4-21-2020

Development of Transonic Cascade for Heat Transfer Research

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Development of a Transonic Cascade for Heat Transfer Research

by

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An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

4/20/2020

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Abstract

The present project considers three-dimensional modeling of complex turbine blade airfoils, a transonic cascade, and a sonic orifice arrangement, using SOLIDEDGE Computer Aided Design (CAD) software. With this approach, the top wall of the cascade is designed to allow measurements using various sensors, in addition to installation of a zinc-selenide window, which allows thermal imaging of a blade tip. The airfoils required for the heat transfer research effort include innovative solutions to integrate thermocouples for calibration. The airfoils also employ a plenum for injection of cooled carbon dioxide gas for film cooling. The sonic orifice provides means for the cooled carbon dioxide gas mass flow rate to be measured. The overall designs of the turbine blade airfoils, the transonic cascade, and the sonic orifice enable data collection and analysis of heat transfer characteristics of transonic turbine blade tips, as applied to gas turbine engine environments.

Introduction

The development for a complex experiment, like a transonic cascade, requires expertise, trial and error, and patience. The development stems from research objective requirements and goals. However, no matter how much analysis and verifications are performed, the design must be iterated to account for unforeseen issues. In addition to the development, logistics must also be managed to account for lead times in manufacturing, on site labor by researchers and contractors, and testing within a research institution. When the three are harmoniously combined, the result is the successful development of a transonic cascade for measurement of surface heat transfer characteristics on a transonic turbine blade tip.

The transonic cascade provides an environment to experimentally examine heat transfer characteristics of turbine blade tips, both with and without different film cooling configurations [3]. After the cascade and blades are in place and operational, initial tests are undertaken to validate the test environment. Afterwards, experimental data are obtained with airfoils with different film cooling arrangements.

Component Designs

The initial design is of the linear cascade is based upon fluid mechanics and heat transfer considerations. The next step is to adapt design ideas into three-dimensional models using SOLIDEDGE Computer Aided Design (CAD) software. The overall goal is development of a linear cascade with appropriate Mach number and surface heat transfer characteristics. Also important are the film cooling configurations, which are included within each turbine blade design. Upon completion of a design, manufacturing materials and processes are determined.

Turbine Blade Airfoil Design

The two-dimensional profile of the turbine blade airfoil is based on information provided by the research sponsor. Shown in Figure 1 is the turbine blade profile, including the squealer recess region. The blue outline within this figure designates the outer profile of the blade, while the orange outline shows the extent of the squealer recess on the tip of the turbine blade. To measure the blade pressure surface and suction surface Mach number distributions, baseline airfoils ae employed with static pressure taps positioned at different blade surface locations. Figure 2 shows a schematic diagram of a blade, with the squealer, and with pressure taps at ninety percent of the airfoil span. Figure 2 also shows that the blade also includes a base. Four mounting holes bear responsibility of anchoring the base of the airfoil to the linear cascade. To ensure the airfoils line up properly to the flow direction and each other, two alignment pins are used. To measure the static pressure along the chord of the airfoil, static pressure ports extend through the span of the blade, through the base (as shown in Figure 3), and then to pressure tap instrumentation connections.

An interior plenum is included within each film cooled blade configuration. With this arrangement, carbon dioxide coolant is delivered to the tip of the blade, or to the blade pressure surface, through film cooling holes. Within the plenum, the temperature of the carbon dioxide coolant is measured using thermocouples placed on thermocouple shelves. Plenum pressure is also measured using multiple surface pressure taps. Figure 4 shows a cross-sectional view of blade plenum, including instrumentation and the carbon dioxide connection location. Figure 5 presents a schematic diagram of the film cooled blade with the plenum door location. including a flange around the edge of the location. Note that this location and the associated door must be large enough so that all parts of the plenum are accessible with tweezers.

To calibrate the infrared camera, surface temperatures must be measured. Thermocouples are used for this purpose as their junctions are placed just below the surface of the squealer recess and just below the surface of the squealer rims. The diameter of the thermocouples is less than half of a millimeter. The associated installation holes traverse through the entire blade span. Each surface thermocouple junction is placed within a tab insert using epoxy, and then each tab insert is then epoxied into the appropriate location on the blade tip. Figure 6 shows surface thermocouple installation tabs as positioned on the blade tip. In the CAD blade manufacturing process, the layer height is 0.1016 millimeters. The minimum number of layers required to form a wall is four. Therefore, the thermocouple junctions are ideally 0.4064 millimeters under the surface of the squealer upon installation, as shown in Figure 7.

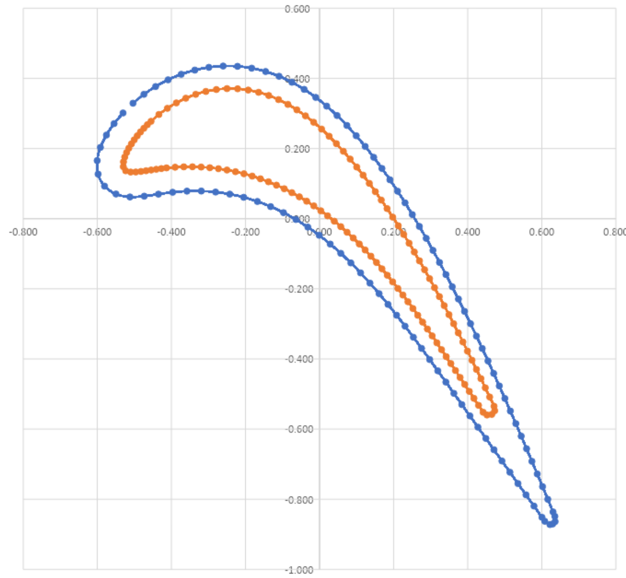

Figure 1: Turbine blade profile, including squealer recess region.

