ACQUISITION AND PROCESSING CONSIDERATIONS FOR INFRARED IMAGES OF ROTATING TURBINE BLADES

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ABSTRACT
As designers aim to increase efficiency in gas turbines for aircraft propulsion and power generation, spatially-resolved experimental measurements are needed to validate computational models and compare improvement gains of new cooling designs. Infrared (IR) thermography is one such method for obtaining spatially-resolved temperature measurements. As technological advances in thermal detectors enable faster integration times, surface temperature measurements of rotating turbine blades become possible to capture including the smallest features. This paper outlines opportunities enabled by the latest IR detector technologies for capturing spatially-resolved rotating blade temperatures, while also addressing some of the challenges of implementing IR for turbine rigs such as the one in the Steady Thermal Aero Research Turbine (START) Laboratory. This paper documents critical steps in achieving accurate measurements including calibration, integration times, spatial noise, and motion blur. From these results, recommendations are provided for achieving accurate IR measurements collected in a rotating turbine facility to study film cooling.

NOMENCLATURE

<table>
<thead>
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<tbody>
<tr>
<td>d</td>
<td>object size</td>
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<tr>
<td>d*</td>
<td>non-dimensional speed-time parameter (vt*/d)</td>
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<tr>
<td>D</td>
<td>diameter of film cooling hole</td>
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<tr>
<td>I</td>
<td>total radiant energy</td>
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<tr>
<td>k</td>
<td>thermal conductivity</td>
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<tr>
<td>m</td>
<td>number of pixels in image</td>
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<tr>
<td>U</td>
<td>blade speed</td>
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<tr>
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<tr>
<td>x</td>
<td>axial distance downstream of cooling hole</td>
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Greek

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<td>Δ</td>
<td>difference</td>
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<tr>
<td>ε</td>
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</tr>
<tr>
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<td>adiabatic effectiveness (T_max-T_aw)/(T_max-T_c)</td>
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<td>θ</td>
<td>nondimensional temperature (T_max-T)/(T_max-T_min)</td>
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<tr>
<td>σ</td>
<td>Stefan-Boltzmann constant ≅ 5.67 x 10^-8 W/m^2K^4</td>
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<tr>
<td>ω</td>
<td>rotation rate [rad/s]</td>
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Subscripts and Accents

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<td>aw</td>
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<td>background</td>
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INTRODUCTION
Manufacturers continue to strive for improved thermal efficiency and reduced emissions with gas turbine engines through increased firing temperatures. These increases require improved cooling designs to maintain hardware integrity. Through the maturation process of turbine component designs, engineers have gained the ability to model and predict component
temperatures at any location in an engine. However, many of these designs are based on global averages rather than discrete local surface temperatures, which require spatially-resolved measurements.

Infrared (IR) thermography is a non-contact measurement technique that captures a spatial map of surface temperatures. With this capability, IR thermography is one particular measurement method that is well-suited to gather high-fidelity measurements on turbine components. The application of IR has been widespread in the turbine heat transfer community. Because of its ability to resolve spatial information, IR imaging has been used for aerospace applications since the late 1960s [1]. Co-authors on this paper have long used IR thermography to capture details of film cooling effectiveness levels, heat transfer coefficients for airfoils and endwalls, combustor liner cooling, and blade tip heat transfer [2-6]. These studies have shown the empowering benefits of spatially-resolved temperatures relative to point-based temperature measurements. As these examples illustrate, the application of IR thermography for turbine cooling measurements has primarily been limited to stationary experiments that circumvent the need to address effects of rotation. Based on this, a primary challenge is the ability to image highly three-dimensional blades that are rotating in an engine-representative environment.

Recent development of new infrared detectors capable of operating with integration times of under 1 μs provides opportunities previously not afforded for IR integration. These detector technologies enable the use of IR in a turbine test rig such as the one in the Steady Thermal Aero Research (START) facility [7] to assess the details of the performance of film cooling designs at engine-representative hardware scales with relevant axial and rotational Reynolds numbers. While there are many advantages in using IR imaging to measure rotating blades, several challenges exist. This paper provides unique and detailed analyses related to specific challenges in applying IR measurements in a turbine test rig used for film cooling studies, as well as how these challenges can be addressed.

**REVIEW OF LITERATURE**

IR thermography operates on the basis of Planck’s Law, which describes the spectral radiance of a perfect emitter (or blackbody) as a function of wavelength and absolute temperature [8]. From Planck’s Law, the peak blackbody emissive power for objects from cryogenic temperatures up to approximately 4000 K occurs in the infrared wave band, a portion outside of the visible light spectrum comprising wavelengths of 0.74 to 1000 μm. Through the use of a detector designed to measure radiant energy in a particular IR wave band, a signal measured by the detector can be correlated with an object’s temperature. IR detectors commonly utilize the 3-5 μm Mid-Wave IR (MWIR) or 8-12 μm Long-Wave IR (LWIR) bands where atmospheric absorption is low. However, detectors in the 1-3 μm Short Wave (SW) are also available [8].

