PHASE-BASED INFRARED MEASUREMENTS OF HEAT TRANSFER COEFFICIENT IN A ROTATING TURBINE RIG

William Davis, Nick Atkins
Whittle Laboratory
Department of Engineering
University of Cambridge
Cambridge, CB3 0DY

ABSTRACT

Accurate knowledge of heat transfer coefficients is critical to the life of turbine components, but remains a challenge with state-of-the-art design methods, necessitating experimental validation. There is a significant body of work on full-field measurements of heat transfer coefficients on stationary vanes and cascades. However, while many *point* measurements using thin-film gauges can be found in the literature, only a handful of *full-field* measurements of heat transfer on rotating blades have been reported.

This work applies a novel phase-based method, which exploits the phase shift between oscillating fluid and wall temperatures, using infrared thermography (IR) to measure full-field heat transfer coefficients on blade tips in a rotating turbine rig. Compared to traditional transient methods, which are based on temperature amplitude, the phase-based method is an order-of-magnitude less sensitive to IR calibration, reflections, and the high noise levels that arise when measuring rotating components. The phase-based method has previously been validated and used to measure heat transfer coefficients in an engine-scaled high-speed turbine stage, but a transient measurement was needed as a reference for the phase shift. In the current work, phase-based measurements are applied with only a time-resolved flow temperature for a reference. Measurement theory is provided alongside numerical analysis of the error sources when applying IR thermography to a *relatively* low temperature rotating turbine blade. Experimental design is described in a medium-speed turbine rig at the Whittle Laboratory, including modular polymer blades, an inlet heater mesh, IR optical access, and data acquisition and synchronisation. Finally, experimental results are shown as Nusselt numbers, demonstrating the phase-based method's ability to resolve differences in heat transfer between tip geometries.

INTRODUCTION

Full-field, rather than point, measurements of heat transfer coefficient are needed on rotating turbine blades to capture the influence of boundary layer transition, tip leakage effects, shock-boundary layer interaction and cooling flows. For this purpose, infrared thermography (IR) is favoured due to its robustness in applications with high rotational speeds and temperatures. However, to capture IR images of moving components with acceptably low motion blur, short IR detector integration times are needed which produce low signal-to-noise ratios (SNR). As a result, to date, fewer than five full-field IR measurements of heat transfer coefficients on rotating blades have been reported in the literature.

To calculate heat transfer coefficients with low SNR IR measurements in an engine-scaled turbine rig, Davis et al. [1] applied a phase-based method, described and validated by Davis and Atkins [2]. When the fluid temperature oscillates at a frequency f, the heat transfer coefficient, h, can be found using the equation

$$h = e\sqrt{\pi f}(\cot\phi - 1)$$

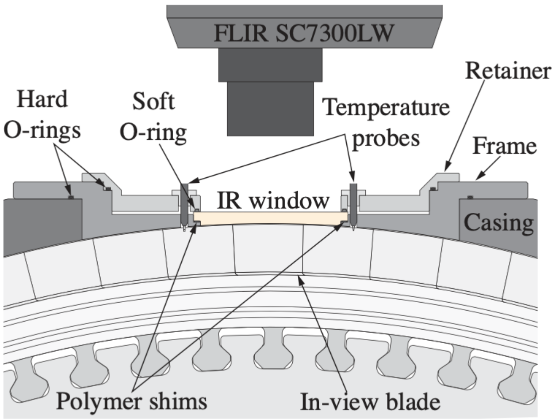
where e is the thermal effusivity of the wall and ϕ is the phase shift between the fluid and wall temperatures, measurements of which, compared to measurements of temperature amplitude, are an order-of-magnitude less sensitive to noise. To calculate true phase shift between fluid and wall temperatures, a reference is needed, and Davis and Atkins [2] showed that this reference can be provided by a sufficiently time-resolved measurement of the flow temperature aligned with IR measurements of the wall temperature. However, time-resolved flow temperature measurements were not available in the high-speed turbine rig used by Davis et al. [1], who instead referenced the phase shift to heat transfer coefficients calculated with a traditional transient method in high SNR regions. In the current work, it is shown how phase-based IR measurements of heat transfer coefficient can be performed in a rotating turbine rig without the need for a transient method, greatly simplifying the experimental procedure to capture full-field heat transfer coefficients on turbine blade tips.

