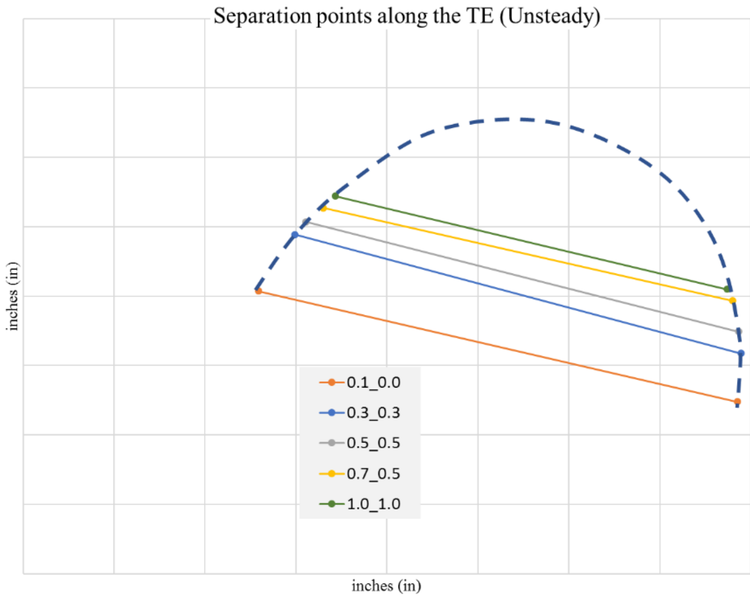
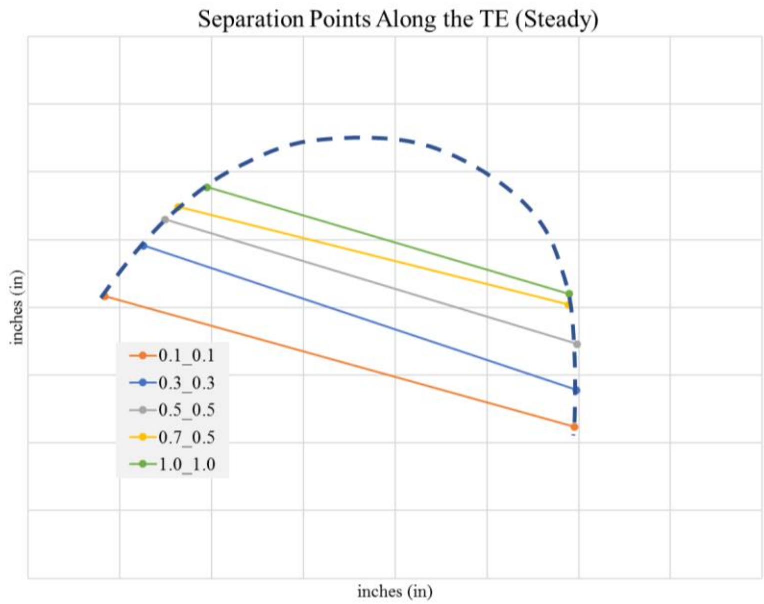


Figure 5. Entropy contour plots for the five steady and unsteady cases.

In comparing the steady and unsteady cases the separation points were analyzed (see Figure 6.). The points on the suction side and pressure side were estimated based on contour plots. In both studies the separation points went in order of roundness factor. The round case had flow separate the farthest downstream and the 0.1 case had its flow separate the earliest. Also, the location of separation coincides relatively close to the location where the roundness factor dictates the curve to deviate from the fully round shape.



a) Unsteady



b) Steady

Figure 6. The relative location of separation for the 5 unsteady cases (a), and steady cases (b).

4. Additional Trailing Edge Shapes

Another part of the trailing edge shape study, was the more unconventional trailing edge shape design. Two additional shapes (see Figure 7) chosen were the elliptical and the profiled trailing edges. The elliptical trailing edge was three times as long as the trailing edge thickness. The advantage for the ellipse was that it would prevent separation from occurring until farther downstream on the airfoil boosting efficiency and thus reducing the effective trailing edge thickness. The profiled case was a round case, but the suction side of the airfoil had been filed down to make it thinner. This makes the trailing edge thickness thinner and increasing efficiency.

