A NEW ROTATING FACILITY FOR INVESTIGATING COOLING PASSAGE INTERNAL HEAT TRANSFER

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ABSTRACT

Hundreds of studies have been performed investigating the heat transfer for turbine blade internal cooling passage geometries utilizing a range of different experimental techniques and configurations. A corresponding number of computational studies have shown that while advanced modelling techniques can capture many important features of the experimental data, there is still a critical need for detailed measurements obtained at engine representative conditions.

The subset of heat transfer experiments performed at high rotation speeds is significantly smaller due to safety, cost, and complexity considerations. This paper will describe the development of a new facility designed to measure the internal heat transfer rate for a large-scale test section operating at speeds up to 3,000 RPM. The facility was originally designed to obtain measurements using the constant wall temperature method of heating individual copper panels, but it has since been modified to also be able to utilize the transient liquid crystal approach for heat transfer experiments.

The facility is able to investigate a wide range of Reynolds numbers up to and possibly exceeding 75,000 and corresponding rotation numbers of 0.3 for Re = 75,000. These experiments utilize GoPro action cameras mounted on the rotating hardware to achieve stable images at high rotation speed as well as miniature butt-welded thermocouples to measure the fluid temperature and embedded RTDs to provide reference values and sidewall data. The signals from these rotating instruments can be passed out through a 200-channel slip ring or recorded by an onboard digital to analog converter controlled by a microprocessor. The thermocouples are equipped with miniature amplifiers mounted on the rotating hardware in order to increase the signal by a factor of 100 prior to going to the slip ring.

Although this paper will not present significant new data, it will explain this new facility in detail and lay the groundwork for the reporting of many subsequent studies.

INTRODUCTION

The fundamental goal of internal cooling studies is to maximize the heat transfer from the hot outer skin of the airfoil to the cooling air flowing through the inside of the blade. Because the coolant supply pressure is set by the compressor bleed and the airfoil discharge pressure is set by the turbine aerodynamics, there is only a small margin between the blade external and pressure drives to drive cooling flow. It is therefore important to minimize pressure losses through the cooling passages while maximizing the heat transfer rate.

As a result, there has been a significant amount of research interest in obtaining detailed heat transfer and pressure drop measurements that replicate the important flow physics of an operating engine but provide a way to evaluate different designs under laboratory conditions. These experiments commonly match the rotation number (Eq. 1), Reynolds number (Eq. 2), and buoyancy parameter of the engine (Eq. 3).

\[ RO = \frac{\Omega D_h}{u} \]  \hspace{1cm} (1)

\[ Re = \frac{\rho D_h}{\mu} \]  \hspace{1cm} (2)

\[ DR \equiv \frac{T_{w} - T_f}{T_w} \]  \hspace{1cm} (3)

More recent studies have also addressed the impact of temperature change due to pumping that occurs as the fluid flows radially inward or outward in a rotating passage [1].

The earliest benchmark data sets utilized a steady-state energy balance technique to determine the heat transfer rate for conductive wall panels maintained at a constant temperature. This method utilizes a series of isolated conductive copper panels backed by heaters. Each heater is controlled to maintain the copper panels at a constant temperature, and the change in power required to maintain this temperature after the start of the cooling air is determined to be the heat transfer from the panel due to
steady vonWolfersdorf and Jones the liquid crystal technique have been provided by summarized by solved to determine the surface heat transfer. An infinite wall model (or related conduction model) can be response to a step change in fluid temperature the time response method relies upon the liquid crystals to measure measured surface temperature, measured fluid temperature, heat transfer coefficient can be determined based on the use of constant heat transients experiment. The steady heat transfer information for either a steady temperature distribution, which can then be used to derive thermochromic liquid crystals to measure the surface this method or variations on it to measure heat transfer for a variety of passage shapes and turbulator designs.

Another important technique is the use of thermo-chromic liquid crystals to measure the surface temperature distribution, which can then be used to derive heat transfer information for either a steady-state or a transient experiment. The steady-state method involves the use of constant heat-flux wall heaters so that the convective heat transfer coefficient can be determined based on the measured surface temperature, measured fluid temperature, and imposed heat flux. This method was employed by Abuaf and Kercher to study heat transfer distributions in realistic blade geometries but without rotation [10] and by Taslim et al. to perform early rotating studies [11]. The transient response method relies upon the liquid crystals to measure the time-accurate temperature change of the surface in response to a step change in fluid temperature so that a semi-infinite wall model (or related conduction model) can be solved to determine the surface heat transfer. Many of the early development efforts and applications of this method are summarized by Ireland et al. [12], and thorough reviews of the liquid crystal technique have been provided by Ireland and Jones [13], Ekkad and Han [14], and Poser and vonWolffersdorf [15].

