Project 056 Turbine Cooling through Additive Manufacturing

The Pennsylvania State University

Project Lead Investigator

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University Participants

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- PIs: Dr. Karen Thole, Distinguished Professor; Dr. Stephen Lynch, Associate Professor
- FAA Award Number: 13-C-AJFE-PSU-054
- Period of Performance: February 5, 2021 to February 4, 2022
- Tasks:
    1. Manufacture and test existing FAA Continuous Lower Energy, Emissions, and Noise (CLEEN) II blade designs
    2. Design new double-wall cooling technologies
    3. Manufacture and test new double-wall cooling designs for linear cascade
    4. Manufacture and test optimal double-wall cooling designs for the Steady Thermal Aero Research Turbine (START) Lab turbine

Project Funding Level

The FAA has provided $800,000 of funding to date. In-kind cost sharing of $1,500,000 has been provided to Penn State from Pratt & Whitney to cover the entire program.

Investigation Team

Name	Affiliation	Role	Tasks
Distinguished Professor Karen A. Thole	Penn State	PI	Management, reporting, and oversight of all technical tasks
Associate Professor Stephen Lynch	Penn State	Co-PI	Management, reporting, and oversight of Tasks 2 and 3
Assistant Research Professor Reid Berdanier	Penn State	Staff Scientist	Task 1 and 4
Associate Research Professor Michael Barringer	Penn State	Staff Scientist	Tasks 1 and 4
Scott Fishbone	Penn State	Project Manager	Tasks 1 and 4
Jeremiah Bunch	Penn State	Laboratory Technician	Tasks 1 and 4
Justin Wolff	Penn State	Graduate Student	Tasks 1–4

Project Overview

Gains in the cooling performance of cooled turbine airfoils directly impact the efficiency and durability (lifetime) of turbine engines, and therefore have undergone substantial development. Currently, many cooling designs for turbine airfoils use complex microchannels placed within the wall of the airfoil to extract heat, in a design known as double-wall cooling. However, the geometric complexities (and thus the effectiveness) of the microchannels are limited by the current design space available using conventional investment casting and core tooling methods to manufacture relatively small intricate internal cooling features. This project will investigate potential thermal performance and aerodynamic efficiency improvements made possible through exploring the expanded cooling design space opportunities provided by direct fabrication of complex cooling geometries using three-dimensional laser powder bed fusion (L-PBF), a common metal-based additive manufacturing (AM) method. L-PBF AM has begun to see many uses in the gas turbine industry, particularly because of the new design space enabled by this new fabrication method. However, the ability to manufacture high-efficiency, intricate, complex double-wall cooling airfoils design concepts is unknown. This research would generate some of the first thermal performance data at engine-relevant conditions, comparing traditional cast airfoils to advanced airfoils manufactured through L-PBF AM. Understanding the potential of new innovative geometric heat-transfer cooling design features coupled with unique airfoil cooling configurations should serve as an important guide for future investments in advanced manufacturing and cooling design technologies.

Task 1 - Manufacture and Test Existing FAA CLEEN II Blade Designs

The Pennsylvania State University

Objective

The objective of this task is to measure the as-manufactured shape of FAA CLEEN II turbine blade airfoils using X-ray computed tomography and to use that information to fabricate additively manufactured (AM) copies for direct comparison in the rotating turbine facility at Penn State. The outcomes of this effort will be to: (1) provide a direct back-to-back comparison of cast versus additively manufactured airfoils; (2) learn the unknown challenges in creating double-wall designs via AM and how to translate them to cast parts for commercialization; and (3) work through the design, fabrication, and testing of additive blades that will spin at engine-relevant conditions.

Research Approach

CT Measurement of FAA CLEEN II Blades

At the end of the prior annual reporting period, an extensive analysis of two types of CT scans had been conducted on six cast FAA CLEEN II blades to down-select one blade to replicate through AM. One set of CT scans was from a Pratt & Whitney vendor, and another set was conducted using on-campus facilities in the Penn State Center for Quantitative Imaging (CQI). From the CT analysis, surface deviations were compared between individual blades and between the as-manufactured blades, relative to the design intent. The analysis also considered the cooling performance of the cast airfoils, as measured through infrared imaging results from a prior test campaign, and coolant flow capacity testing results. At the start of this annual reporting period, the package was reviewed with Pratt & Whitney, and one blade was selected for replication in AM.