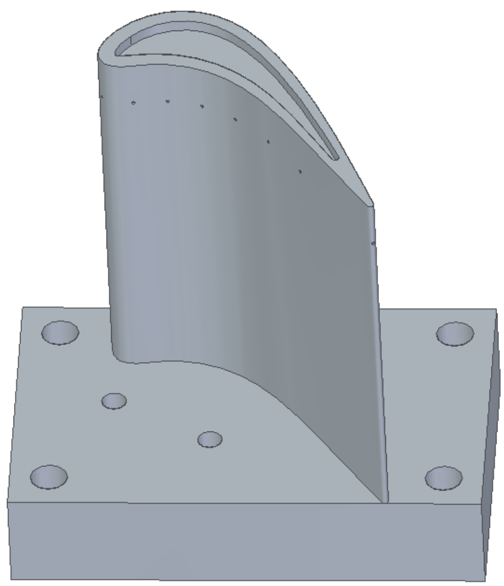

Figure 2: Turbine blade with squealer and surface static pressure taps located at 90 percent span.

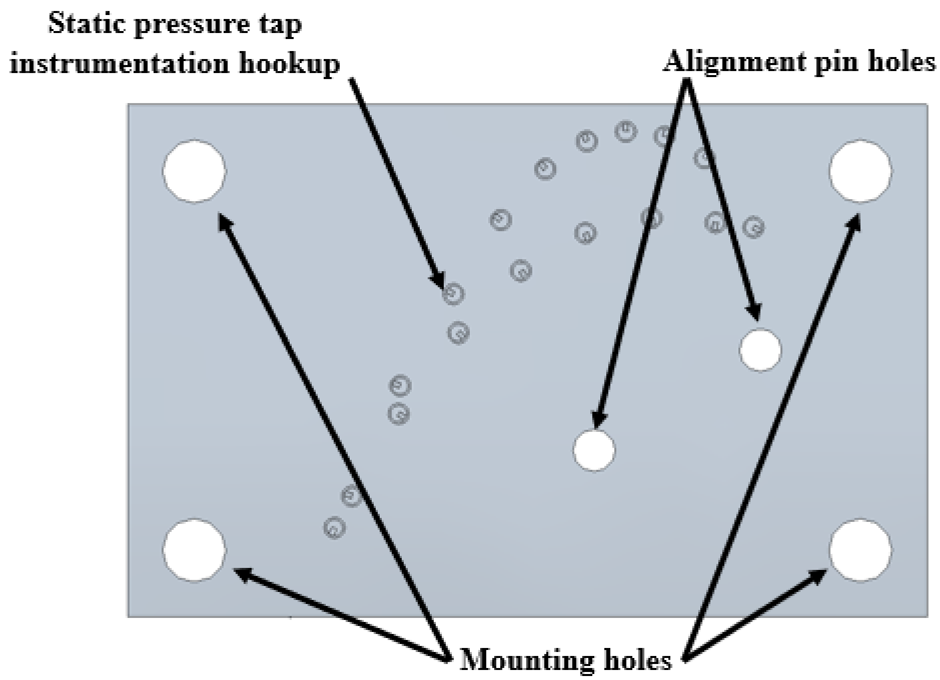

Figure 3: Bottom view of blade base with static pressure tap locations.