Several published experiments have used IR imaging for rotating disks, and some have even used IR imaging for rotating blades. Some notable work involving rotating disks include studies performed by Cardone et al. [9] and Astarita et al. [10]. Cardone et al. utilized a heated thin foil on the rotating disk that allowed for Nusselt numbers to be calculated as a function of Reynolds number. The imaged disks were axisymmetric and therefore image blur due to rotation and long integration times was not a primary concern. Image blur due to motion, known as motion blur, is a result of subjects moving during the time the image is captured (the integration time). In the study by Astarita et al., unsteady spiral vortices were visualized during the rotation of an axisymmetric disk. To accomplish this goal, the line scan function of an IR camera was utilized to increase the frame rate from 15 Hz to about 2,500 Hz; the high frame rate afforded by scanning a single line of the focal plane array (FPA) was essential in capturing unsteady heat transfer effects.

The use of IR thermography to capture blade temperatures was performed by Brunner et al. [11], although a focal plane array was not used and therefore a spatial map of temperature was not measured. Instead, two pyrometers (single-point IR sensors) were used to simultaneously measure blade surface temperatures on second stage low-pressure turbine (LPT) blades in a heavy duty gas turbine engine. The use of relatively low-cost pyrometers for engine monitoring was demonstrated. Thermal transients were measured on the blade surfaces during operation as turbine conditions changed. Optical access was achieved using probes with optical fibers and sapphire lenses. While these tests were significant as some of the first temperature measurements on rotating blades, using an IR detector with an FPA to measure a spatial map of temperature provides more information for studying blade heat transfer effects.

A spatially-resolved IR system was developed for condition monitoring of thermal barrier coated (TBC) blades in power generation turbines as described by LeMieux [12]. A custom infrared system was used that included an Indium Gallium Arsenide (InGaAs) detector sensitive to the 0.9 to 1.6 μm Near-IR (NIR) band. An FPA allowed a spatial map of temperature to be measured with an integration time as low as 0.5 μs for linear speeds of 400 m/s. An uncoated sapphire window and a telescopic lens arrangement provided optical access needing two blade views to image the entire blade. Following this development, IR was presented as an option for condition monitoring of power generation engines [13].

Patent applications of industrial IR condition monitoring demonstrate interest in both the power generation [14,15] and aviation [16] sectors. In addition to industrial condition monitoring applications, IR has also been used to measure temperatures of rotating blades in academic research. Spatially-resolved IR measurements of rotating blades were captured by Mori et al. [17,18] and Novak et al. [19]. In these studies, uncooled blades in a room-temperature turbine rig were rotated at speeds up to 1500 RPM and a high-speed IR camera was used to capture surface temperatures. Due to the relatively slow rotational speed, an integration time of 100 μs was suitable to capture thermal images.

Other researchers have since used IR systems at shorter integration times to capture rotating blades that are more relevant to turbine conditions. Markham et al. [20] measured blades coated with TBC in an aero engine using a custom-designed IR system. They also measured rotating blades on a molecular turbopump at speeds of up to 60,000 rpm using an integration time of 1.08 μs. Markham et al. used a custom optical probe with Zinc Selenide (ZnSe) optics to allow the thermal detector to view the surface of rotating cooled blades. Similar to Brunner et al. [11], Markham’s optical probe protruded from the wall near the vane casing and faced downstream allowing blades to be imaged. This study demonstrated a method to successfully measure rotating blades in an engine, further identifying that IR thermography may be used to measure heat transfer in areas critical to blade design, such as the endwall.

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Recently, IR thermography has been used to study endwall heat transfer. Lazzi Gazzini et al. [21] and Hänni et al. [22] measured contoured rotor endwalls at 2700 RPM in a low-temperature, moderate speed, rotating turbine facility to assess effects of purge flow on Nusselt number and adiabatic wall temperature. Three ZnSe windows mounted in the casing were used to grant optical access so the blade endwalls could be imaged. In each of these studies, image processing and reconstruction were an integral component of generating results.

Post-processing often dictates the way in which data is collected. Most IR camera manufacturers utilize their own software for processing before the user sees any data [23]. For integration times less than 10 μs for common detector types such as MCT, a large number of images must be averaged together to reduce noise. Markham et al. [20] averaged 100 images together to form a representative measurement, while Lazzi Gazzini et al. [21] averaged 1000 images to form a single measurement. The number of images needed for averaging is likely a function of integration time, but no post-processing has previously been defined by researchers utilizing IR imaging for rotating parts to determine the optimal number of images for averaging.

Lazzi Gazzini et al. [21] also describe an image deblurring and reconstruction procedure which involves images collected at two different integration times: 10 μs and 50 μs. Using these two image sets, the reduced image blur at 10 μs and the reduced spatial noise at 50 μs were combined to form a composite image with both low motion blur and low noise. Their research provided some initial insight into the tradeoffs associated with the selection of integration time and suggested that further investigation may be of interest to optimize image quality to minimize spatial noise and motion blur.

Past applications of implementing IR have brought to light the many challenges that exist for accurately capturing surface temperatures on rotating turbine blades where rotational speeds are engine-relevant: achieving optical access, using appropriate surface coatings and calibration methods, and determining acceptable integration time and post-processing for rotating parts. This study addresses these primary challenges to provide insight into using IR for making turbine blade temperature measurements. In particular, this paper addresses the implementation of IR thermography into the START experimental facility.

**IR Calibration**

For an opaque surface at temperature $T_s$, with surroundings at temperature $T_b$, the energy balance at the surface may be described by

$$I = \varepsilon\sigma T_s^4 + (1-\varepsilon)\sigma T_b^4$$  \hspace{1cm} (1)

where $I$ is the total radiant energy measured by an IR detector viewing the surface, $\varepsilon$ is the emissivity of the surface, and $\sigma$ is the Stefan-Boltzmann constant. From Eq. (1), the amount of radiant energy collected by an IR detector is affected by both the surface temperature, $T_s$, and the background temperature, $T_b$. However, if the emissivity of the surface is maximized, the impact of the background temperature may be minimized. Researchers have used coatings to increase the emissivity of a target surface to reduce temperature measurement uncertainty.

