APPLICATION OF THE TRANSIENT HEATER FOIL TECHNIQUE FOR HEAT TRANSFER MEASUREMENTS

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ABSTRACT

An electrically heated foil glued on top of an acrylic wall is employed to measure convective heat transfer on turbine vane platforms. The use of a heater foil requires specific filtering techniques to obtain the searched quantities – heat transfer coefficients and the heat release from the foil. In this paper, limitations of the transient measurement technique are summarized and discussed. Moreover, a method is presented to assess the conditioning of a transient test for un-cooled configurations. This method can be extended to transient measurements involving advanced film cooling schemes.

INTRODUCTION

In the context of advanced film cooling studies on turbine blades, the well established transient Thermochromic Liquid Crystal (TLC) measurement technique has been successfully applied to obtain convective heat transfer and film cooling effectiveness on airfoil surfaces – see for example Drost and Bölcs (1999) and Wagner et al. (2007). Heat transfer is created by rapidly inserting a pre-cooled turbine blade model into a warmer gas flow. The use of acrylic wall material allows the assumption of one-dimensional heat conduction in a semi-infinitely thick wall. Without film cooling, assuming the heat transfer coefficient to be constant in time, the temperature at the wall surface has the following solution:

$$\frac{T_w - T_i}{T_g - T_i} = 1 - \exp\left(b^2\right) erfc\left(b\right) \tag{1}$$

where *erfc* is the complementary error function and

$$b = \frac{h\sqrt{t}}{\sqrt{krc}}\,. \tag{2}$$

The heat transfer coefficient is defined here for incompressible flow:

$$h = \frac{q_h(t)}{T_g - T_w(t)} \tag{3}$$

The chosen wall material produces time lags of the temperature evolutions that can be conveniently measured with colour cameras in combination with TLC coatings. Narrow band type TLC mixtures indicate well defined temperatures (T_{LC}) corresponding to a specific filtering of the colour spectrum as sketched in Figure 2 (left). Considering the relative ease to implement the technique, together with the affordability of paints and cameras, this technique is attractive for heat transfer and film cooling measurements. The assumption of a semi-infinitely thick wall is only valid until the heat pulse reaches the backside of the wall. Thus the maximum measurement duration is determined by the wall thickness. Schultz and Jones (1973) determined the maximum testing time to:

$$t < \frac{d^2}{16a} \tag{4}$$

Vogel and Weigand (2001) showed that longer times can be allowed under certain circumstances. In the present work, Equation 4 is used as upper time limit due to other constraints treated below.

A variant of the above transient TLC technique has been implemented by Vogel et al. (2003) using an electrically heated foil to achieve the transient heating (Figure 1). An additional unknown, the electric heat release in the foil, is determined by varying the power input in multiple tests and performing a non-linear regression analysis on the measured temperature-time pairs. This gives a reference heat release distribution (q_{ref})

that is scaled in each of the multiple tests by a measured gain factor G with respect to a reference test, usually the one with lowest heating power:

$$q = Gq_{ref} \tag{5}$$

The advantages compared to the insertion technique are twofold; a precise heating step and no need for an insertion mechanism. Therefore, shorter time responses can be measured when employing the heater foil compared to the insertion mechanism.

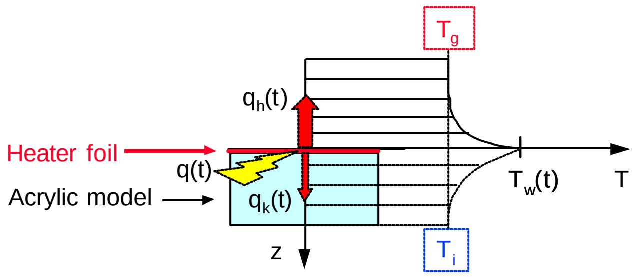

Fig. 1: Heater foil concept.

Due to the new heat transfer situation, the data reduction procedure originally developed for rapid insertion tests require some modifications before application on the heater foil case. This is because the driving temperature difference is now a function of the heat transfer coefficient as seen in the corresponding transient temperature solution:

$$T_w = T_i + q/h \left[1 - \exp\left(b^2\right) erfc\left(b\right)\right] \tag{6}$$

The dependency of the heat transfer coefficient leads to significant variations in the steady-state temperatures that the wall approaches as shown in Figure 2 (right). This effect can be even more important if there are spatial variations in the electrical heat release, e.g. due to cooling holes that alter the heating distribution in the foil. Therefore, a single indication temperature (T_{LC}) will not cover the complete test surface within each transient test, especially if there are large variations in q and h. Fortunately, multiple tests with different heating powers are required to solve for the two unknowns. This means that TLC events can still be obtained over almost the whole test surface in at least two of the multiple tests. In addition, two different TLC paints can be employed in order to obtain more data in each test as shown in Jonsson et al. (2008), effectively reducing the total wind tunnel time.

