LIQUID CRYSTAL THERMOGRAPHY FOR TRANSIENT HEAT TRANSFER MEASUREMENTS IN COMPLEX INTERNAL COOLING SYSTEMS

Rico Poser* and Jens von Wolfersdorf
Institute of Aerospace Thermodynamics (ITLR)
Universität Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany
(* Corresponding author: rico.poser@itlr.uni-stuttgart.de)

Thermochromic liquid crystals (TLCs) are frequently used as optical surface temperature sensors. Typical applications include the investigation of heat transfer characteristics for cooled gas turbine components using optically transparent models. By applying a suddenly changing fluid temperature to a test specimen, the delayed wall temperature response is visualized by the TLC coating on the surface and observed with a digital color video camera as shown exemplarily in Fig. 1.

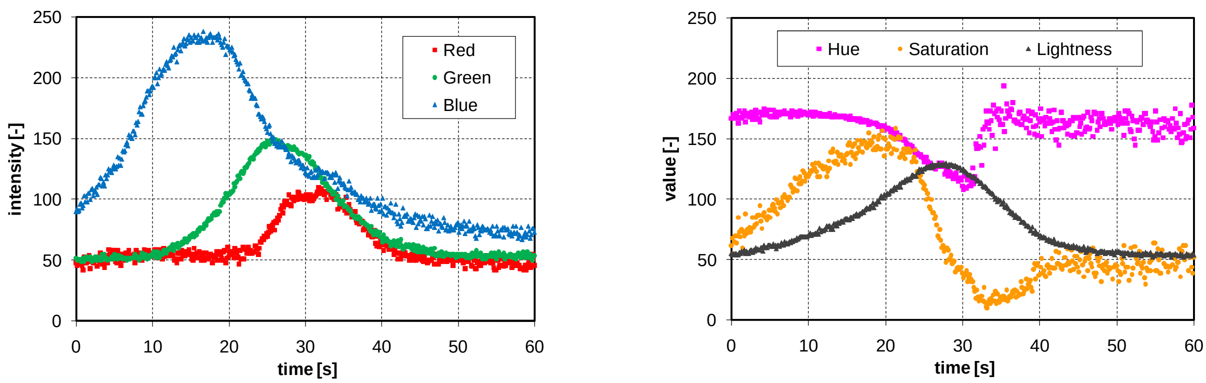

Figure 1: Temporal TLC signals in RGB (left) and HSL (right) color coding during a transient test

Common evaluation techniques associate a calibrated temperature to a unique TLC color or peak intensity and detect the corresponding surface response time. Considering 1D heat conduction in a semi-infinite medium with a convective boundary condition, the analytical solution of Fourier's equation for an ideal step change is given (see e.g. Ireland and Jones [2000], Ekkad and Han [2000]) and can be applied to calculate local heat transfer distributions. Due to the heat exchange between fluid and walls, the fluid temperature is a function of stream-wise position and time ($T_f(x,t)$) for long cooling channels in particular. A common approach to take this local fluid temperature history into account is based on the Duhamel superposition principle, approximating $T_f(x,t)$ by a series of small discrete temperature steps $\Delta T_{f(j,j-1)}(x)$ (see e.g. Ekkad and Han [2000]):

$$T_w - T_0 = \sum_{j=1}^{N}\left[1-\exp\left(\frac{h^2(t-\tau_j)}{\rho ck}\right)\operatorname{erfc}\left(\frac{h\sqrt{t-\tau_j}}{\sqrt{\rho ck}}\right)\right]\Delta T_{f(j,j-1)} \tag{1}$$

Despite the universality of Eq. 1, we consider three classes of applications of the transient TLC technique for heat transfer measurements in internal cooling systems. The first one relates to the

investigation of individual heat transfer enhancement devices using large scale test channels and structures. The second one is represented by large scale simplified cooling passages as parts of more complex overall cooling typical for gas turbine blades. Comprehensive aspects must be considered for the third class of applications – complex cooling systems representative for actual engine designs – as such models need to represent the actual machine geometry including different surface curvature conditions, individual coolant flow distributions, flow extraction locations and small scale features. The size of these models is usually much smaller as in the aforementioned cases due to scaling considerations with respect to engine Reynolds and Mach numbers. Therefore the reliable detection of the TLC indications and the local bulk temperature histories is much more challenging taking the model complexity, lighting and viewing conditions for the differently shaped surfaces, and the need to avoid extensive instrumentation (e.g. thermocouples) in the fields of view into account. Additionally, the local heat transfer coefficients cover a much wider range due to the combination of different heat transfer enhancement methods within the system or mass flow splits for e.g. bleeds, film cooling or dust holes. A typical test model is shown in Fig. 2.
In this respect, state-of-the-art techniques and some novel developments associated with the application of the transient heat transfer measurement technique especially for such complex cooling systems are presented in close and causal connection in this paper.