A commonly-used high-emissivity coating is a matte paint with previously-reported emissivity values of 0.93–0.96 [3,5,24]. Two specific high-emissivity coatings which have been used for IR thermography include Krylon flat black spray paint [25,26] and Nextel Suede coating [27]. The emissivity of a particular Krylon spray paint has been measured by the NASA MASTER project [28] to be $\varepsilon = 0.95$. The Nextel Suede coating was measured by Adibekyan et al. [27] to be $\varepsilon = 0.97$.

Due to the fact that these coatings are typically manually applied, there is a likelihood for variation in thickness and emissivity. For example, Kerns et al. [29] showed that the application method (sprayed or brushed) and number of coats has a notable effect on optical properties. In their study, Kerns et al. measured the relative reflectivity of various black paints with different application methods and found that the reflectivity of Nextel Suede coating varied by over 50% depending on application method (spray or brush) and number of coats. This result implies that a coating with an expected emissivity of $\varepsilon = 0.95$ may have an actual emissivity as low as $\varepsilon = 0.90$. This study emphasizes the need to measure the surface emissivity to ensure an accurate temperature measurement.

In each of the turbine cooling studies previously mentioned, the emissivity is either deduced using an in-situ thermocouple calibration and equation (1) with a factory calibration [2–6], or the emissivity is not measured at all. In studies with stationary targets, the in situ calibration method is commonly used [2–6,24,30–32]. The in-situ calibration method employs temperature sensors placed on the target surface in the field of view of the camera. The raw value of the camera near the temperature sensors is correlated with the surface temperature measurements to create a calibration curve between the raw camera value of the total radiant energy and the surface temperature. This calibration method allows for simultaneous accounting of background temperature effects and emissivity.

When calibrating a camera for imaging rotating turbine blades, the prospect of obtaining accurate surface temperature measurements is challenging. Surface mounted thermocouples are difficult to achieve given wire routing issues and data transmission. As a result, an in-situ calibration with rotating blades requires significant custom instrumentation. An alternate method is to calibrate the IR detector externally as outlined by Mori et al. [17]. For the method described, a heated plate of high-thermal conductivity material is coated with the same paint as the blades and then used to calibrate the detector. Ideally, the emissivity and background temperature are matched to that of the blade conditions. In the study by Mori et al. an uncertainty in temperature measurement of 1-3% of full scale is reported.

**CAMERA SYSTEM AND OPTICAL ACCESS**

IR detector technologies fall into two categories: thermal detectors and photon (or quantum) detectors. The off-the-shelf IR cameras for wind tunnel applications are thermal detectors, such as uncooled microbolometers that are relatively inexpensive and have integration times on the order of milliseconds. The integration time of these cameras is not generally important since time-averaged thermal images of stationary subjects are used. Photon detectors, such as InSb-based or HgCdTe (Mercury Cadmium Telluride, MCT)-based detectors, allow for integration times on the order of microseconds. The newest generation of IR photon detectors includes type-II InAs/GaInSb Strained-Layer Superlattice (SLS) architectures and also offer integration times under 1 microsecond [33]. Table 1 shows a summary of these detectors. High-speed detectors including InSb, MCT, and SLS have integration times on the order of 1 microsecond that enable IR imaging for rotating applications.

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The thermal imaging system chosen for the present study is a commercial Sofradir MiTIE MARS LW camera engine which utilizes a high-performance HgCdTe (MCT) IR detector that enables measurements of fast-moving subjects using full-frame (320 x 240 pixel) integration times of less than 1 μs. With on-chip binning and windowing, the frame rate can be increased above the specified 244 Hz full-frame rate up to 130 kHz in line-scan operation. This IR detector was integrated to create a custom-designed camera system with optics and synchronization hardware. The detector operates in the LWIR band, which was chosen based on the range of blade temperatures in the turbine facility at START. For a common main gas path temperature (122 °C), there is approximately twice the blackbody emissive power in the LW band as in the MW band on the basis of Planck’s Law.

The non-contact approach of IR thermal imaging requires optical accessibility, either through a viewing window or some sort of lensed probe. Flat optical windows are often used in wind tunnel and cascade experiments. Optical access in turbine rigs, however, is challenging because the outer casing is cylindrical and there is typically blockage from upstream airfoils. The blockage, in particular, restricts the ability to view every surface of a turbine blade from a single perspective so it is beneficial to make use of several views to measure the entire surface of a blade. The compromises and approaches that allow for optical access in an engine or rig are specific to the application and are not the main subject of this paper. In this regard, the detector and optics are treated as a system that can be quantified by measurable parameters in a pretest calibration set-up, without requiring an understanding of the optical design. With this in mind, a general description of the optical assembly is provided below.

For the START test turbine, the optical access challenges were overcome through the use of a specially-designed optical system. The detector is mounted in an enclosure outside of the casing, while the optical probe consists of a series of lenses and a 90° prism that is inserted into an additively manufactured (AM) vane designed to enable direct viewing of the downstream blade while minimizing probe impact on the target locations. The custom vane was designed using industry-standard CFD practices with aerodynamic concerns in mind to ensure that the flowfield of the imaged blades would not be affected by the presence of the probe in the vane.

