Experimental and Computational Turbine Cooling Analyses

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2015 Southwest Research Institute

University Turbine Systems Research Program

1. Introduction

As gas turbine manufacturers are becoming more competitive and proficient in turbine design, maximum thermal efficiency and power output are target goals. Raising the firing temperature directly increases the output power of the turbine, but introduces a need for turbine component cooling. As modern gas turbines operate with TIT's (Turbine Inlet Temperatures) hundreds of degrees hotter than the melting point of the materials used in blades and nozzles, turbine component cooling is necessary, and is becoming a hot topic of innovation and study.

Turbine components (namely blades and vanes) are cooled using highly compressed air routed around the combustor from the compressor exit. This air, though heated in the compression process, is cool relative to the melting point of these metal components. Routing air around the combustor reduces the efficiency of the engine so it is imperative to minimize the amount of coolant used performing the necessary component cooling. Since the turbine expands and cools the hot flow while extracting work, the 1st stage turbine nozzles (stators) and blades (rotors) require the most cooling.

Turbine blades can be cooled both internally and externally. Both internal and external cooling systems rely on complex geometries and cooling passages to maximize the cooling potential of the coolant air. Modern cooling system innovations typically require computational and experimental studies before being validated. In my work at Solar Turbines I participated in experimental testing of external film cooling and computational studies of internal cooling geometries.

Some of the tests outlined in this report are proprietary, so limited information is provided.

2. Experimental Approach to External Cooling

The 1st stage turbine nozzle and rotor are engulfed in hot gas flow at TIT conditions. The turbine airfoils experience significant convective heat transfer from the hot gas flow. The goal of external cooling is to create a “film” of coolant around turbine hot section components, interfering with the heat transfer between hot gas and metal. This film of coolant is applied at strategic locations through film cooling holes. The location, orientation, and shape of film cooling holes are all designed so that the largest area of the airfoil can be cooled with a minimal amount of coolant.

PSP

At Solar Turbines new external cooling designs are tested in a scaled turbine cascade (shown in Figure 1) using pressure-sensitive paint (PSP) to measure film effectiveness. The PSP method of studying cooling was developed at Solar Turbines as a way of measuring film coverage without the influence of heat transfer coefficients.

Pressure sensitive paint emits light at an intensity related to the partial pressure of oxygen on the paint. The lower the partial pressure of oxygen, the more light is emitted. By analyzing the adiabatic wall condition in heat and mass transfer, an analogy is created between adiabatic wall temperature and oxygen concentration at the cooled wall. This analogy enables information from the pressure sensitive paint to be translated into a useful film cooling effectiveness coefficient.

$$(1) \qquad \eta = adiabatic\ film\ effectiveness\ (heat\ transfer) = \frac{T_{mix} - T_\infty}{T_{coolant} - T_\infty}$$

$$(2) \qquad \eta = adiabatic\ film\ effectiveness\ (mass\ transfer) = \frac{C_{mix} - C_\infty}{C_{coolant} - C_\infty}$$

Equations 1 and 2 can be compared effectively with the assumption that the Lewis number is ~ 1. The adiabatic efficiency of the test section can be calculated using the mass transfer analogy and the relationship between the image intensity and oxygen concentration (PSP intensity to oxygen partial pressure to oxygen concentration).

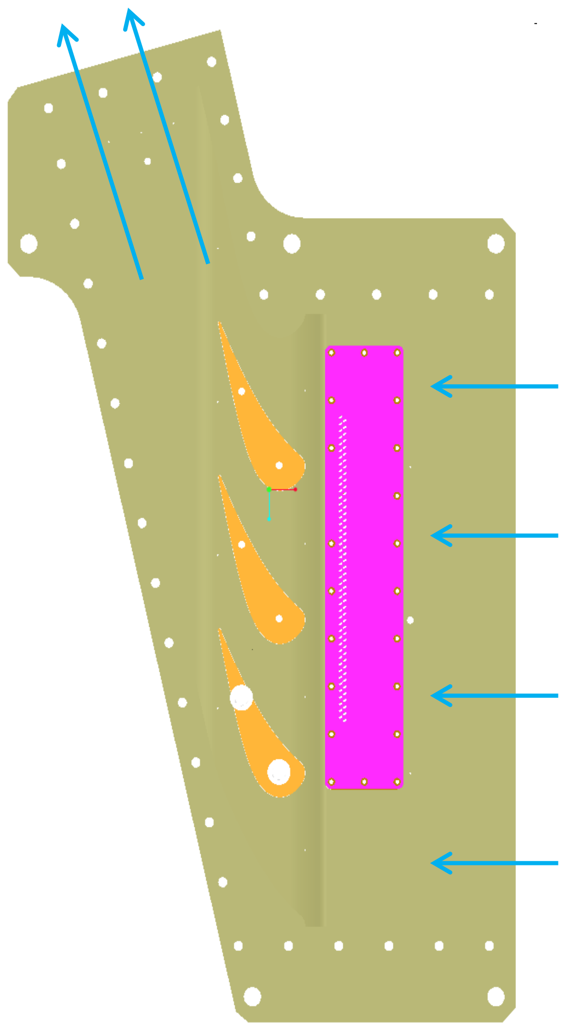

Figure 1: Diagram of the test section area in the scaled cascade. Freestream flow entered from the right side of the picture, and coolant air entered from the film holes.