Mechanical Analysis, AM Design, and Manufacturing

Pratt & Whitney was engaged as a subcontractor in the Task 1 effort, to provide mechanical analysis, generation of manufacturing drawings for the additively manufactured airfoils, and assistance with securing an additive manufacturing vendor. Pratt & Whitney engineers performed structural analyses of the existing FAA CLEEN II airfoil under the conditions of the START turbine rig and determined that there were no operational concerns, even after accounting for the material properties of additively manufactured airfoils.

Pratt & Whitney engineers used the CT scan data to understand the as-manufactured dimensions of the internal features of the FAA CLEEN II airfoil relative to the design intent, then updated the blade model accordingly. The final design was reviewed by the team for suitability for additive manufacturing, and Pratt & Whitney developed drawings and material specifications.

Pratt & Whitney also assisted the team in engaging additive manufacturing vendors, and two of those vendors (Keselowski Advanced Manufacturing and Vertex Manufacturing) were initially selected for demonstration trials after non-disclosure agreements were established with Penn State and Pratt & Whitney. The trials included evaluation of the overall external shape, the dimensional accuracy of internal features, and the potential to directly print small-scale cooling holes. In general, external and internal features could be reasonably replicated by the current state of the art in AM, although the cooling hole features did not print as expected. According to the demonstration trials, Vertex Manufacturing was selected for fabrication of the AM airfoils. The manufacturing (including machining) is expected to be completed in early Q1 2022, at which point testing in the rotating turbine facility (START turbine) will commence.

Task 2 - Design New Double-Wall Cooling Technologies

The Pennsylvania State University

Objective

The objective of this task is to develop novel double-wall cooling designs that feature microchannel concepts that are being explored in the literature and could potentially be achieved via AM. The designs will be generated according to advice from Pratt & Whitney, so that the concepts can be translated to the FAA CLEEN II airfoil later in this project and leveraged for commercialization. The designs will be packaged into cascade test articles that will be measured in the high-speed linear cascade at Penn State by using infrared thermography in Year 2 of the project. The best designs will be identified for reintegration into the FAA CLEEN II airfoil shape and run in the START turbine to confirm operational benefit.

Research Approach

Design of Linear Cascade Test Articles and Infrastructure

For common testing of novel internal microchannel cooling features, the 75% span cross-section of the FAA CLEEN II airfoil was implemented into the cascade hardware design to produce a linear pattern of seven two-dimensional (2D) airfoils similar to the example shown in Figure 1. Static pressure taps were incorporated into the cascade hardware to enable validation of the flowfield before testing of new cooling technologies. The pressure taps were strategically placed within the cascade hardware design by using computational fluid dynamics (CFD) to locate the taps at important points on the airfoil. Figure 2 shows an example of a typical airfoil static pressure plot used to select static pressure tap locations with respect to the axial chord.

Figure 1. Example vane linear cascade with pressure tap design (the actual airfoils for this project are proprietary and therefore not shown).

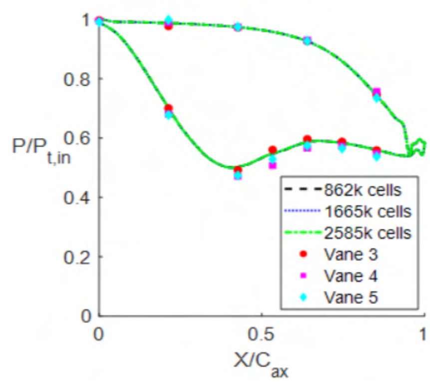

Figure 2. Example vane pressure loading plot, with points representing locations where pressures are measured.

Three removable center test airfoils were incorporated into the cascade hardware design to enable rapid changeout of novel cooling designs. In addition, the data reduction technique of the cascade requires an infrared camera calibration airfoil set, which has both spatial calibration markers that can be used to transform the IR image, as well as variable internal temperature that can be used to develop a camera-observed temperature-to-true temperature mapping. This calibration airfoil, as well as a generic microchannel cooling airfoil with appropriate coolant feeds, were designed with instrumentation enabled by AM fabrication. Figure 3 shows a schematic of the coolant routing from the base of the test airfoil insert, with flowpaths leading to the microchannels in the airfoil body and instrumentation locations at the inlets and outlets of the microchannels.