Figure 1 shows a notional representation of this optical access for a particular blade view. By adjusting the position of the optical probe, the entire pressure side and leading edge of the blade is imaged, as shown in Figure 2. The blade’s suction side is not visible from this view. Adjacent views overlap such that phase-locked steady surface temperatures can be compared between tests conducted at different times for different blade views. The views are designed to maximize blade coverage, ensuring the entire pressure side and leading edge can be imaged at viewing angles of less than 45° to ensure near-constant emissivity [8].

<table>
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<tr>
<th>Detector</th>
<th>Wave band(s)</th>
<th>Integration time</th>
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<td>Microbolometer</td>
<td>SW, MW, LW</td>
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</tr>
<tr>
<td>InSb [33]</td>
<td>SW, MW</td>
<td>~ 1 μs</td>
</tr>
<tr>
<td>HgCdTe (MCT) [33]</td>
<td>SW, MW, LW</td>
<td>~ 1 μs</td>
</tr>
<tr>
<td>SLS [34]</td>
<td>LW</td>
<td>~ 1 μs</td>
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Image triggering is accomplished through a custom designed controller that provides positional accuracy using an encoder signal from the rotating shaft and can maintain targeting even during engine transients. Frame rate is then dictated by the rig speed, which is typically lower than the design frame rate of the camera. Where speeds exceed that framerate, the system can be designed to skip revolutions. Overall trigger timing of comparable electronics has been measured with a standard deviation of 30 ns, which is well below the natural jitter in the rotating machinery trigger sources.

**SURFACE COATINGS AND CALIBRATION**

Applying a high-emissivity coating to the blades is essential to reduce the effect of reflections and minimize surface temperature measurement uncertainty. This is particularly important for a turbine blade row where the measurement surface sees a wide variety of background temperatures including other blades, which may be cooled, the casing, and even upstream into the supply piping in the case of the START rig. The key components directly impacting the blade through radiative heat transfer are also coated to minimize reflections and to allow for direct temperature measurements to estimate the background temperature.

For this study, emissivity and surface coating thicknesses were evaluated for Krylon flat black spray paint and Nextel Suede coating. To characterize the coatings in this study, coupons were created to test the emission and thickness of Krylon and Suede with sprayed paints that consisted of three, four, or five coats. To
quantify the thickness of each coating, smooth acrylic coupons measuring 25.4 x 25.4 x 3 mm were painted with half of the coupon covered in masking tape. The Krylon paint was applied using a spray can and the Suede coating was applied with a pneumatic, V-nozzle spray gun at 50 psig, each at a distance of approximately 30 cm from the coupon and in a 20 °C, low-humidity environment. With these coupons, the thickness was determined by using a Zeiss Smartzoom 5 digital 3D microscope to measure the height of the coating relative to an uncoated section.

To quantify the relative (rather than absolute) emissivity of each surface coating as a function of wavelength for each coating thickness, a set of copper coupons measuring 25.4 x 25.4 x 1 mm were characterized using a Bruker Vertex 70 Fourier Transform Infrared (FTIR) spectrometer. Each coupon was mounted to a copper block with thermocouples at the coupon interface and a cylindrical cartridge heater was installed in the block for temperature control. The temperature of the coupon was controlled using the heater with the thermocouple as feedback to reach a coupon temperature of 100 °C, an expected blade temperature with cooling, and steady state conditions were achieved before collecting FTIR measurements. Figure 3 shows the relative emission of each sample across the 4-12 µm wavelength band. The relative emission E_{rel} is plotted as the emission of a sample divided by the emission of Suede, 3 coats, which had the highest average emission. The noise in the 5-7 µm range is due to atmospheric absorption, but the selected detector operates outside of these wavelengths. From these measurements, the relative emissivities of each coupon were known, but the absolute values were not known without a reference emission value. A custom calibrator was used to determine the absolute emissivity of one coating as a reference value and appropriately convert the non-normalized emission results into usable emissivities.

A custom calibrator was developed for camera calibration at elevated background temperatures, as shown by the schematic in Figure 4. A heated copper plate with embedded thermocouples was surrounded by a heated cylindrical aluminum tube with embedded thermocouples. Using simple relations between surfaces, the geometric view factors between every surface was calculated using view factor relations found in Modest [35]. Through this process, the effective background temperature of the plate was solved iteratively based on the emissivity of each surface, the measured temperature of each surface, and the view factors. Calibrations were conducted at two background temperatures for surface temperatures from 90°C to 150°C. Using the two background temperatures and equation (1) to align raw data as a function of I, the emissivity of the target surface was calculated as the value of ε in equation (1) that minimizes error between all raw values and a 4th-order polynomial fit between the raw values and the total radiation, I.

Figure 5 shows the emissivity and thickness results for each of the coatings. In Figure 5, each data point represents the mean value of three tested coupons, and the error bars correspond to a 95% confidence interval. Based on these measurements, the Suede coating was substantially thicker than the Krylon coating, which was attributed to the specific Suede primer. The actual thickness values varied little between three to five coats for the Krylon while the Suede coating became significantly thicker with each additional coat. In both cases, the data exhibited little or no change in emissivity with increased thickness. For Krylon, a maximum emissivity of ε = 0.92 was measured versus the expected 0.95 [28]. For Suede, a maximum emissivity of ε = 0.92 was measured versus the expected 0.97 [27]. Based on these results, the Krylon paint with five coats was chosen to be applied to blades as the optimal balance of low thickness to reduce conductive effects, and high emissivity to minimize reflections. The arithmetic mean roughness of the Krylon-painted surface with five coats was measured with optical profilometry at several locations to be 2.8 µm.