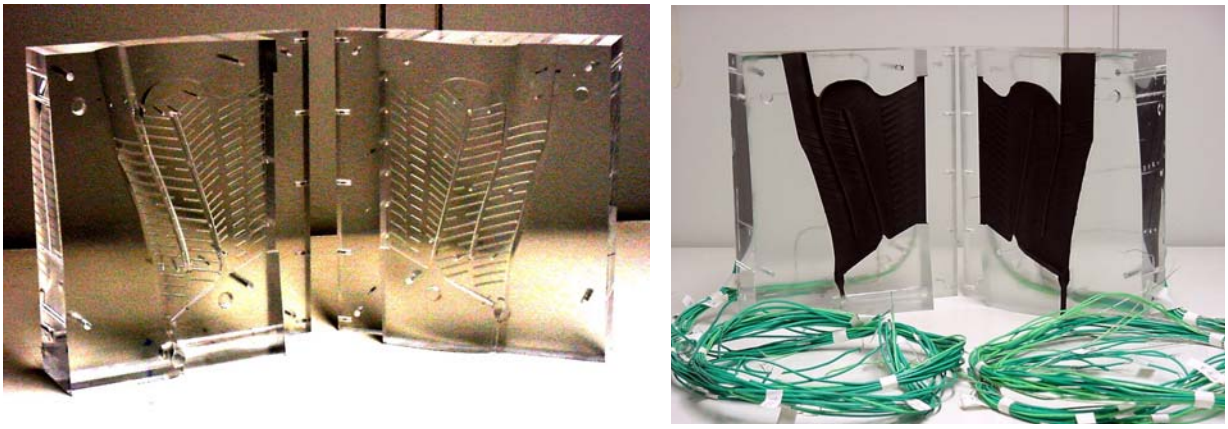

Figure 2: Full cooling scheme model parts for a gas turbine blade as machined from Perspex (left), coated and instrumented model parts (right).

TEST RIG AND BASIC MODEL DESIGN

The experimental setup to perform transient heat transfer experiments for complex cooling schemes is illustrated in Fig. 3 (left). There are two main flow paths for the air supply system. By using an electric heater and a heat exchanger, fluid temperatures between -70°C and +80°C can be provided. The mixing of both flow passages allows for precise temperature settings and a versatile setup for positive and negative temperature steps including realistic temperature gradients as found in real engines.
To achieve a uniformly reflected color spectrum from the TLCs, a warm lighting with a color temperature of ca. 3000K is used. Thereby the usually weak red fraction of the reflected light from TLC is intensified and the often dominating blue fraction is reduced such that the quality of the video recordings could be improved as seen exemplarily in Fig. 3 (right).

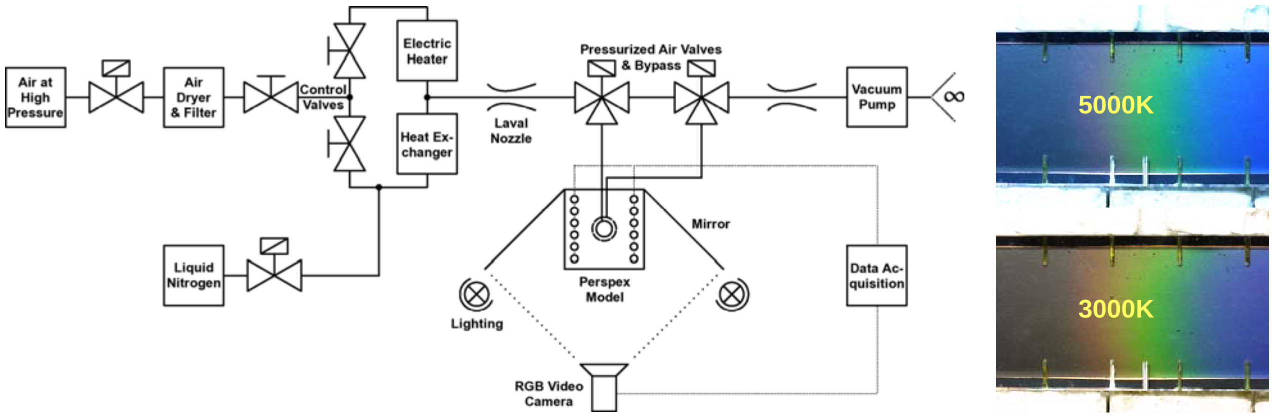

Figure 3: Experimental Setup for Transient Heat Transfer Experiments in Complex Cooling Schemes (left) and impact of color temperature of lighting on TLC observation (right)