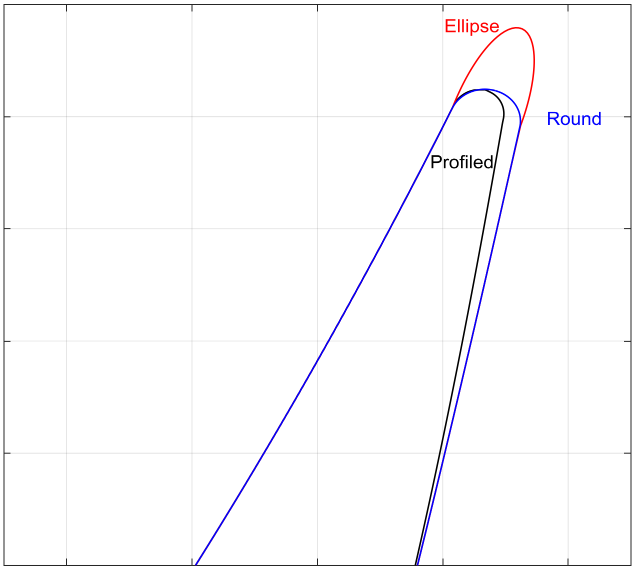


Figure 7. Plot of the three best trailing edge shapes that were overlaid upon each other.

Shown below in Figure 8 is the comparison of the ellipse and profiled cases compared to the steady and unsteady round cases that were used as the baseline. The elliptical trailing edge had the best efficiency in both the steady and unsteady runs. The elliptical trailing edge was much longer which allowed it to have separation points the farthest downstream of all the trailing edges studied. Thus, giving the elliptical shape a smaller trailing edge. The profiled case was better than the round case but not as efficient as an ellipse. This was expected because the profiled case had a smaller trailing edge thickness than the original round case.

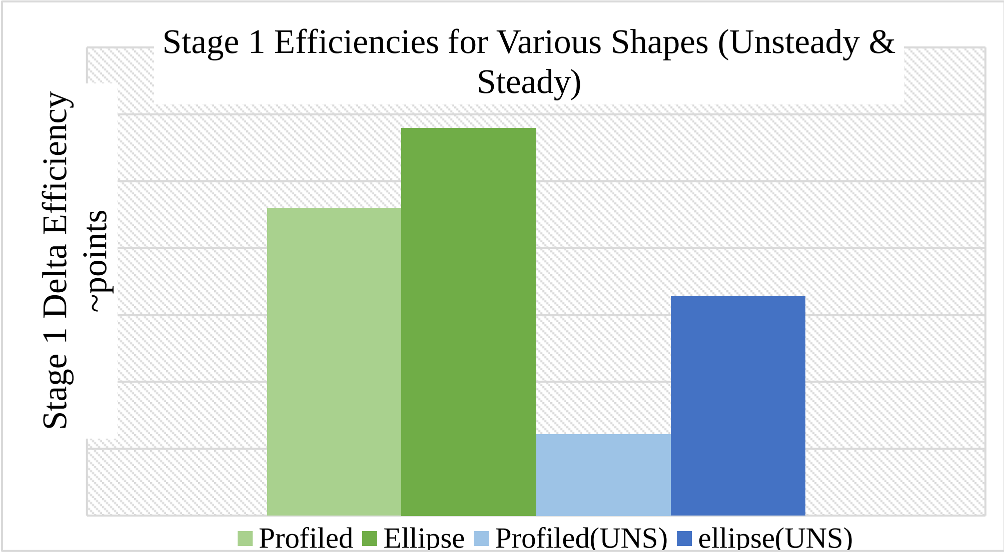


Figure 8. The delta efficiencies of the shapes shown in figure 7, where the baseline is the round case (case 1.0).

The last results for the trailing edge shape study were on the losses due to the profiled case. The original profiled case was cut at the tangency points (cut profiled) and at the separation points (cut profiled 2) to understand the amount of loss that would occur when compared to the original profiled case. (See Figure 9). Looking at Figure 10, as expected there was more loss for the cut at the tangency points (cut profiled) than a cut at the separation points (cut profiled 2). Also, it was found that it was not worth profiling an airfoil if the edge is going to be cut at the tangency points, because a round trailing edge (case 1.0) would perform better. However, a cut at the separation points (cut profiled 2) would still produce a better efficiency