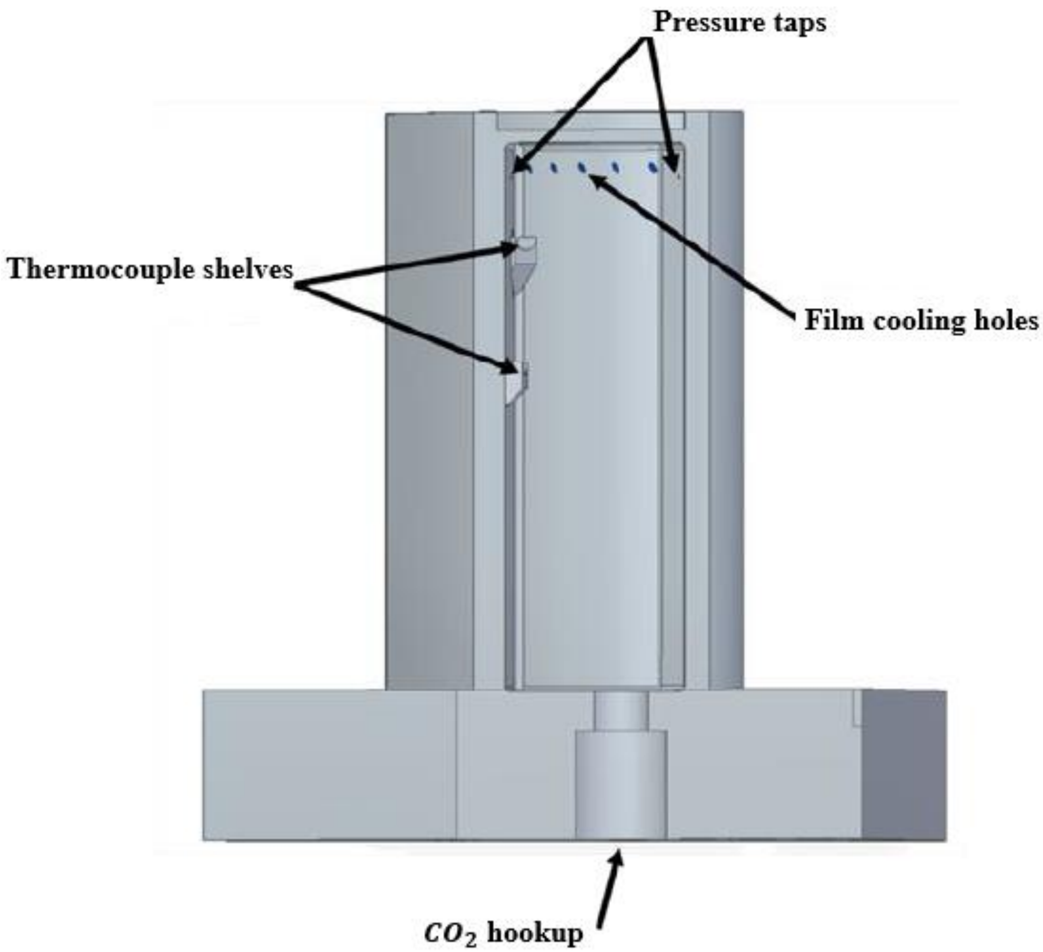

Figure 4: Cross-sectional view of blade plenum, including instrumentation and the carbon dioxide connection location.

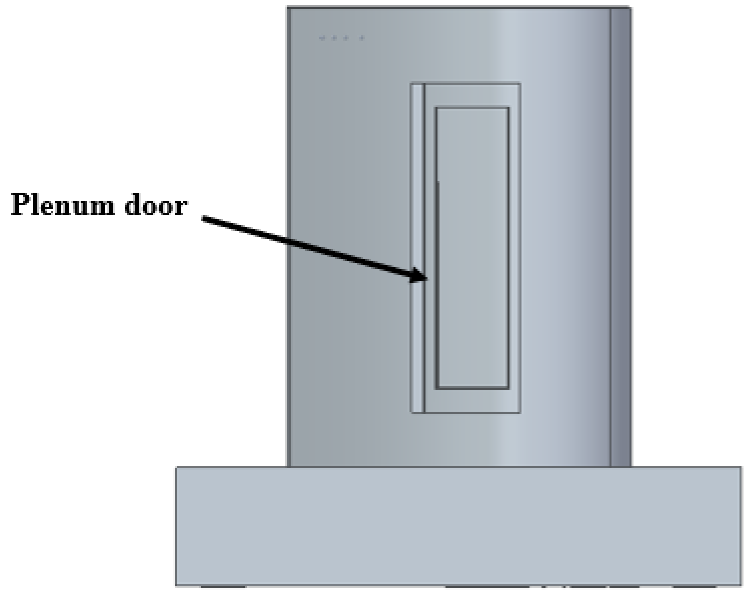

Figure 5: Film cooled blade with plenum door location including an edge flange.

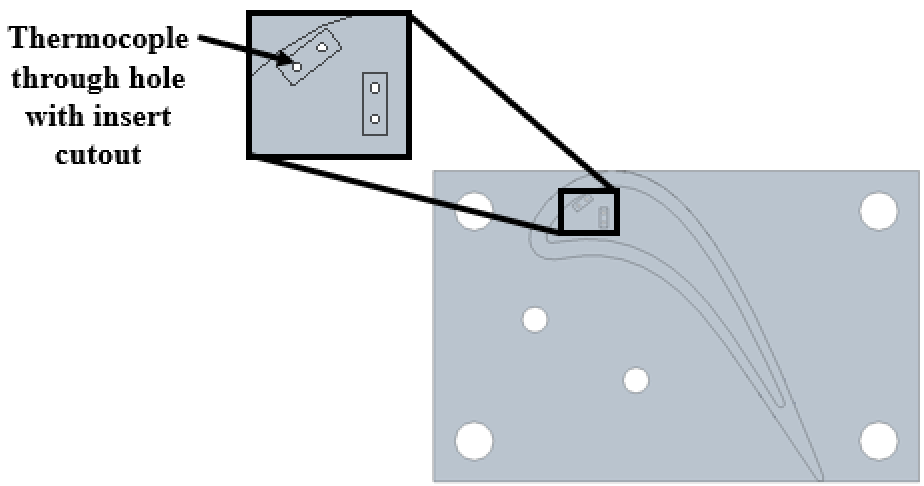

Figure 6: Surface thermocouple installation tabs as positioned on the blade tip.

Figure 7: Thermocouple junction to squealer recess surface distance.