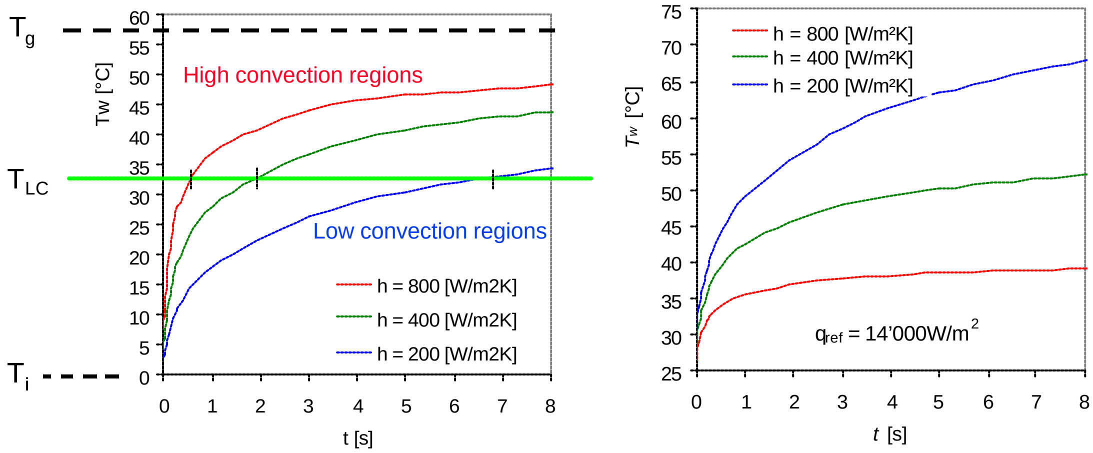

Fig. 2: Theoretical wall temperature evolutions using the rapid insertion technique (left) and, heater foil technique (right).

However, the test method will also capture indications that are no longer transient in nature but too close to steady-state. Moreover, time events captured just before the end of a video sequence will be averaged in an inconsistent manner compared to previous signals. This is typically visible as non-physical contours. Thus, it is essential to define an upper time limit for the transient tests when h is high or q is low, and to filter out non-physical effects. Rearranging Equation 6 into to the form of non-dimensional wall temperature,

$$q \equiv \frac{T_w - T_i}{q/h} = 1 - \exp\left(b^2\right) erfc\left(b\right) \tag{7}$$

shows that the wall temperature evolution in the heater foil situation (Figure 3) is similar to the insertion situation (Figure 2, left). Note that the temperature indications with a single TLC now occur at different non-dimensional temperatures.

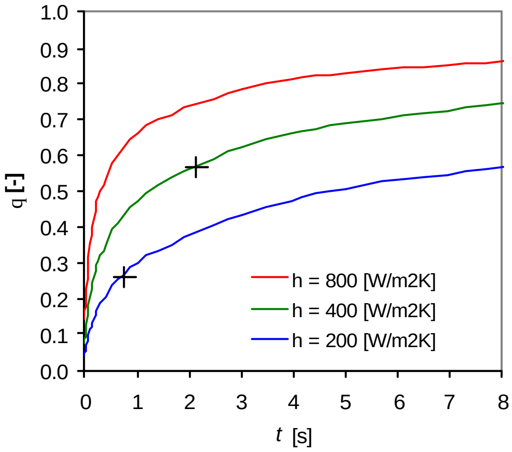

Fig. 3: Theoretical non-dimensional wall temperature evolutions for the heater foil method.

RESULTS AND DISCUSSION

The regression method minimizes the total difference in temperature between measurements and theory in a least square manner. Figure 4 shows the successful matching of q and h (black points) for the measurements averaged on a small region indicated in the contour plot. The regression approach can easily distinguish the correct solution from other combinations of q and h as shown on the left. On the contrary, the graph also show significant offsets if a higher heat transfer coefficient is assigned. In this case, the solution is relatively well defined since the data is nicely distributed on the time axis. Thus, the shape of the temperature evolution can be resolved which produces a stable regression. It is consequently important that the measurement points are well separated in time. Otherwise, the resulting combination of q and h may be ambiguous, leading to significant errors. Fortunately, such errors are typically visible as non-physical patterns in full surface measurements providing a method to verify the quality of the results.