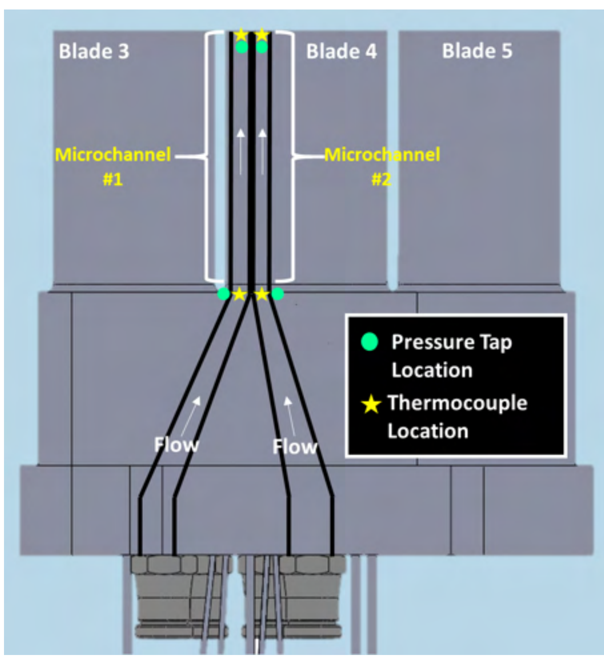

Figure 3. Design of cooling flowpath and instrumentation for microchannels in linear cascade hardware.

Several novel microchannel cooling geometries were developed for study according to concepts reported in the literature, some of which have previously been demonstrated by using AM. Figure 4 shows some of the designs, grouped by type. Pin fin designs include a standard circular pin (manufactured in AM by Kirsch & Thole [2017]), as well as a triangular pin design tested by Ferster et al. (2018). These designs are expected to have high pressure loss but also high cooling effectiveness. The second grouping is for ribs (turbulators), which do not span the entire channel but act to locally trip the flow. The discrete W shape by Wright et al. (2004) is a conventional design, but the wavy S-shaped ribs by King & Pietraszkiewicz (2018) are based on a patent and may have a similar effect to that of the wavy channels studied by Kirsch & Thole (2017).

The channel-only configurations include the baseline empty microchannel, which replicates the existing FAA CLEEN II design, as well as a wavy microchannel based on the findings of Kirsch & Thole (2017). All these designs have been packaged into the cooled airfoil shape and sent to vendors for build evaluation and quoting. We expect that the hardware will be fabricated by the end of Q4 2021 or early in Q1 2022.

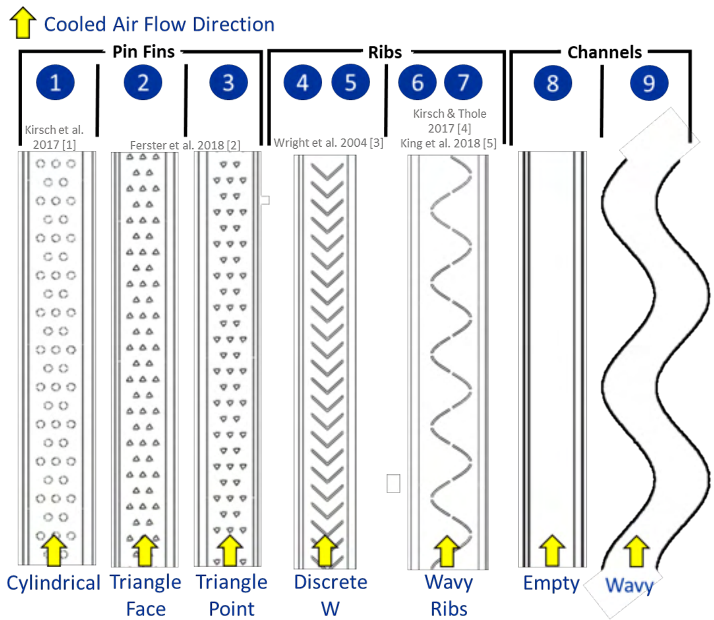

Figure 4. Examples of novel cooling concepts packaged into a microchannel.