Cascade Design

Figure 8 shows a schematic diagram of the linear cascade components: a top wall, a bottom wall, two side walls, and a tailboard. Figure 9 shows a top view of linear cascade top wall. The top wall provides a means to mount some of the instrumentation for the cascade. In addition to the instrumentation, a radial bleed is integrated directly into the top wall. A zinc-selenide thermal imaging window is mounted within the top wall. Also included are two blade shaped cutouts to support the outermost airfoils. Figure 10 shows a bottom view of linear cascade bottom wall design. The bottom wall shares cutouts for the outermost airfoils, but also includes cutouts for the inner airfoils. The bottom wall additionally includes a pressure and instrumentation hole like the top wall. Also note that the other side of the radial bleed is included within the bottom wall. The bottom face of the bottom wall houses the interface to mount the airfoils into the cascade. To accomplish precise mounting, the wall uses four mounting holes with two alignment pins so that each blade is correctly positioned and mounted.

Figure 11 shows a top view of side wall and tailboard components. Side walls and a tailboard comprise the walls of the cascade. The two forward walls integrate the mounting faces of the cascade. Mounting faces connect the wind tunnel duct to the cascade. The two forward walls also include the circumferential bleed slots. The circumferential bleeds are shaped to follow the curvature of the turbine airfoils. The tailboard is designed to be tangent to the trailing edge of one of the exterior turbine blades. Note that the tailboard angle is adjustable to plus or minus a few degrees. To assemble the cascade, a clamping design is used to provide a strong connection between the top and bottom walls. The clamp design also allows the mounting holes for the tailboard to be shaped to adjust the tailboard a few degrees without the use of a more complex assembly system. To accomplish the clamping force, threaded studs are inserted through the top wall, bottom wall, and side walls before being tightened together with washers and bolts. Figure 12 shows this clamping force assembly for linear cascade top and bottom walls.

After the cascade is assembled, the turbine blades are inserted. Instrumentation components are then connected, and installed, including the zinc-selenide window. The assembled cascade is then attached by the mounting faces on the side walls to a flange on a inlet duct of the wind tunnel. The linear casacde is also mounted and bolted to a wooden structure which supports the entire assembly. Figure 13 presents a schematic diagram of the complete linear cascade.

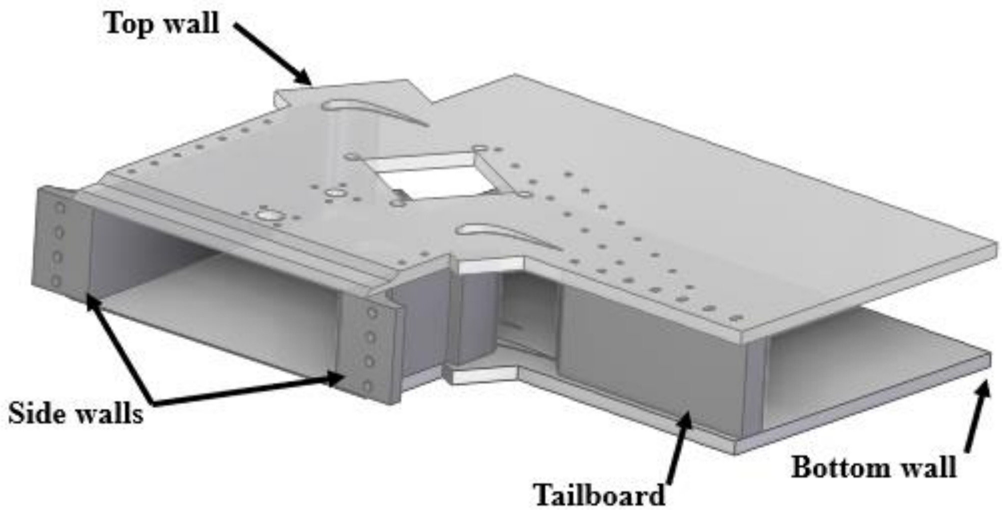

Figure 8: Linear cascade components.