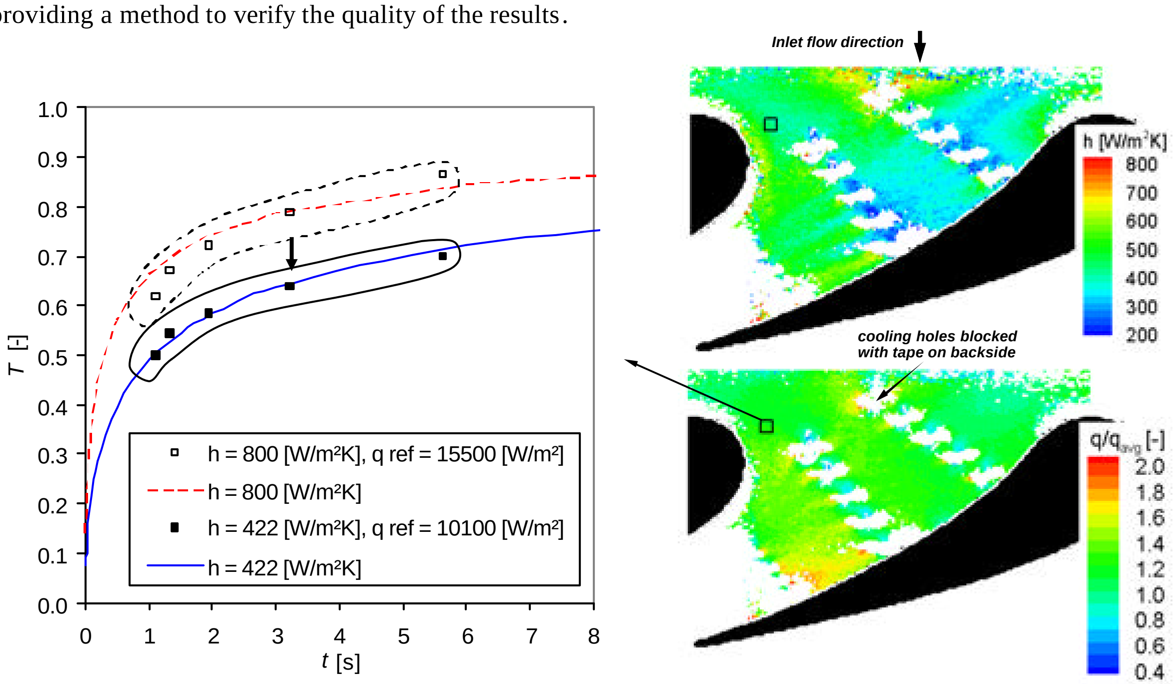

Fig. 4: Example results obtained on the platform near the leading edge of a turbine vane.

Therefore, a conditioning factor is proposed to eliminate results where only a small part of the time axis is covered by measurements. Pixels where the relative distribution of time in the multiple tests is smaller than a certain level are discarded:

Filter out if: $$\frac{s_{t_{LC}}}{\overline{t_{LC}}} < const.,\quad where\quad s_{t_{LC}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(t_{LC,n}-\overline{t_{LC}}\right)^2}\quad and\quad \overline{t_{LC}} = \frac{1}{N}\sum_{n=1}^{N} t_{LC,n} \tag{8}$$

Working with relatively small temperature differences has several practical advantages and it allows the assumption of constant viscosity and conductivity of the flowing gas. Nevertheless, it is important to ensure sufficiently strong heating in regions with high convective heat transfer in order to minimize the impact of temperature uncertainties. On the other hand, when high heating power is employed, the transient signal may appear too fast to be captured by the camera system. With the fast step change in heating power, the minimum testing time is limited by the camera speed and light sensitivity. Moreover, the non-dimensional indication temperature may be too low to yield an accurate transient measurement. In case approximate solutions of q and h are available, the test envelope allows for identification of poorly conditioned data that can be excluded from the non-linear regression analysis. Noise can therefore be reduced.