There are many other methods for determining heat transfer that have been applied through the years including steady-state infrared measurements with heated walls [16], transient heating with external infrared temperature measurement [17, 18], and various mass transfer configurations [19, 20]. One issue with these different techniques that remains to be fully addressed is determining how to handle changes in wall temperature boundary conditions, which effects how the buoyancy parameter changes through the test section. It is important to understand how this change in buoyancy can impact measurement results as well as how these results can best be scaled to engine condition.

Despite the large number of studies focused on internal heat transfer, there remains a small number of facilities around the world capable of making these measurements in a rotating environment. There is an even smaller number of facilities that are able to achieve the high rotational speeds needed to match the engine order rotation numbers for some cooling designs. The new facility described in this paper is designed to achieve these high rotation speeds in a safe environment and with a flexible test section attachment that enables easy changeover from one cooling geometry to the next. It builds from recent experiments performed with heater copper panels [21] and is designed so that experiments can be performed with heated panels or the transient liquid crystal method. This paper will describe the fundamental characteristics of this facility to lay the groundwork for the future reporting of detailed data.

**MECHANICAL DESIGN**

The rotating facility is constructed to accommodate a generic blade internal geometry scaled up by a factor of 5-10 from engine hardware. Current test articles have focused on replicating simplified three passage geometries from the NASA HOST experiments with different cross-section aspect ratios. However, the test section support box is designed for flexibility so that other geometries can be easily inserted. It is also possible to adjust the hub-to-tip radius ratio if desired.

The test section is mounted into a high-strength aluminum box, which is in turn mounted to a rotating union piece, as shown by the CAD model in Figure 1 and the photograph in Figure 2. This hub piece acts as a mechanical support for the test section and counterweight, a manifold for the air supply and return, and a connection to the centerline shaft. The shaft is supported on each end by a set of high-stiffness bearings, and it is driven by an air motor. It has a hollow center so that instrumentation wires can be routed through the shaft and out to a slip ring located on the top end of the shaft.

**Figure 1: Schematic of rotating facility**

![Figure 1: Schematic of rotating facility](image1.png)

**Figure 2: 1x1 test section installed in underground spin pit**

![Figure 2: 1x1 test section installed in underground spin pit](image2.png)
Air is supplied through a stationary manifold, and Stein Seals are used to prevent leakage from the supply side to the surroundings or to the return side of the circuit. From this stationary manifold, air enters channels in the rotating union and is supplied to the rotating union and then to the test section. The air entering the stationary manifold is typically chilled to about 220 K by upstream heat exchangers, but heat pickup though these distribution manifolds can be a problem. In order to achieve low test section inlet temperatures, the stationary manifold and rotating union must also be chilled by circulating heat transfer fluid for several hours prior to the start of the experiment.

The cameras for recording the color change of the liquid crystals are actually mounted onboard the rotating assembly. They will be described in more detail later in the paper, but it should be noted here that one camera is mounted on each side of the test section to capture simultaneous images of the turbulated surfaces of the passage.

The turbulated surfaces of the acrylic test section are shown in Figure 3. The turbulators are machined into the “roadbed” of the internal passage using a 4-axis CNC mill, and they fit tightly with additional acrylic pieces that form the sidewalls. Black aluminum clamping pieces provide additional support to the test section and enable it to be pressurized up to 60 psi above the surrounding pressure.

For safety, this entire assembly is located underground in a spin pit containment tank. This tank is pumped down to a vacuum while the experiment is underway in order to eliminate windage losses and heating. Figure 4 shows the above ground support infrastructure for this facility including the housing for the air motor that drives the rotating shaft, the slip ring on the end of the shaft, and the oil system for the bearings. The picture also shows pass throughs to the tank where the vacuum line and test gas supply and return lines are connected.

OPERATING RANGE

This facility is designed for a high rotational speed. The core hardware pieces are rated for speeds as high as 3000 RPM, and the current configuration is designed to operate at a speed of 1800 RPM. Recent experiments performed for a Reynolds Number of 25,000 with the 1:1 aspect ratio have explored speeds as high as 1200 RPM, and there was no limit to accelerating to higher speeds. These conditions correspond to a Rotation number of 0.24. Experiments currently underway will continue to explore the upper limits of this operating range to achieve higher Rotation numbers for the Re=25,000 case and similar rotation numbers for higher Reynolds number cases. Figure 5 shows the designed operating range of this facility for the current experimental program that is underway as well as points that indicate where data is currently available.
INSTRUMENTATION

even though the primary method for determining heat transfer in this experiment relies on the color change of the thermochromic liquid crystals, there is still a significant amount of traditional instrumentation including miniature butt-welded thermocouples for measuring the fluid temperature, embedded RTDs for roughly determining the sidewall heat transfer, flush-mounted RTDs exposed to the fluid flow for in-situ liquid crystal calibration, and both differential and absolute pressure transducers. Several different installation types are shown in Figure 6.