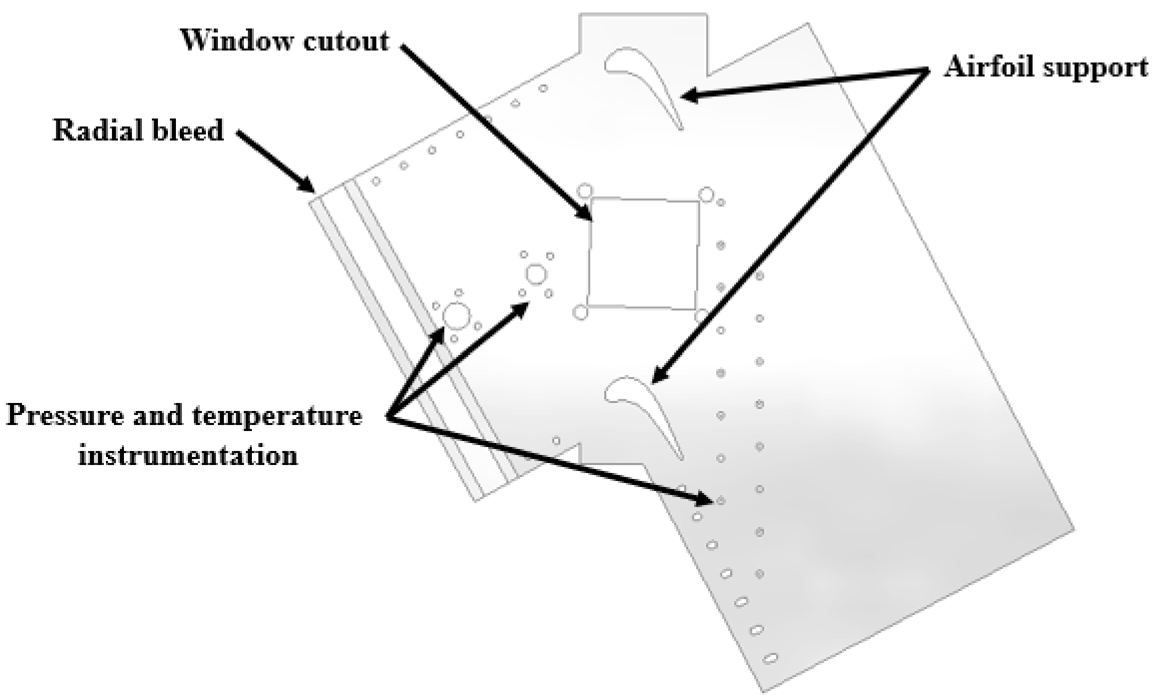

Figure 9: Top view of linear cascade top wall design.

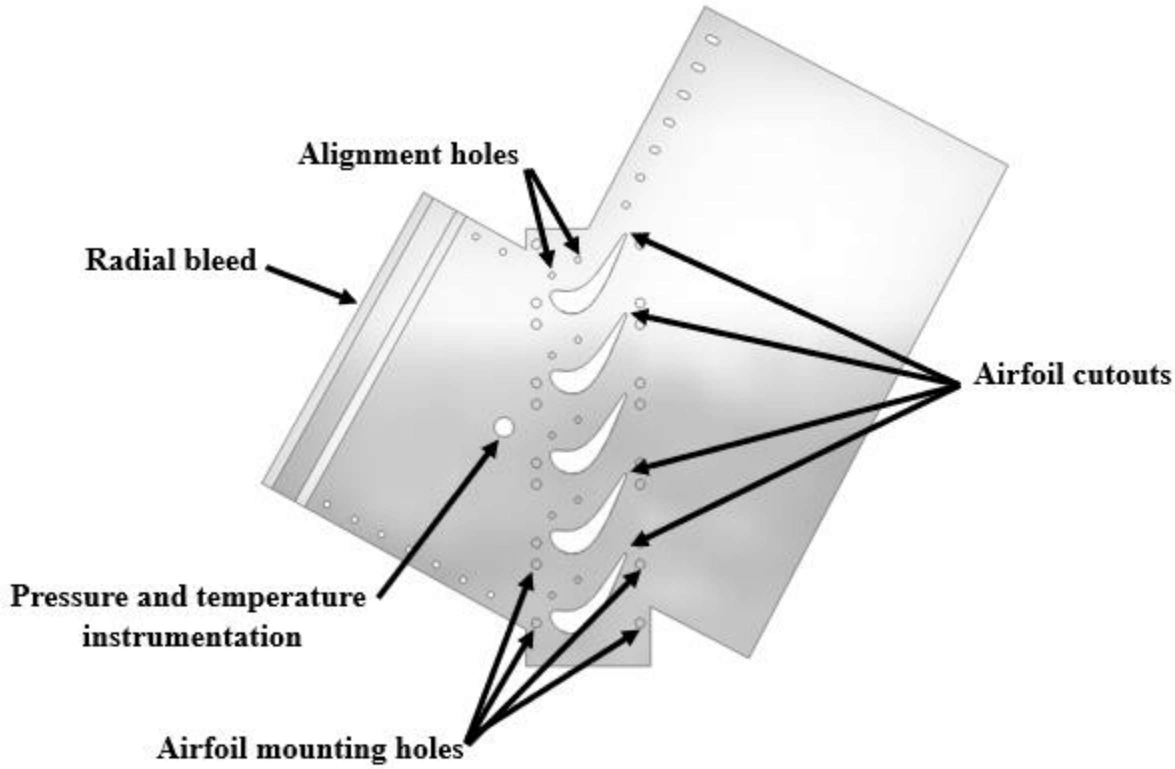

Figure 10: Bottom view of linear cascade bottom wall design.