RESULTS AND DISCUSSION

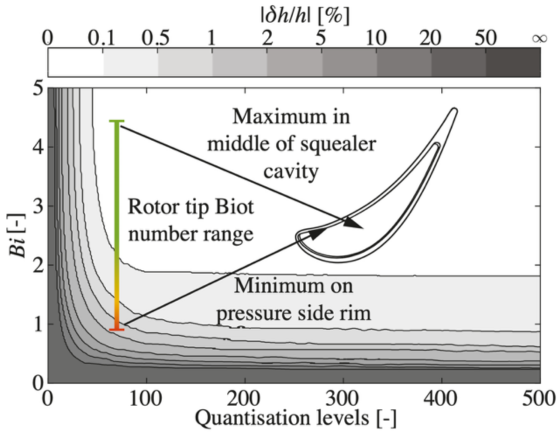
Measurements are performed in the Secondary Air Systems (SAS) rig, a medium-speed, single stage turbine facility at the Whittle Laboratory. Figure 1(a) shows the IR measurement set up. A FLIR SC7300LW IR camera is used with a 10μs integration time to image rotor blades through a zinc sulphide window, custom ground to match the cylindrical profile of the turbine casing. A cold-wire thermometer and a fine wire thermocouple are inserted in the stator-rotor axial gap, providing time-resolved and temperature-accurate measurements, respectively, of the flow temperature at the measurement location.

Figure 1(b) shows contours of uncertainty for heat transfer coefficients calculated with the phase-based method. Biot numbers greater than 1 are critical for low uncertainty, and this is achieved in the SAS rig by manufacturing the blades in two parts: an aluminium root for fixation in the disc, and a polycarbonate, interchangeable aerofoil for low thermal conductivity. Figure 1(b) also shows that at least 50 quantisation levels across the flow temperature range are needed. The radiosity of an emissive surface depends on the fourth power of its temperature, meaning that, compared to engine-scaled turbine rigs that may run with flow temperatures of 400-500K, the near-room temperature of the SAS rig produces 4-6 times less radiative power for an IR detector to measure. To prevent quantisation noise from destroying the measurement, a sufficient flow temperature amplitude is needed. In the SAS rig, this is provided by a copper heater mesh installed in the inlet bell mouth. A total of 60kW of heating power is provided by four DC power supplies, generating a square wave with 12K peak-to-peak amplitude. Example flow and wall temperature signals, measured with the cold-wire and IR camera, respectively, are shown in Fig. 1(c). Also shown is the trigger signal, generated by a rotary encoder and microcontroller, used to synchronise IR camera frames to the rotational speed of the turbine, allowing for an individual blade to be captured in the same location each time it passes the IR window.

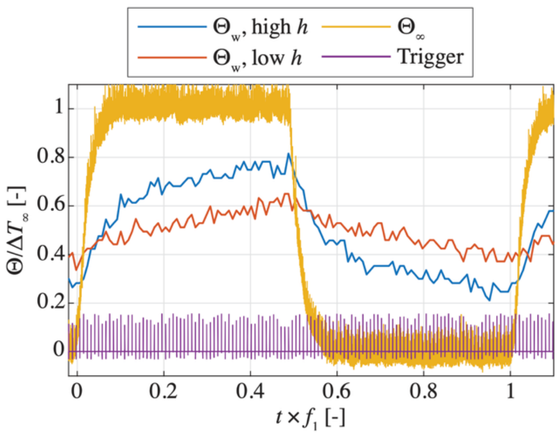
Nusselt numbers calculated from measurements on the squealer tip of a blade are shown in Fig. 1(d). High values can be seen where flow impinges on the floor of the squealer cavity and exits over the aft suction side rim, demonstrating that the phase-based method is able to resolve key features critical to the thermal design of the blade.



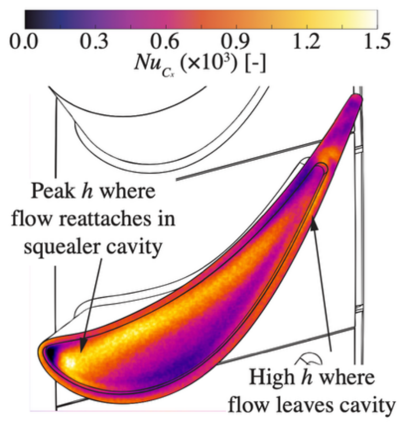
(a) IR measurement set up in the SAS rig



(b) Monte Carlo uncertainty analysis for quantisation error propagation



(c) Flow and wall temperature signals at two points on a blade tip



(d) Nusselt number measurements on turbine blade squealer tip

Figure 1. Phase-based measurements in a rotating turbine rig

REFERENCES

[1] Davis, W., Playford, W., Perrot, A., Hewkin-Greggor, M., Desset, J., Arts, T., Atkins, N. R., 2026, "Infrared Heat Transfer Coefficient Measurements in an Engine-Scaled Turbine Stage," ASME J. Turbomach., 148(4), p. 041013.

[2] Davis, W., and Atkins, A., 2025, "A Phase-Based Method for Measuring Local Convective Heat Transfer Coefficients," Int. J. Heat Mass Transf., 247(1), p. 127116.