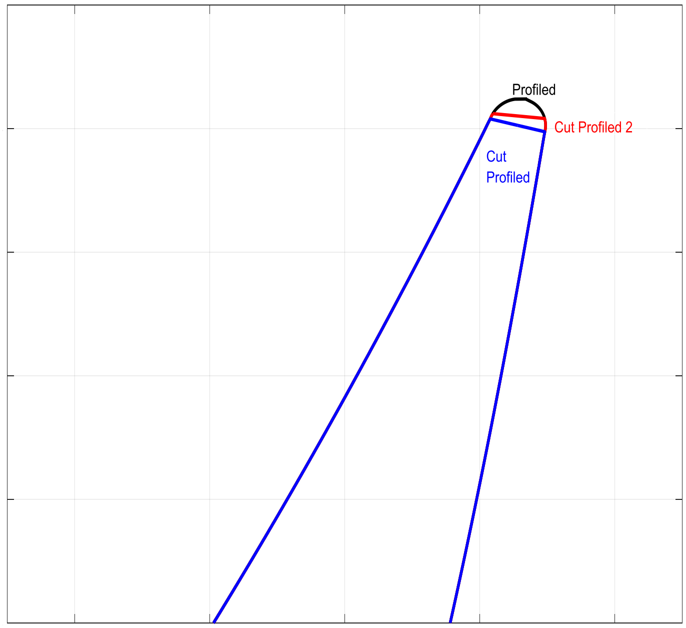


Figure 9. A plot of the three profiled cases displaying the differences between each cut.

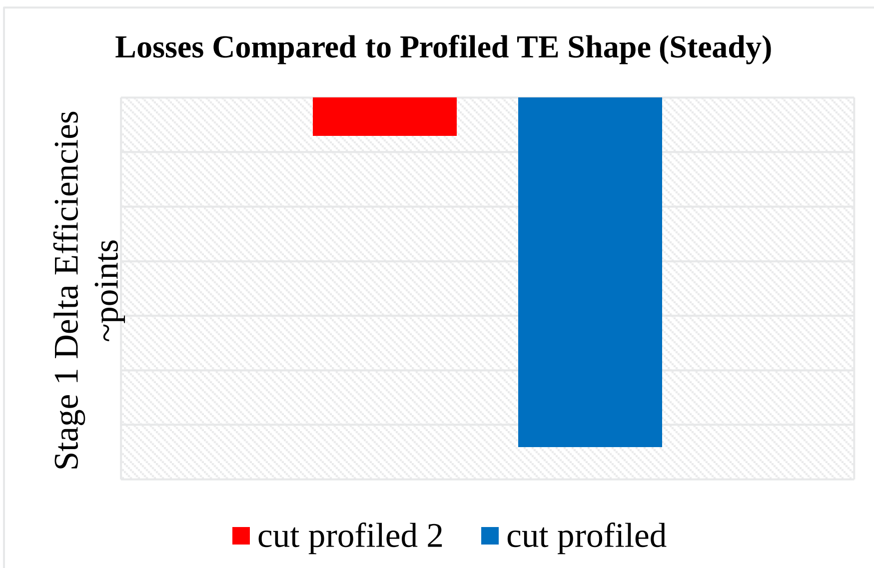


Figure 10. Plot of the delta efficiencies of the cut profiled and cut profiled 2 cases where the baseline is the original profiled case. These cases were run steady only. The shapes can be seen in figure 10.

5. Trailing Edge Cooling

The study on trailing edge cooling used source vectors to model the cooling holes as shown in Figure 11. The study can be broken down into two sections. The first section involves increasing the temperature of the coolant while keeping the total flow constant. The ratio of the coolant temperature (TTc) to mainstream temperature (TTm) was kept consistent within each case so the cases could be compared easily. The coolant temperature would change, while the mainstream would remain constant. In order to obtain a constant total flow, while also changing the coolant temperature, the number of holes modeled in the airfoil had to change with the mass flow rate of the coolant per hole.

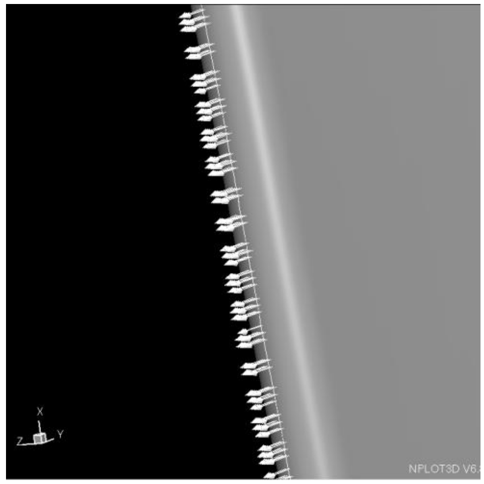


Figure 11. A picture of the trailing edge showing the source vectors from the cooling holes.