Following the coating selection, the selected IR detector was calibrated. The calibration process for an IR detector consists of two steps: first, relating the raw pixel values to total radiation, and second, employing equation (1) to tune the calibration for a specified emissivity and background temperature. To complete the first calibration step and convert raw pixel values to total radiation values, stationary calibrations were performed using a heated copper plate painted with five coats of Krylon paint. This calibration plate contained embedded thermocouples following the same procedure described by Mori et al. [17].
maximum spatial and temporal variations in temperature were less than 0.5 °C and 0.1 °C, respectively, within the uncertainty of the thermocouple measurement. Raw images were captured at several integration times ranging from 1 to 10 microseconds, and for 11 temperatures ranging from 24 to 164 °C in increments of approximately 15°C. This temperature range includes all expected blade temperatures during rig operation. During calibration the temperature of the optical probe was maintained at temperatures representative of those during rig testing. To further characterize effects of noise on calibration images, 200 images were captured for each combination of integration time and surface temperature.

The total radiation, I, for the calibration data was computed using equation (1) with the measured surface temperature, T, the measured background temperature which was room temperature, T₀ = 27 °C, and the emissivity which was found from previous measurements to be ε = 0.92. Camera raw value was determined as a function of total radiation using a 4th-order polynomial fit. Once the coefficients were determined, raw images could quickly be converted to total radiation maps.

Once the first calibration step was completed, additional raw images not used for the calibration were captured to validate the calibration using a similar procedure. The calibrations were qualitatively in agreement with the measured thermocouple temperatures, but the accuracy and image quality were found to be strong functions of both integration time and sampling.

**INTEGRATION TIME AND SAMPLING WITHOUT ROTATION**

Selecting the appropriate integration time is critical to achieve desired image resolution and accuracy. To capture moving targets with minimal blur, short integration times are needed. For example, a gas turbine blade rotating at 11,000 rpm in the START facility rotates 1 degree circumferentially in only 15 μs, resulting in a blur of 50 pixels for an image captured in that time. Selecting too short an integration time results in excessive noise, while too long an integration time results in motion blur. Typically higher target temperatures or longer integration times are used to improve signal quality.

It should be noted that integration time and frame rate are separate descriptions of high-speed IR detectors. Integration time describes the response capability of the underlying detection electronics, while frame rate describes the ability to transfer information off the camera. Most modern system with typical 1 μs integration times have frame rates on the order of 100 to 300 Hz. This section focuses on the impact of the selected integration time, as opposed to frame rate, on image quality and provides a methodology to relate integration time with rotational speed that can be used quantify any imaging system.

For purposes of this study, the quality of the calibration curve fit is quantified by RMS error, which describes the mean absolute error between each calibration point and the fitted curve. The RMS error is computed by:

\[
\text{RMS error} = \frac{\sum_{i=1}^{n} \sqrt{(T_{\text{fit}} - T_{\text{meas}})^2}}{n}
\]

(2)

where \( n \) is the number of calibration images, \( T_{\text{meas}} \) is the measured thermocouple temperature, and \( T_{\text{fit}} \) is the mean image temperature based on a polynomial fit. Figure 6 shows the averaged RMS error as a function of integration time, \( t_{\text{int}} \), and the number of averaged images, N.

As shown in Figure 6, RMS error decreases both as integration time increases and the number of images averaged increases. The benefits of averaging decreases as integration times are increased. Even with a large number of averaged images, the RMS error at short integration times is higher than at long integration times with less averaging.

Another important image quality parameter to quantify is the spatial noise, \( s_T \), defined as the standard deviation in temperature of all pixels when an isothermal surface is imaged:

\[
s_T = \sqrt{\frac{\sum_{i=1}^{m} (T_i - \bar{T})^2}{m-1}}
\]

(3)

where \( m \) is the number of pixels in the image, \( T_i \) is an individual pixel’s temperature measurement, and \( \bar{T} \) is the average temperature in the image. Figure 7 shows the average \( s_T \) across all calibrated temperatures as a function of integration time for several numbers of averaged images, N. The magnitude of spatial noise decreases with increasing temperature but the trends with N and \( t_{\text{int}} \) are constant across all temperatures.

Similar to RMS error, the spatial noise decreases with both increasing integration time and increasing number of averaged images. Together, Figure 6 and Figure 7 suggest that at least 50 images should be averaged to minimize both RMS error and spatial noise. Requiring a large number of images for averaging increases acquisition time, data storage requirements, and processing time. For a steady turbine facility such as START, phase-locked acquisition times are not a significant concern. However, for applications of IR imaging in a short duration facility, acquisition time becomes a key parameter governing the number of images available for averaging.

One of the advantages of quantifying overall performance using this type of information is that any system can be evaluated before a test using relatively simple equipment. As shown in Figures 6 and 7, the relative improvement in calibration accuracy for the current system between 50 and 200 images is relatively small for any given integration rate, and marked changes only occur with changes in integration time. While the spatial component is a larger contributor to overall accuracy relative to...
the calibration accuracy, improvements in either component will impact overall image quality. Finally, as new detectors become available, the relative impact in image quality can be assessed before detailed designs are started, removing a significant time and cost risk to new design efforts.