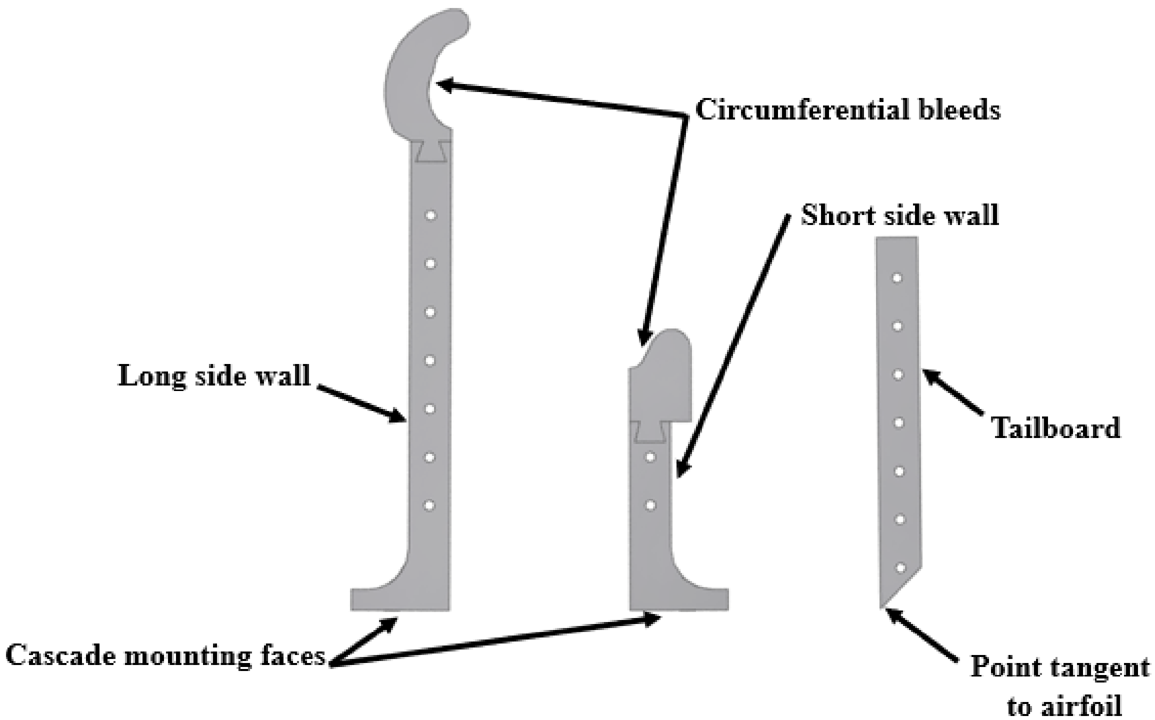

Figure 11: Top view of side wall and tailboard components.

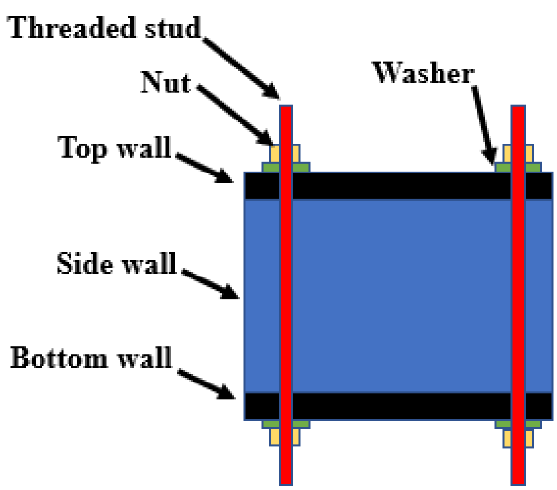

Figure 12: Clamping force assembly for linear cascade top and bottom walls.

Sonic Orifice and Carbon Dioxide Injection System Design

Figure 14: Sonic orifice mass flow measurement device cross-section. To regulate the mass flow rate of the carbon dioxide, a sonic orifice is employed between the carbon dioxide supply and the turbine blade. Because of the pressures and location of the orifice in the lab, off the shelf parts are used to assemble the carbon dioxide system to ensure safety. The only custom component of the system is the orifice. Instrumentation needed on the sonic orifice includes a stagnation temperature and pressure measurement. The flanges of the sonic orifice then connect to the rest of the injection system. Some important parts of the injection system include the carbon dioxide tank, the carbon dioxide regulating valve, the mass flow rate device, the copper tube heat exchanger used to cool the secondary flow, the metal airfoil insert placed into the turbine blade, and the airfoil blade. Figure 15: Carbon dioxide supply system components.

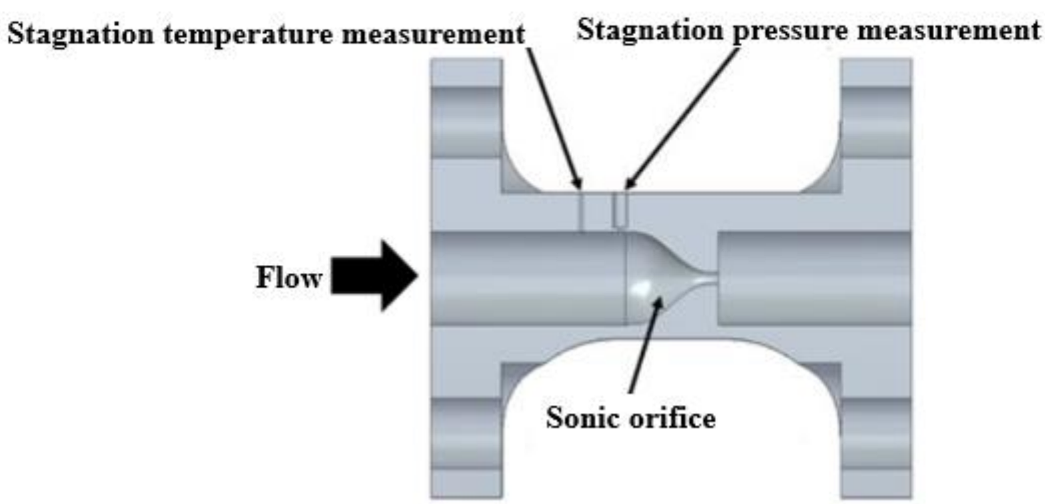

Figure 14: Sonic orifice mass flow measurement device cross-section.