The other section of the study, involved a 2x increase in area for the film holes and analyzing the effects on stage efficiency (see Figure 12). Changing the area of the holes was done by increasing the diameter of the film holes (S) to trailing edge thickness (TET) ratio. The total coolant mass flow and temperature were held constant. The number of holes had to change with the mass flow rate of coolant per hole, to ensure the total flow was constant.

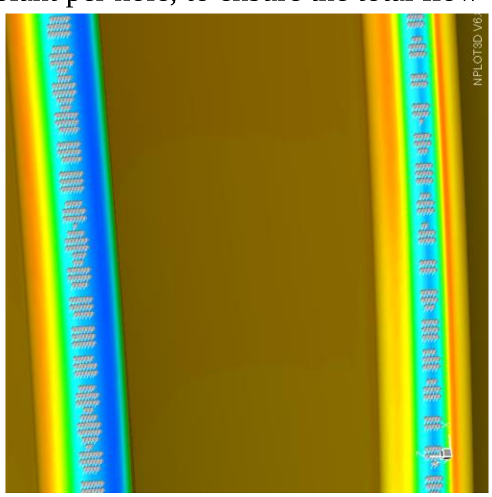


Figure 12. Two trailing edges are pictured, the one on the left has 2x more hole area than the right trailing edge.

The Mach number ratio is the Mach number of the coolant (Ma, c) per the Mach number of the mainstream flow (Ma, m). To make the Mach number ratio vary consistently, the number of holes on the airfoil were changed by adding and subtracting 30 holes to the baseline case. In Figure 13 it can be seen, that as the Mach number ratio increases the loss also increases. A higher coolant to mainstream temperature ratio (TTc/TTm) showed similar loss to the lower temperature ratio, except at higher Mach number ratios where it had more loss.

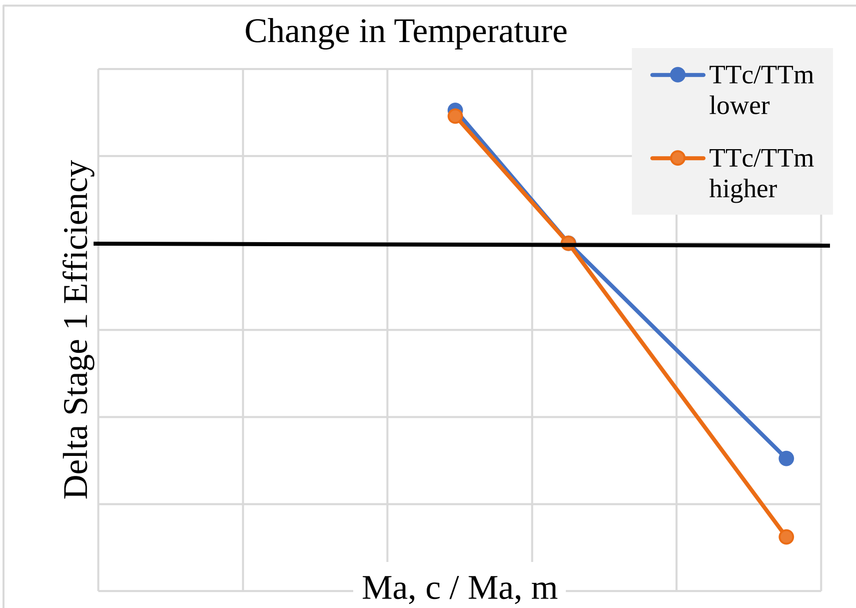


Figure 13. Plot of the stage 1 delta efficiency vs. the Mach number ratio at two different coolant temperatures.

The second section of the trailing edge cooling study kept the total flow constant, along with the temperature of the coolant flow. In order to double the film hole area, the number of holes were changed along with the mass flow rate. This enabled the total flow to be constant and the Mach number ratio consistent with other cases. As seen in Figure 14 the higher diameter to trailing edge thickness ratio peaks and then loses efficiency. The smaller diameter to trailing edge thickness ratio loses efficiency as well. The reason for this "peak" in the higher ratio curve is probably due to wake filling. Wake filling is when the cooling jets add some flow to the wake just behind the airfoil that counteracts some loss that would have otherwise occurred there because of the flow around the trailing edge. Ideally a trailing edge would have a lot of holes with a high Mach number ratio because it would increase the wake filling. However, if the number of holes increases, the Mach number ratio must decrease to keep a constant total flow. This explains why there is a peak, which is it at the optimum level of efficiency for wake filling.