Figure 6: Detailed pictures of installed instrumentation

There are seven thermocouples installed to measure the fluid temperature at the inlet and outlet of each of the three passages as well as at the outlet of the third turn. The thermocouples are constructed from wire that is 25 microns (0.001 inches) in diameter, and the two dissimilar metals are joined together in a welding process that does not create a bead. This means that the thermocouples respond very quickly to fluid temperature; previous experiments with these thermocouples have observed frequency responses on the order of 2000 Hz. Unfortunately, schedule constraints dictated that existing thermocouple probes be used, so the back of these probes protrude from the outside of the acrylic test section, as shown in Figure 3. This partially obstructs the camera’s view of the test surface and has been rectified by the use of custom-built probes in later versions of this experiment.

In addition, there are 6 RTDs installed in each turbulated wall of the test section (total of 12) so that there are two measurements of the surface temperature in each passage. These RTDs are exposed to the air surface and are primarily used after the run is completed to measure the air temperature near to the surface and provide a method of obtaining an in-situ calibration. There are an additional 12 RTDs embedded in the sidewalls to measure local temperature there during the experiment and provide a rough method of determining the heat transfer rate to those walls.

Lastly, there are flush-mounted absolute Kulite pressure transducers installed at the inlet and exit of the test section. In most cases the Mach number in the test section is so low that these static pressure measurements are very close to the total pressure, but the total pressure can also be derived based on the mass flow through the test section. There are also differential pressure taps that measure the pressure drop through the first passage and across the full three-passages of the test section. The tubing used for these measurements is highlighted in red in Figure 3b.

IMAGING SYSTEM

There are two basic methods for capturing images in the rotating frame. The most common method is to utilize a stationary camera triggered by a once per revolution TTL pulse to capture an image of the test section every time that it passes the camera. This system, combined with a stroboscopic flash can provide high-resolution images of the moving object. However, the movement of the test section can cause motion blur, which must be corrected in post-processing, and any variations in the triggering system will cause the image to “jitter” or move back and forth by a few pixels in each frame.

One way to avoid these challenges is to mount the cameras in the rotating frame. This method has traditionally proven challenging due to the obvious complexities of safely spinning an expensive camera and controlling it remotely. Surprisingly, consumer electronics have provided a viable option for capturing high-definition video in this challenging environment. Lamont et al. first showed that digital “action cameras could be used to capture TLC measurements in the rotating frame.

In the same vein, the current study utilizes two GoPro Hero4 Black cameras mounted on the rotating test section. One camera is mounted on each side of the test section to capture the color change occurring on the two turbulated surfaces. In addition, there are three possible camera mounting locations on each side of the test section to enable the camera to cover the center of the passages and to get more detailed views of the tip and root turns. At this time, only one camera per side has been used and repeat runs have been performed to capture images from every perspective.

The GoPro cameras offer several important advancements over previous embedded camera systems in both imaging and control capabilities. The Hero4 Black models used in this experiment capture video at a resolution of 1920 x 1080 and up to 120 frames per second or at a resolution of 3840 x 2160 and 30 frames per second. Because the camera is moving with the test section, these high frame rates mean that the measurement frequency response will only be limited by the color change of the liquid crystals and not by other factors like the rate of rotation of the test section.

Another important feature of the GoPro cameras is that they can be controlled wirelessly over a standard Wi-Fi network. This means that by placing networking antennas inside the spin-pit facility, it is possible to turn on the cameras, stream live video, start video recording, download the results, and change any camera setting from a computer located in the control room. Rotating testing showed that it was possible to stream live video from a GoPro mounted at a radius of 610 mm (24 inches) at 350 RPM (a linear speed of 22 m/s or 73 ft/s) before enough data loss occurred to interrupt the video. Above this speed, it was not possible to deliver the high data rate required to obtain smooth video, but it was still possible to control every other aspect of the camera. In fact, wireless control has not been lost in testing up to 1200 RPM.
**Image Stability**

One initial concern with these cameras is that the lenses would distort due to centrifugal forces at higher speed. However, they have proven to be surprisingly robust, and no speed related artefacts have been observed. Figure 7 provides a comparison of images obtained by a GoPro camera when the rig is stationary and when it is rotating at 1200 RPM. The base image and coloration is taken from a stationary run, and the bright white edge lines have been extracted from a rotating run using image processing software.