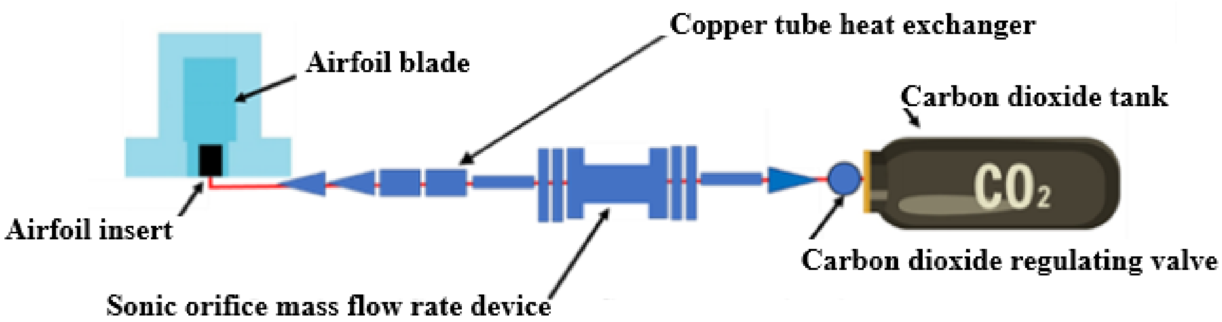

Figure 15: Carbon dioxide supply system components.

Materials and Manufacturing

Cascade blade components are comprised of Somos Watershed XC 11122 plastic, and are manufactured by Protolabs Inc. of Maple Plain, Minnesota, USA. This material is selected for cascade testing for several reasons. First, thermal conductivity is relatively low with a value of 0.18 W/mK. Second, associated components are manufactured without shrinkage or distortion, and with high dimensional accuracy and low manufacturing tolerances, which means that scaled geometric similarity relative to actual engine hardware is maintained. Third, the strength of the material allows it to employed for testing of airfoil components subject to large pressure differences, including intricate film cooling supply passages and complex film cooling hole array arrangements. One lesson learned during testing is that the Somos Watershed XC 11122 plastic generally fails from cycle fatigue after 30 to 35 wind tunnel blowdown runs. However, even with this limitation, the watershed material is the best blend of rigidity and flexibility for the present transonic experiment. To incorporate the complex geometry and internal features associated with the turbine blades, additive manufacturing, commonly referred to as three-dimensional printing, is employed. Note that the larger parts, such as the top or bottom wall, are too large for additive manufacturing. In addition, traditional subtractive manufacturing processes are faster and more economical for such components.

All **additively manufactured** parts are constructed with a process known as **StereoLithography Apparatus (SLA)**. Information on the process is provided in Figure 16. SLA printing provides a strong bond between plastic polymers, as well as excellent resolution with layer heights in the hundreds of microns. The printing process uses a vat of liquid resin. The bottom of the vat is a clear film. A build platform then lowers into the vat where a laser shines through the film to cure the resin. The parts that are manufactured with SLA printing are the turbine blades, side walls, circumferential bleeds, tailboard, and sonic orifice.

The remaining major components of the cascade utilize **subtractive manufacturing**. With this approach, **Computer Numerical Control (CNC) machining** is used to create the top wall and bottom wall. The top wall is comprised of a clear polycarbonate. The bottom wall is machined from an aluminum alloy. A typical CNC machining operation starts with a stock material. The stock is then clamped down in the CNC machine where a tool head removes and drills the stock as needed to provide a finished product. Associated machine operation is shown in Figure 17.

The thermal imaging window is made of zinc selenide. Within the present investigation, an existing zinc selenide window is reshaped using **Single Point Diamond Turning (SPDT)**. Figure 18 shows a machine used for this process. To turn the piece, the SPDT machine uses a vacuum chuck to hold onto the workpiece. The diamond tool head is then manipulated to reshape the material. In addition to the machining, special precautions are taken when machining zinc selenide. The chips produced by the material are toxic, which requires the use of Personal Protection Equipment (PPE).

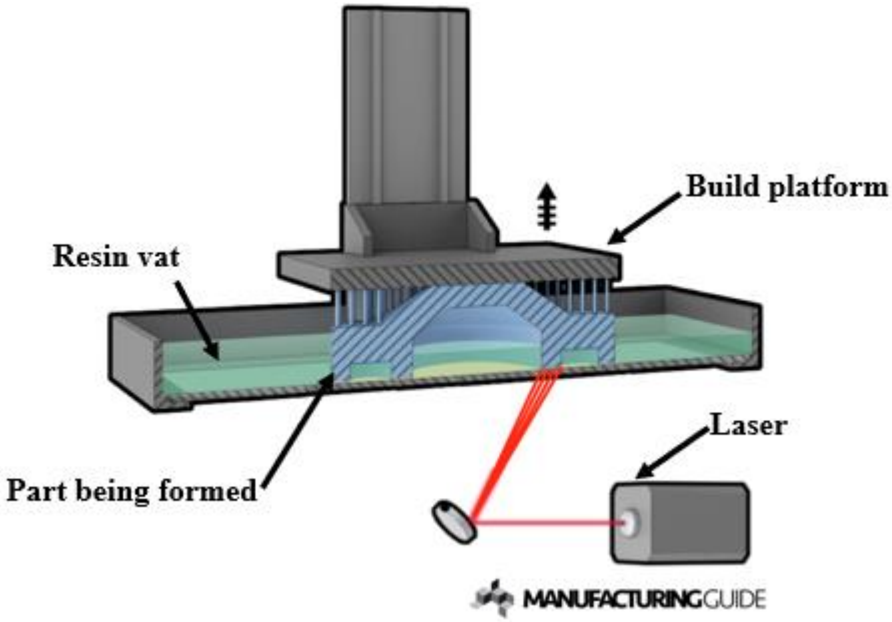

Figure 16: StereoLithography Apparatus (SLA) process [4].