INTEGRATION TIME AND SAMPLING WITH ROTATION

To assess the IR sensor’s capability to resolve small subjects on rotating surfaces, a Krylon paint dot approximately the size of a typical film cooling hole was applied to a large-diameter aluminum disk on a motor-driven shaft. The irregular shape is due to the difficulty in accurately painting a dot at this scale. For purposes of these tests, the difference in emissivity between the high-emissivity paint spot and low-emissivity aluminum disk were used to create contrast in thermal images. To improve contrast in the images, a high-emissivity heated plate was positioned behind the optical probe to radiate toward the disk, as shown in Figure 8. The radiating plate raised the background temperature significantly, causing the low-emissivity (and therefore high-reflectivity) aluminum to provide a higher signal for the measured radiation energy of the painted dot. The heated plate temperature reached approximately 100 °C and was held at a steady temperature throughout the tests presented here. The optics temperature was controlled to be representative of rig conditions and the heated plate caused a disk temperature increase of under 2 °C from static thermocouple measurements.

A microscope photograph of the paint dot is shown in Figure 9(a). Thermal images of the paint dot were captured for different integration times while the disk was stationary and rotating, as represented by a normalized temperature in Figure 9(b). The absolute temperatures on the paint dot were between the coolant and mainstream temperatures in the START rig and are relevant to highly-cooled turbine conditions. The thermal images in Figure 9(b) represent single frames without multi-frame averaging. The object speeds are expressed as a percentage of U, the linear speed of the turbine blades at START when spinning at 11,000 rpm. For this experiment, the rotation rate of the disk reached 3,800 rpm and the linear speed of the disk $v = r\omega$ reached as high as 43% U.

For these data, the normalized temperature $\theta$ is defined as

$$\theta = \frac{T_{\text{max}} - T(x)}{T_{\text{max}} - T_{\text{min}}} \tag{4}$$

such that $\theta = 1$ corresponds to the minimum temperature in the image and $\theta = 0$ corresponds to the maximum temperature. As shown by the vector in Figure 9(b), the direction of motion is nearly vertical with a small horizontal component. With rotation at the longest integration time, the spot appears blurred toward the top right. While the sensor captured the image, the spot was allowed to travel a further distance compared to the short integration times, and the fully integrated image shows the average position of the dot while the image was captured. Because the images in Figure 9(b) are single frame representations, identified noise (RMS error and spatial noise) can be reduced with averaging, as suggested by Figures 6 and 7.

Figure 10 extends the 43% U measurements shown in Figure 9(b) by evaluating image quality effects due to integration time and averaging. Averages of $N = 1, 10, \text{ and } 100$ images are shown such that samples with the same total measurement time (e.g. $N = 1$ at 10 μs and $N = 10$ at 1 μs) can be directly compared. When more than 100 images were averaged, the image quality and values were nearly the same as the $N = 100$ case.
The observations in Figure 10 are consistent with the stationary calibration conclusions in Figure 6. In particular, at short integration times, visible spatial noise is present. While increasing the number of averaged images reduces noise, there is persistent spatial noise in the form of striping: vertical stripes appear in the images with low integration time due to the nonuniformity limitations on the detector’s noise equivalent differential temperature (NEΔT) [36]. At longer integration times, the image appears to have low noise, even with minimal averaging. At longer integration times, however, motion blur is present as the nearly-circular object becomes blurred in the direction of motion, as identified in Figure 9(b).

The impacts of motion blur and spatial noise can be quantified by taking the absolute difference between the stationary image and the rotating image, as illustrated in Figure 11. The absolute normalized temperature error is defined as

\[ |\Delta \theta| = |\theta_{rot} - \theta_{stat}| \]

where \( \theta_{rot} \) and \( \theta_{stat} \) correspond to the rotating and stationary normalized temperature, respectively. Figure 12 shows an absolute error map between the stationary and rotating images for each integration time with different image processing steps applied. Considering first the unprocessed images (a-g): at low integration times the spatial noise is present in the error map; at high integration times there is little spatial noise but the motion blur causes significant temperature errors. These spatial noise characteristics are well-known for IR FPAs, and researchers have developed processing routines to reduce noise [36].

Binning is a processing tool that is often used to reduce noise in images by averaging across pixels with an effect of reducing final image resolution and causing raw pixel values to be biased toward the local average. If binning is used in post-processing, it needs to also be implemented into the calibration routine to prevent bias due to unequal processing of calibration and measurement data. Finally, the addition of a 3x3 median filter after binning removes outlying values, which may be the result of nonresponsive pixels.

The overall impact of different post-processing steps can be further quantified by computing an area-averaged value to represent each error map in Figure 12. Figure 13 shows this area-averaged absolute normalized temperature error as a function of integration time. The area-averaged normalized temperature error is defined as

\[ \bar{|\Delta \theta|} = \frac{\sum_{i=1}^{m} |\Delta \theta|}{m} \]

Figure 11 validates the qualitative trends identified in Figure 12: these post-processing steps provide additional error reduction benefits for low integration times while there are little benefits for high integration times.
Because the binning process reduces resolution with limited benefit to accuracy at high integration times, binning is not recommended for integration times above 4 μs with the present camera system. Median filtering results in a slight error reduction for integration times at 4 μs and below, but does not improve error above 4 μs and, as a result, is also not recommended for these longer integration times.