In addition to the cooled airfoil designs, the linear cascade cooling facilities have been upgraded to account for an increased number of cooling circuits and the necessary flow control. Figure 5 shows a schematic of the cooling circuits being constructed to allow for independent control of the coolant flow to four microchannels in the test airfoils. Of note, because the cascade inlet air temperature is only 100 °C, the cooling air is cooled with liquid nitrogen to temperatures below freezing, to maintain the coolant-to-mainstream temperature ratios relevant to engine conditions.

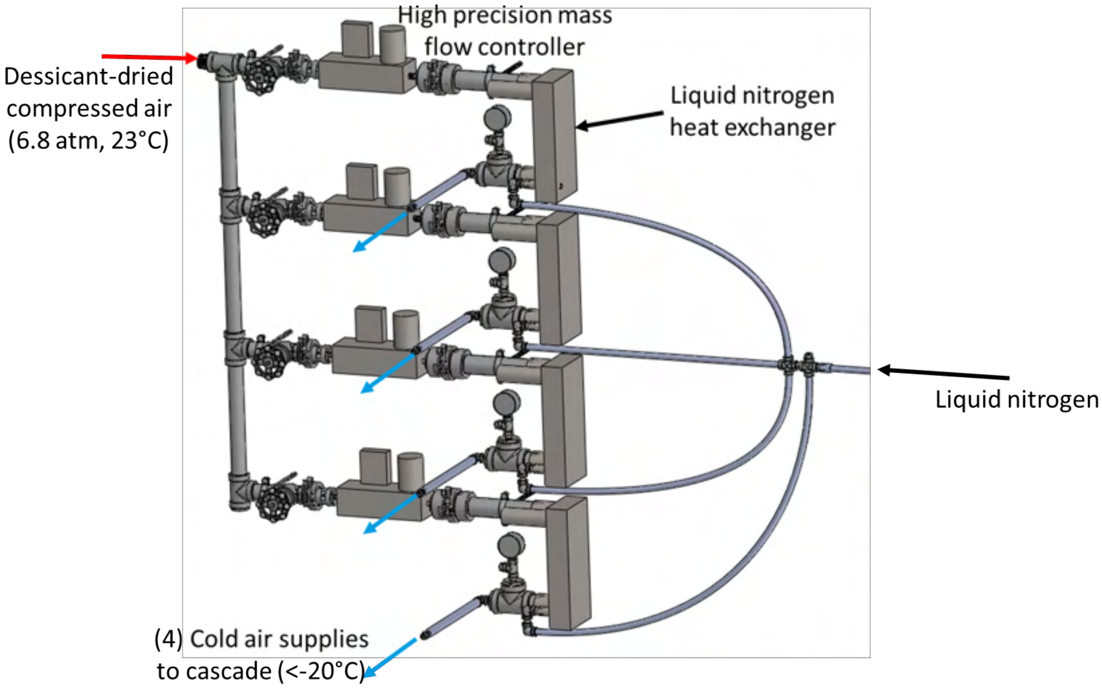

Figure 5. Upgraded cooling supply system for cascade including high-precision mass flow controllers and liquid-nitrogen-cooled cooling air.

Fabrication of Linear Cascade Hardware and Validation of the Flowfield

The FAA CLEEN II 2D airfoil pressure tap design was fabricated by Keselowski Advanced Manufacturing with L-PBF. The vendor also applied a heat treatment for stress relief and a bead-blast finish. After its receipt, the hardware was generally evaluated. The pressure tap holes were produced to satisfaction, and the required dimensions for installation into the linear cascade were met. However, some post-processing on the pressure tap holes was necessary to properly fit the pressure taps; the pressure tap holes were slightly undersized because of printing tolerance.