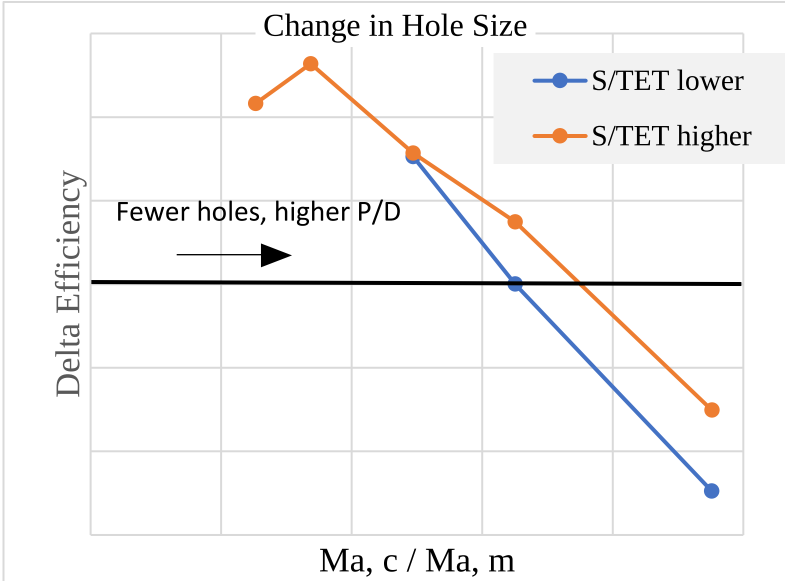


Figure 14. Plot of the delta efficiencies vs. the Mach number ratio.

Figure 15 shows that as the pitch to diameter (P/D – 1) decreases the pitch must decrease as the diameter is constant. The pitch decreases by adding more holes. Therefore, a similar peak is noticed due to the radial filling. The more holes the more the more the wake is filled and thus the better efficiency. The wake filling depends on both the Mach number ratio and pitch to diameter.

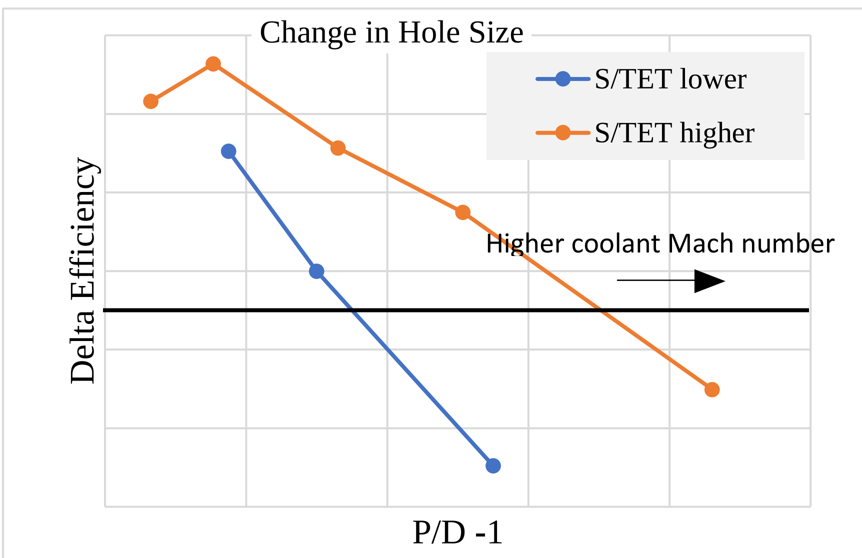


Figure 15. A plot of the delta efficiencies vs. the Pitch / Diameter -1.

6. Conclusions and Future Work

Overall the best trailing edge shape was the ellipse, because it prolonged separation until farther downstream which allowed for better efficiency due to the thinner trailing edge. The best cooling parameters for the trailing edge was at the peak in the plots of delta efficiency vs. the

Mach number ratio because of the wake filling. However, much more investigation could be done, such as studying the flatness factor, and better understanding the nozzle loss results. Also, more cases could be run for the trailing edge cooling studies to give more accurate results. There are many opportunities for future work.

7. Acknowledgements

I would like to thank GE for being my sponsor company this summer along with Gunnar Siden, my manager, for making me part of his team. Also thanks to Scott Holloway, Sylvain Pierre, Justin Mussetto, and the entire Turbine Aerodynamics for helping and guiding me along the way. Lastly thank you to SWRI for providing the funding allowing me to learn about this topic.