To optimize integration time as a function of speed, images of the paint deposit were collected over a range of object speeds. Figure 14 shows the area-averaged normalized temperature error as a function of integration time for several object speeds as percentages of blade speed \( U \). The shaft speeds for these data ranged from 650 rpm to 4,000 rpm. In Figure 14, the optimal integration time represents the point at which the temperature error is minimized. By this method, Figure 14 shows a trend of decreasing optimal integration time as object speed increases. Although these data could be used to determine optimal integration time as a function of speed for an arbitrary speed, the results are specific to a 0.8 mm object size. Because the integration time, \( t_{int} \), object speed, \( v \), and object size, \( d \), are the key factors in each of these curves, a nondimensional parameter \( d^* \) is proposed which takes into account each of these driving factors:

\[
d^* = \frac{vt_{int}}{d}
\]  

By this definition, the parameter \( d^* \) represents the number of diameters that an object travels while the image is captured. For example, a \( d^* \) value of 2 represents an object which has traveled a distance equal to twice its size while the image is captured, indicating that significant blur would be expected. In calculating \( d^* \), the speed, \( v \), and object size, \( d \), may be expressed either in terms of physical size or pixel size; the resultant relative speed \( v/d \) would be the same in either case.

Figure 15 shows effectively the same data as Figure 14, but re-cast in terms of the nondimensional parameter \( d^* \) instead of integration time. Figure 15 shows that data from several different speeds begin to collapse, enabling identification of three regimes: (1) at values of \( d^* < 0.2 \) where the error is high as the spatial noise dominates; (2) at \( 0.2 < d^* < 0.6 \) where the error is minimized as the spatial noise and motion blur are balanced; (3)
for d* > 0.6 where the error is high as motion blur is the main contributor to error. Based on the information in Figure 15, a value of d* between 0.2 and 0.6 is recommended for the particular imaging system evaluated in this study. For example, if a gas turbine blade is rotating at 11,000 rpm at a radius of 0.3 meters (v = 346 m/s) and feature resolution of d = 0.8 mm is desired, the recommended d* values would yield recommended integration times of 0.5 to 1.4 μs.

While the recommended values for d* would vary with each camera system as noise levels continue to decrease with improved detector technologies, this method can be used to benchmark different cameras to compare performance at capturing moving objects and determine the integration time that optimally balances motion blur and spatial noise for a particular application. In addition to the spatial noise and motion blur which are both taken into account by |Δθ|, the RMS error in calibration curve fitting should also be considered before selecting an integration time. The optimal integration time would balance all three factors: spatial noise, motion blur, and RMS calibration error.

PROJECTED MOTION BLUR ON FILM COOLING

One of the key cooling features of turbine airfoils is film cooling holes that eject coolant onto the surface. To evaluate the effects of motion blur from the chosen camera on film cooling effectiveness measurements, projected errors were calculated using data for a baseline shaped hole published by Schroeder and Thole [37]. The motion blur was simulated corresponding to two different values of d*. The magnitude of the motion blur (in pixels) for a given object speed was generated by applying blur to stationary images and comparing the results to measured rotating images. The selected magnitude for each speed minimized error between the simulated and rotating images. Motion blur was applied in several directions of motion including 0° (motion in the flow direction), 30°, 45°, 60°, and 90°.

Schroeder and Thole [37] utilized scaled-up film cooling holes to collect high-resolution effectiveness measurements. Since the d* parameter is normalized based on the object size d, the motion blur applied to the temperature map was scaled based on the size of the cooling hole in pixels. The following results are generalized to holes of any size, as the error due to motion blur is not dependent solely on hole size, but depends on object speed and integration time as well. For example, a value of d* = 2.0 would correspond to imaging a 2 mm object on a blade traveling at 11,000 rpm at a radius of 0.3 m (v = 346 m/s) using an integration time of 12 μs or d* = 2.0 would equally correspond to imaging a 1 mm object at the same speed using an integration time of 6 μs. To quantify the motion blur the difference in effectiveness Δη is defined as

$$\Delta \eta = \eta - \eta_{\text{ref}}$$

where η_{ref} is the no motion case. Figure 16 shows a detailed map of Δη near the film cooling hole for the five angles of motion with blur corresponding to d* = 2.0. The data presented here represent a high blowing ratio M = 3.0 with a density ratio DR = 1.2 and a low turbulence intensity Tu = 0.5%, which is the baseline case tested by Schroeder and Thole [37]. Figure 16(a) shows that the 0° motion causes small error primarily upstream of the hole, while Figure 16(e) shows that the 90° case makes effectiveness appear much higher to the left and right of the hole and the film trace, while the trace itself has much lower effectiveness.
Figure 17 compares the error in centerline effectiveness for each of the motion blur directions for \(d^* = 0.4\) and 2.0 with blowing ratios of \(M = 0.5, 1.0,\) and 3.0 over a range of \(x/D\) values from 0 to 40. For the recommended \(d^* = 0.4\), the errors due to blur are small. In the worst case, the maximum error of effectiveness is \(\Delta \eta_{CL} = -0.02\) (3% relative error) and occurs at an \(x/D = 5\). For a value of \(d^* = 2.0\), which represents images captured with much longer integration times than optimal, the errors in effectiveness are much more significant with a maximum error of \(\Delta \eta_{CL} = -0.21\) (28% error) in the worst case. At these conditions, the error in effectiveness is also a stronger function of both direction and blowing ratio. Specifically, errors increase as the direction approaches a lateral condition (90°) and the blowing ratio increases. In contrast, effectiveness errors are low when the direction of motion is streamwise with the cooling flow (0°), an observation attributed to low gradients of effectiveness in the streamwise direction.