The flowfield of the FAA CLEEN II 2D airfoil for the linear cascade studies has also been validated. The validation was performed by comparing the pressures from computational fluid dynamics (CFD) predictions of the airfoil and the measured surface pressures from the linear cascade hardware. Figures 7–9 show the percentage difference, as in Equation (1), between the CFD and cascade pressure data at selected locations around the three center airfoils (airfoils 3, 4, and 5 of seven in total). Figure 6 provides a generic example of airfoil geometry with corresponding pressure tap locations, such as pressure side 1 (PS1) and suction side 4 (SS4). The airfoil's static pressure data were collected at three exit Mach number conditions corresponding to low, normal, and high operating conditions for turbines; Figures 7–9 correspond to an exit Mach number under normal operating conditions. Each Mach number condition was tested at two separate Reynolds numbers. The figures indicate that the percentage difference between the expected pressure and measured pressure was within approximately 3%, well within the expected variation.

$$\%\ difference = \left|\frac{P_{Cascade} - P_{CFD}}{P_{CFD}}\right| \times 100\% \quad (1)$$

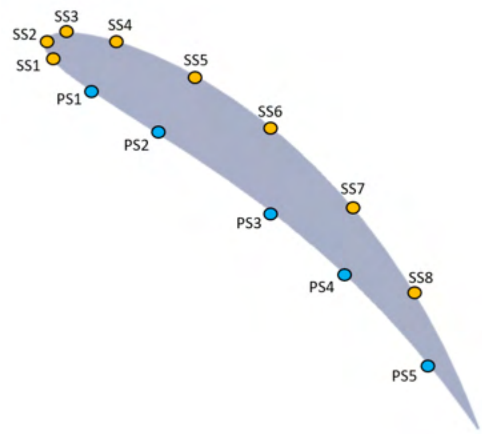

Figure 6. Generic airfoil geometry with example static tap locations.

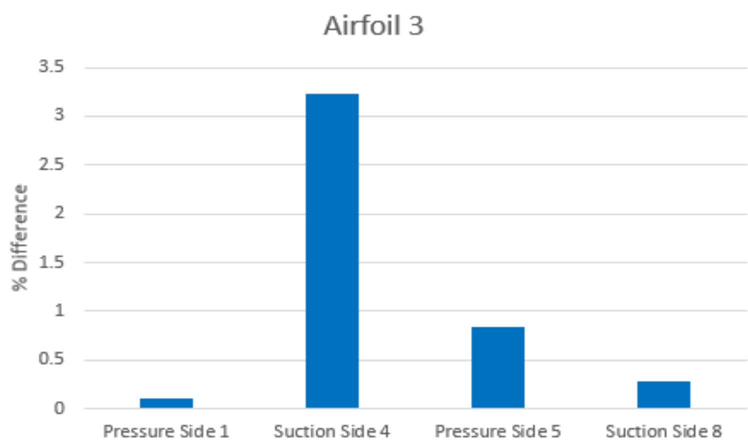

Figure 7. Percentage difference between airfoil 3 CFD and linear cascade pressure data.

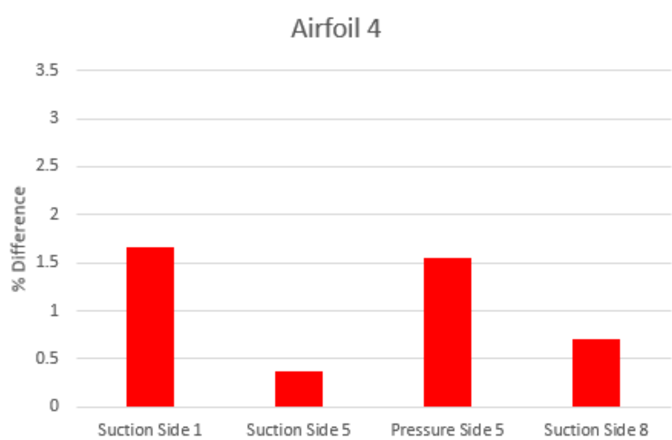

Figure 8. Percentage difference between airfoil 4 CFD and linear cascade pressure data.

