A PHASE-BASED METHOD FOR MEASURING LOCAL CONVECTIVE HEAT TRANSFER COEFFICIENTS

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ABSTRACT

In thermally limited components knowledge of local heat transfer coefficients is critical to predict hot spots that constrain part life. Heat transfer measurements must have the spatial resolution needed to resolve the smallest length-scales on components where heat damage occurs, such as cooling holes, trailing edges and squealer rims. Attaining this level of spatial resolution with existing measurement techniques in realistic turbomachinery rigs requires impractical heating power inputs to achieve good signal-to-noise ratio while staying within Fourier number limits. This paper presents a novel measurement technique that utilises the phase shift between wall and fluid temperatures to measure convective heat transfer coefficients. Analysing the response of a wall to a periodic temperature variation allows for measurements with high signal-to-noise ratio at low Fourier numbers. This enables high spatial resolution without the need for large heating power inputs. In this paper the new phase-based measurement technique is developed theoretically, demonstrated numerically and validated experimentally in comparison with existing best practice.

INTRODUCTION

When predicting convective eat transfer local quantities must be captures to identify hot spots that constrain part life. Common heat transfer measurement methods rely on transient techniques where heat transfer quantities are found by measuring the amplitude of the unsteady wall temperature response and fitting the result to a model. To measure local quantities with high spatial resolution it is desirable to use measurements with a low Fourier number, which for a fixed geometry means a short measurement time. Playford (2018) showed that for a given instrumentation type these methods require large flow temperature changes, and therefore large heating power inputs to a rig, to achieve usable signal-to-noise ratios (SNR). SNR can be increased by using longer measurement times, but this comes at the cost of reduced spatial resolution.

This paper introduces a novel measurement method where the phase-shift, rather than the amplitude, of the wall temperature response to periodic heating is used to calculate heat transfer coefficients. It can be shown that heat transfer coefficient h is given by

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

where e is the thermal effusivity of the solid, f is the forcing frequency and φ is the phase shift between the fluid and wall temperatures. By measuring the phase shift with a long periodic signal high SNR can be achieved with small temperature changes and Fourier numbers, allowing for high spatial resolution measurements without impractical power inputs.

RESULTS AND DISCUSSION

Measurements are performed in a heat transfer rig on a series of plates with different geometry. Both transient and phase-based methods are used to compare results. The key enabler of the phase-based is time-resolved measurement of the fluid temperature. Here this is achieved with a cold wire thermometer, while wall temperature measurements are made with an infrared camera. Measurements of fluid and wall temperature are hardware aligned by measuring cold wire voltage and triggering the IR camera from the same analogue I/O device. Phase-based measurements are performed using a 0.2Hz square wave with an amplitude of 5K, requiring 2kW of power input to the flow, while transient measurements are performed with a 50K temperature pulse, requiring 20kW.

Results for Nusselt number over a forwards-facing step are shown in Fig. 1. The data used to the transient measurement is limited to the same Fourier number as the phase-based measurement. The phase-based measurement agrees well with the transient result, both capturing the peak in heat transfer as flow reattaches downstream of the step. A third line is shown in Fig. 1 for a transient measurement performed with 2kW of power input. At this power level the SNR of the transient measurement is too low for accurate measurements, while at the same power the phase-based method remains accurate.

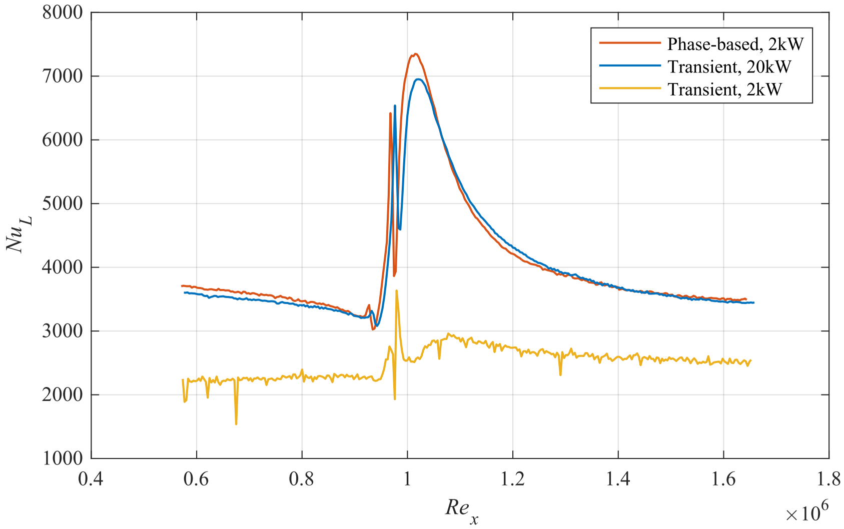

Figure 1. Measurements of Nusselt number over a forwards-facing step with the new phase-based method using a 2kW heat input and the existing transient method using both 2kW and 20kW inputs.

REFERENCES

W. Playford, Well-conditioned heat transfer measurements on engine scale gas turbine rigs, Ph.D. thesis, University of Cambridge (2018). doi:10.17863/CAM.22150.