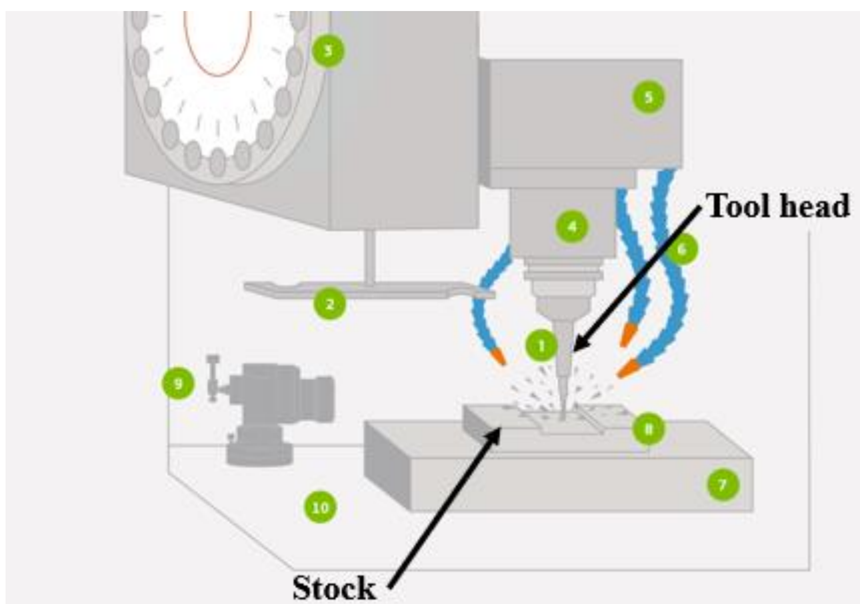

Figure 17: Computer Numerical Control (CNC) machine operation [2].

Summary and Conclusions

An example of results obtained with the present experimental arrangement is provided in Figure 19, which shows the Mach number distributions on the suction and pressure sides of a baseline turbine blade, as measured at fifty percent span. Also obtained are blade tip heat transfer data for a variety of different film cooling experimental conditions. The associated data are providing important benefits in regard to design and modelling of transonic squealer turbine blade tips with film cooling.

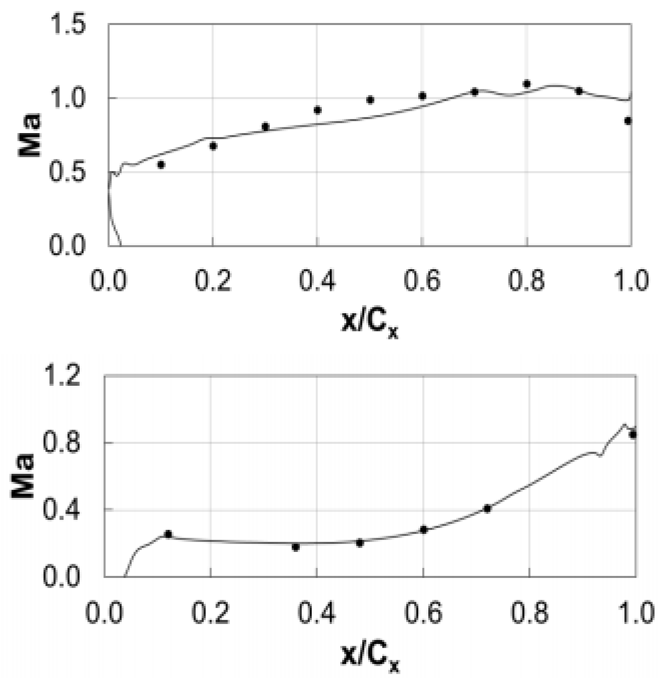

Figure 19: Mach number distributions on the suction and pressure sides of a baseline turbine blade, as measured at fifty percent span. Solid lines represent predicted data. Symbols represent experimentally measured data.

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[1] B. M. Barkachary, and S. N. Joshi. “Finite Element Simulation of Single Point Diamond Turning (SPDT) of Silicon.” *International Conference on PRECISION, MESO, MICRO AND NANO ENGINEERING* II (December 2013).

[2] “CNC Milling: Prototypes & Production Parts: Plastic & Metal.” Protolabs, n.d. http://www.protolabs.com/services/cnc-machining/cnc-milling/.

[3] M. Sampson, A. Fairbanks, J. Moseley, P. M. Ligrani, H. Xu, and M. Fox. “Linear Cascade and Wind Tunnel Development for Turbine Blade Tip Heat Transfer Investigations With and Without Film Cooling,” Paper Number GT2019-91074, ASME TURBO EXPO 2019: Turbomachinery Technical Conference and Exposition, Phoenix, Arizona, USA, June 17-21, 2019.

[4] “Stereolithography, SLA.” Find suppliers, processes & material, n.d. http://www.manufacturingguide.com/en/stereolithography-sla.

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Jake,
Thank you - the thesis is ready for submission to our Department Chair and he is copied onto this message.
Sincerely,
Phil

--
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