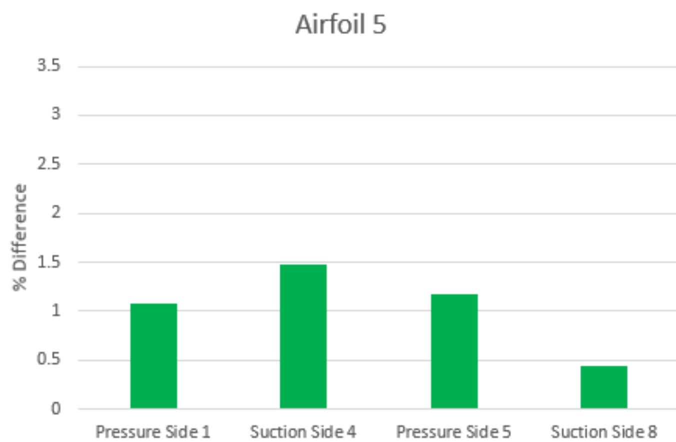

Figure 9. Percentage difference between airfoil 5 CFD and linear cascade pressure data.

With the flowfield benchmarked, we expect to begin testing cooled designs in Q1 2022 immediately after fabrication by the vendors is completed. In addition, we will use the same CT technology as that in Task 1 to evaluate the manufacturing accuracy of the microchannel features.

References

Ferster, K. K., Kirsch, K. L., & Thole, K. A. (2018). Effects of geometry, spacing, and number of pin fins in additively manufactured microchannel pin fin arrays. Journal of Turbomachinery, *140*(1). https://doi.org/10.1115/1.4038179

King, C., & Pietraszkiewicz, E. F. (2018). S-shaped trip strips in internally cooled components.

Kirsch, K. L., & Thole, K. A. (2017). Pressure loss and heat transfer performance for additively and conventionally manufactured pin fin arrays. International Journal of Heat Mass Transfer, *108*, 2502–2513.

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Wright, L. M., Fu, W. L., & Han, J. C. (2004). Thermal performance of angled, v-shaped, and w-shaped rib turbulators in rotating rectangular cooling channels (AR=4:1). Journal of Turbomachinery, *126*(4), 604–614.

Milestones

Milestone	Due Date	Estimated Date of Completion	Actual Completion Date	Status
Workplan	3/4/20	3/4/20	3/5/20	Completed
COE Meeting 1	4/1/20	4/1/20		Cancelled
COE Meeting 2	10/1/20	10/1/20	10/28–10/29/20	Completed
COE Meeting 3	10/26/21	10/26/21	10/26-10/28/21	Completed
Annual Report	12/17/21	11/22/21	11/22/21	Completed
Project Closeout	2/4/22	2/4/22		

Major Accomplishments

The major activities are as follows: (1) completion of the design of an AM version of an FAA CLEEN II airfoil; (2) fabrication of trial airfoils from two AM vendors, and down-selecting of the final vendor; (3) design, fabrication, and initial testing of linear cascade hardware. Activities 1and 2 lead directly to the completion of Task 1 in Q1 2022, and Activity 3 positions us to be able to select the top performing microchannel cooling designs in Q1–Q2 2022 for incorporation into the CLEEN II airfoil by the end of the project.

Publications
None

Outreach Efforts
Research findings were presented to Pratt & Whitney (cost-sharing partner) at bi-annual Center of Excellence review meetings on November 30, 2020 and August 19, 2021.

Awards
None

Student Involvement
Justin Wolff (currently nearing the end of his 2-year master's degree) has been responsible for analyzing CT scan data of the FAA CLEEN II blades; compiling a review package, which he presented to Pratt & Whitney; researching and designing novel cooling strategies into the linear cascade hardware; and testing linear cascade hardware to confirm the expected flowfield. Justin's role has covered all aspects of reverse engineering, AM design, fabrication, and testing.

Plans for Next Period
Fabrication of the AM version of the FAA CLEEN II airfoil will be completed in Q1 2022 and will subsequently be tested in the START turbine by using the recently developed IR thermography capability. The results will be compared with the original FAA CLEEN II cast airfoils to provide the first back-to-back comparison of cast versus AM.

The novel microchannel designs have been completed and will be fabricated in Q4 2021 through Q1 2022. They will be tested in the linear cascade in Q1 2022, and the best designs will be evaluated for incorporation into the next version of the AM FAA CLEEN II airfoil for testing in the final year of the project.