Figure 7: Overlay of stationary image (color) and rotating image (white outline)

Even though the camera is subjected to 800 g of acceleration in the overlay image, it is clear that the white edge lines are perfectly aligned with the air channel boundaries and every bolt location. This shows that no optical distortion is taking place.

**Image Processing**

Figure 7 also illustrates one of the challenges of the onboard camera system. It is not feasible to utilize a long standoff distance between the camera and the test section because the rotating forces and size requirements would be quite large. Instead, the cameras are mounted approximately 150 mm (6 inches) from the face of the test article, and a wide-angle lens is used to capture the entire article of interest. This results in the “fisheye” effect observed in Figure 7. Fortunately, the distortion caused by the wide-angle lens is repeatable and well characterized, so it is possible to correct for this distortion using tools in Matlab or the basic video editing software provided with the GoPro camera. Figure 8 shows the results of these corrections for a run obtained at 1200 RPM. The final form has nice straight edges and the measurements are easily mapped to the experimental geometry.

Figure 8: Color change for test section rotating at 1200 RPM

**Illumination**

Each exposed surface of the acrylic test section is illuminated by four white LEDs that are mounted in a square arrangement around the outside of each GoPro camera. The LEDs are positioned so that their reflection to the camera will fall on the matte-black aluminum support material between the passages. This is intended to prevent color washout due to reflection. Early experiments, like the one shown in Figure 8, experienced some oil leakage onto the test section surface that increased the reflectivity of aluminum pieces and also caused reflection that interfered with the passage itself. This was rectified for later builds so that the washout region due to the reflection was very small.

**Calibration**

Achieving accurate heat transfer measurements using the transient liquid crystal method requires careful determination of the relationship between the recorded liquid crystal color and temperature. The color values recorded can depend on many factors including the camera itself, camera settings, lighting conditions, view angle, and of course temperature. It is therefore beneficial to perform bench-top and in-situ calibrations utilizing the actual experimental hardware where possible and duplicating all relevant settings. These include the lighting arrangement, LED types, and supply voltage as well as the camera effective ISO value, white balance, color profile, and exposure.

**EXPERIMENTAL SEQUENCE**

A typical experiment begins with the spin pit completely evacuated and completely dark, the large air supply tank pressurized to approximately four atmospheres, and the air supply heat exchangers refrigerated to a temperature around 200 K. Similarly, the stationary manifold and rotating union parts are also chilled to low temperatures. The GoPro cameras are turned on and connected to the control room via a wireless network. The air motor is then used to spin the rotating test section up to the desired speed. As the test section approaches the target speed, video recording is started on the GoPros. Once the speed has stabilized, the experiment is initiated by pressing a button that turns on the LED illumination system built onto the rotating test section support, triggers the control room data acquisition system, and starts an electronic timer that controls the air supply valves. The start of this lighting period is used to align the videos with the beginning of the data acquisition record. The electronic timer waits two seconds to give some baseline data and then opens the fast-acting supply valve, which opens completely in 40 ms. There is then a brief startup period as the initial compression wave is cleared out and the flow settles down to a stable low temperature. The experiment then lasts until the liquid crystal color change has completed, which can take anywhere between 15 and 80 seconds depending on the flow conditions being investigated. At the end of the experiment, the supply valve is shut off to stop the airflow, and the test section is allowed to decelerate and stop. Additional valves are closed to isolate the air supply heat
exchangers, and they are pumped down to a vacuum to prevent ice formation.

CURRENT AND FUTURE WORK

Following the initial 1:1 aspect ratio experiments, a new test section has been constructed to investigate the heat transfer in high aspect ratio passages of 1:6 (width to height). This test section, pictured in Figure 9, capitalizes on many lessons from the first measurement campaign by better integrating the embedded instrumentation and fluid temperature thermocouples. In the new configuration, the thermocouples are supported from the sidewalls and do not block visual access to the liquid crystal surfaces in any way.

CONCLUSION

This new facility adds to the small but busy collection of facilities around the world investigating cooling passage heat transfer in a rotating frame. It will cover a wide range of operating conditions and can easily accommodate many different experimental geometries while providing unique camera angles on the liquid crystal surfaces. Ongoing comparisons between data obtained using the transient liquid crystal method and the constant wall temperature heater panel method will provide greater confidence in the quality of these results and new insights into how this data can be utilized in a design environment.

NOMENCLATURE

Ω Rotation frequency
ṁ Mass flow rate
u Bulk fluid velocity
A Cross-sectional area of passage
D₀ Hydraulic diameter of passage
DR Coolant to wall density ratio
Re Reynolds Number
Ro Rotation Number
Tᵢ Fluid temperature
T_w Wall temperature

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