Experimental Setup

A diagram of the scaled cascade test section is shown in Figure 1. The freestream temperature was controlled using a mist-cooling system, and the coolant plenum was heated to match the freestream air to within 1 degree Fahrenheit.

The test section is painted with pressure sensitive paint, a LED light source is directed at the test section, and a camera filtered to only receive wavelengths emitted from the paint is used to capture images of the test section. Instead of cooled air, air or N2 at the mainstream flow temperature was flowed through a plenum to the test cooling holes as the “coolant”. Since there is no oxygen in the N2 flow, PSP surfaces in contact with this flow would appear more intensely in images and the coolant flow path can be studied. By comparing images at different test conditions with a reference image (with no cooling) and a dark image (with no light, to subtract background intensity from all images), the test section’s film cooling effectiveness can be determined at each test condition. The raw images are shown below in Figure 2.

Figure 2: Raw images from platform cooling tests. In order, the images are of the test section with air blowing, N2 blowing (notice the holes are white), nothing blowing (reference image), and nothing blowing with no light (dark image).

Tests were performed on nozzle endwall inlet film cooling hole geometries. The different geometries varied in hole diameter, hole spatial density, and injection angle. The images were processed with MATLAB and a user-written program, and a single “image” of spatial cooling coefficients was created for each test condition. Multiple test conditions were compared to understand the effect of flow condition on the cooling effectiveness, along with the cooling geometry.

3. Computational Approach to Internal Cooling

While the external cooling holes create a film of coolant over the platforms and blades, there is a complicated geometry on the interior of each blade that cools the blade from the inside. Networks of passages, pin fins, and impinging flows all work together to reduce the temperature of the blades. After traveling through the internal passages the cooling air is expelled through slots on the trailing edge of the airfoil.

Sometimes the cooling geometries are tested statically, without the influence of high rpm rotation. However, these tests do not incorporate rotational effects such as the Coriolis Effect, which can impact coolant flow paths and leave some areas inadequately cooled. To study the Coriolis Effect, Solar Turbines created a larger rotating cooling passage. By monitoring the pressure and temperature in different parts of the internal passages, differences between the static and rotating coolant flows can be analyzed.

Computational Model

The pressure and temperature sensors in the Coriolis rig can only provide information at specific locations, and a more encompassing view of the internal fluid flows was desired. CFD simulations of the corresponding blade had been created for engine test conditions, but were not matching the experimental data from the rig. This was possibly attributed to the Coriolis rig not running at engine test conditions and the larger scale of the passages in the test rig. To compare the computational and experimental results, a CFD simulation of the Coriolis rig (with proper scaling and correct test rig conditions) needed to be created.

After editing the CAD models of the internal fluid geometry, it was uploaded into Star CCM+. The inlet-exit pressure ratio was provided from the rig testing as the governing flow parameter, so stagnation pressure inlet and static pressure outlet boundary conditions were desired. These conditions would be applied to match the CFD simulation pressure ratio to the rig test in the hopes of providing comparable data.

Once the boundary conditions were applied and the flow physics models were edited, three different meshes with different mesh base sizes were run. As the mesh base size decreases, the number of cells in the mesh increases, increasing solution accuracy and necessary processing capabilities. The solutions from the three meshes were compared in a mesh density study. A mesh size was chosen based on the accuracy of the solution and the time required to run simulations with the mesh.

Multiple different flow cases were simulated with the passage geometry to study coolant flow losses around a particular flow split. Pressure ratios between cases were matched to .3%, so the different cases could be compared with accuracy. The simulations matched the test in terms of pressure ratio, mass flow, and flow split losses, validating the rig test data. The flow was analyzed with streamline animations and data report plots.

4. Conclusion

The external film cooling tests provided data for current and future first stage nozzle cooling configurations. The data will be used to determine the most efficient use of coolant, and the effects different inlet film cooling hole geometries have on downstream coolant flow coverage.

The internal cooling simulations validated test data by matching target parameters, and offered more information about flow path changes under blade rotation. Further rig tests will be performed to study different consequences of rotation, and internal geometry updates may be performed to better control coolant flow under rotation.

During my internship at Solar Turbines I saw a wide variety of experimental techniques and became experienced with computational fluid dynamics simulations. I also gained experience with both internal and external cooling concepts. With these different outlooks, I now have a comprehensive perspective of 1st stage turbine airfoil cooling.

References

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