In the theoretical example with $h = 800\ \mathrm{W/m^2K}$ shown in Figure 4, the temperature evolution approaches steady-state ($q = 1$) relatively fast. After a certain time, the TLC signals no longer give distinct transient information. A method to filter out any data is proposed in the following. The band width of the liquid crystal temperature indication DT_{LC}, is determined by the paint mixture and the subsequent colour filtering of the video sequence. The latter is a compromise between temperature precision and noise as determined by the light sensitivity of the camera system. For a given DT_{LC} the number of time events detected in a video sequence adds up to Dt_{LC} as shown in Figure 5. If Dt_{LC} is longer than a certain value, the point of interest is most likely very close steady state or not precise enough to yield reliable transient results. Therefore:

Filter out if: $$\Delta t_{LC} > const. \tag{9}$$

This filter can be used when the video sequence is long enough to accumulate sufficient number of TLC signals to indicate an emerging steady-state. Figure 5 (left) summarizes the above limits in a transient test envelope:

1. Maximum time t_{max} due to wall thickness constraint (see Equation 4).
2. Minimum time t_{min} depending on the quality of the heating step, camera speed and light sensitivity as well as possible inertia of the TLC molecules.
3. Maximum non-dimensional temperature, indicating that the wall approaches steady-state (requires approximate results a priori).
4. Minimum non-dimensional temperature can be of interest since a low value tends to amplify the impact of time and temperature uncertainties (requires approximate results a priori).
5. Maximum number of time events due to steady-state type results or imprecise time measurement caused by over-tolerant filtering of the TLC colour spectrum. The total time over which the TLC signals are visible can be used to identify such results (see criteria in Equation 9). The application of filters (1) and (5) is explained in Figure 5. Starting with the raw time measurement (a), the constant of filter (5) is set manually for each test (b) since the number of captured time events depends on noise as well as the global heating power. The effect of filter (5) is a gap in the time contours which confirms where filter (1) should be set in order to remove excessively long measurement times (c). This filter does not require any prior knowledge of q and h.

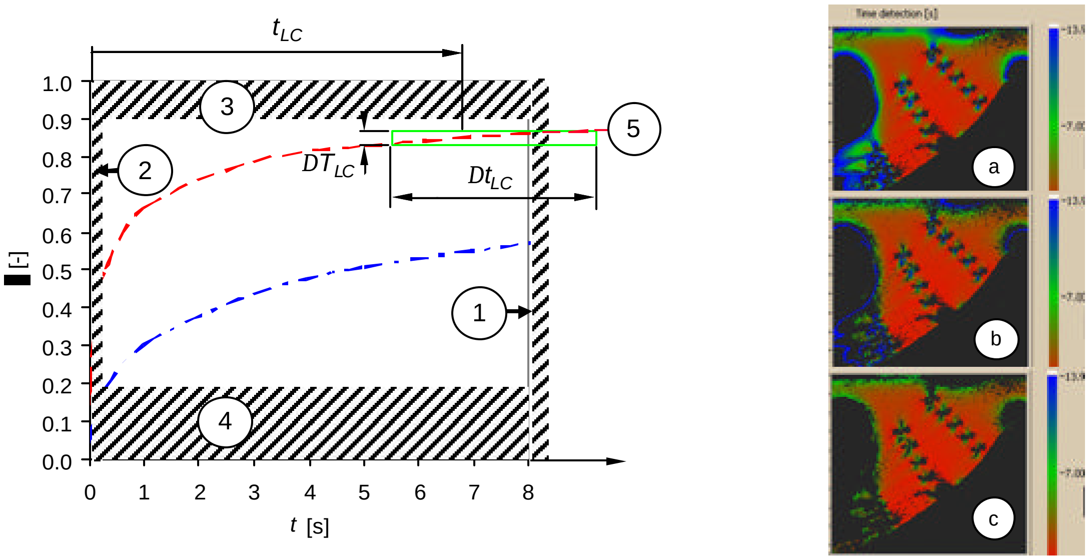

Fig. 5: Transient test envelope with theoretical temperature evolutions (left). Work flow for filters (5) and (1) (right).

6. Mathematical conditioning of the multiple test ensemble (Equation 8).

Altogether, the above listed filters allow for measurement of largely varying values of q and h to be done in the same test. The establishment of the limits can be used as a guideline for test preparations, but also during the actual measurements. Furthermore, by checking the mathematical conditioning of the test ensemble, non-reliable results can be identified in a post processing step.

NOMENCLATURE

c	specific heat of the wall	[J/kgK]
G	electric heating power gain	[-]
h	local heat transfer coefficient	[W/m²K]
k	thermal conductivity of the wall	[W/mK]
N	number of tests	[-]
q	heat flux	[W/m²]
t	time	[s]
T	temperature	[K]
z	wall depth ordinate	[m]

Subscripts

avg	average
i	initial
g	gas flow
h	convection
k	conduction
LC	liquid crystal indication
n	test index
w	wall

Greek Symbols

α	thermal diffusivity of the wall	[m²/s]
β	non-dimensional time	[-]
δ	wall thickness	[m]
ρ	density	[kg/m³]
θ	non-dimensional temperature	[-]
σ	standard deviation	[s]

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