In evaluating the lateral spread due to the image blur, adiabatic effectiveness errors at \(x/D = 5\) for the same blur directions, \(d^*\) values, and blowing ratios are evaluated in Figure 18. Even with an appropriate \(d^* = 0.4\), there is some asymmetric error in effectiveness which increases with blowing ratio. Similar to the observations with centerline effectiveness, Figure 18 shows that errors in effectiveness due to motion blur are more pronounced at \(d^* = 2.0\). As the angle becomes increasingly lateral (closer to 90°), the centerline effectiveness reduces further, while the off-center effectiveness increases. This effect is particularly pronounced at high blowing ratios when the coolant jet is narrowest in the lateral direction. Finally, there is negligible effect of blur on adiabatic effectiveness for the 0° direction of motion cases across all values of \(d^*\) and \(M\).

![Figure 17. Error in centerline adiabatic effectiveness due to motion blur for \(M = 0.5, 1.0,\) and 3.0 and \(d^* = 0.4\) and 2.0.](image)

![Figure 18. Error in adiabatic effectiveness at \(x/D = 5\) due to motion blur for \(M = 0.5, 1.0,\) and 3.0 and \(d^* = 0.4\) and 2.0.](image)

**VALIDATION WITH ROTATING COOLED BLADES**

To demonstrate the effects of motion blur on feature resolution and film effectiveness, infrared images of rotating, Krylon-painted blades with true-scale cooling features in the START facility were captured for two speeds with the same range of integration times. Figure 19 shows a thermal image with the recommended averaging and post-processing steps applied. Consistent with the stationary images, increasing the number of samples and using binning and median filtering reduces noise in rotating images. In this figure, the blade is moving at a speed of 43% \(U\), blade cooling is supplied to achieve a moderate blowing ratio, and the image is captured at an integration time of 4 \(\mu s\). The film cooling traces downstream of each cooling hole are resolved by the IR system, which will enable more detailed studies of overall effectiveness in a rotating reference frame. The cooled blades were imaged at three test conditions, all of which included main gas path flow. Figure 20 shows thermal images of a single cooling hole at each of three different test conditions for several
integration times. In Figure 20, a portion of the image has been cropped for comparison, as outlined by the white rectangle in Figure 19. Figure 20 demonstrates that there may be multiple suitable integration times for a particular speed.

In condition A shown in Figure 20, the blade is moving at 43% U and coolant is supplied at a high blowing ratio which causes the jet to detach from the surface. For this condition, the ability of the imaging system to resolve fine features is demonstrated, similar to the paint dots shown in Figure 10. At low integration times the shape of the cooling hole is well-resolved with minimal blur. Qualitatively, an integration time of 3 μs is ideal for balancing spatial noise and motion blur at this speed, which agrees with the recommended range of optimal d values outlined in Figure 15. In condition B, the blade is moving at 43% U and coolant is supplied at a moderate blowing ratio. Comparing condition B to A, the film trace is now visible as the coolant jet remains attached to the blade surface.

In condition C shown in Figure 20, the blade speed is doubled to 86% U and coolant is supplied at a moderate blowing ratio. Comparing condition C to B, the magnitude of motion blur increases with the blade speed, requiring a shorter integration time to resolve features clearly. At condition C, motion blur begins to become evident at the 4 μs integration time, which is outside the range of recommended d values for the rotor speed. Qualitatively, the best balance of spatial noise and motion blur for condition C is achieved at integration times of 2 μs and 3 μs. Both of these integration times are within the range of optimal d values, which serves as further demonstration of the utility of the predictive approach outlined by Equation (7) and Figure 15.

CONCLUSIONS

With the development of new infrared detectors, it is possible to achieve integration times on the order of 1 μs enabling spatial measurements of radiant energy from turbine components in a rotating framework. Spatially-resolved blade temperatures provide the means for assessing cooling technologies in a rotating reference frame at engine-relevant speeds. This study outlined key considerations for IR imaging in a rotating environment. In particular, considerations were provided for integration and performance of an IR system for measuring surface temperatures of rotating blades. Challenges were addressed on topics of optical access, selecting an appropriate surface coating, performing detector calibrations, and determining optimal integration time.

A modern infrared detector was benchmarked with stationary and rotating experiments to assess its performance and optimize integration time, sample size, and post-processing routines for given conditions. Tradeoffs exist between spatial noise and motion blur, and the optimal integration time balances both factors. A nondimensional parameter was introduced to determine the optimal integration time as a function of object speed and object size. It was demonstrated that when using the optimal integration time, local errors in film cooling effectiveness can be reduced to 5% as a result of motion blur.

The work outlined here describes a procedure critical to high speed rotating tests where integration rates are driven mostly by image blur and can no longer be set based on overall image quality as typically done in non-rotating tests. However, these techniques can also be used in tests whether they are rotating or not, where surface temperature conditions are expected to change rapidly. The ability to quantify the optical performance of an infrared detector, or a full optical IR system, before a test allows for detailed experimental planning.

In summary, infrared imaging for a test turbine was shown to be a viable measurement method that allows high-resolution thermal images of rotating true-scale turbine blades to be captured. Ultimately, these measurements will provide the turbine community with data that highlight important cooling features needed for advancing turbine designs.

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