TLC INDICATION ANALYSIS

The local wall temperature response time can be determined for a calibrated Hue-value or a maximum intensity value of R, G or B. For complex geometries, a variant of the latter method using the peak in the green intensity history (Gmax) has been found most reliable (Poser et al. [2007]). A background noise detection technique using a neural network is used to calculate the indication probability. Further improvements were found by using the relative signal entropy of each signal as a replacement input to the neural network. Besides ensuring a high quality to detect TLC response times, complex instrumentation region and boundary masks for further processing tasks can be generated automatically by this technique.

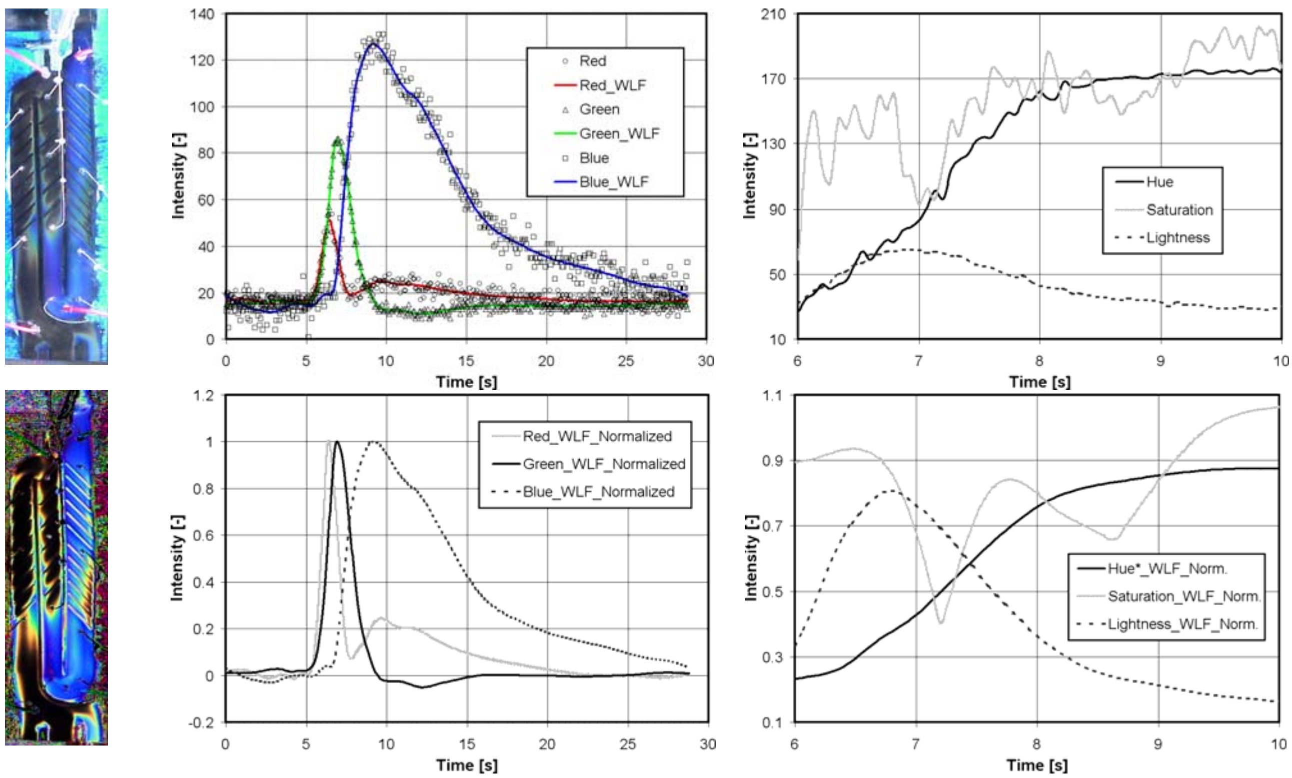

Figure 4: Impact of TLC signal preprocessing on visual perception and signal quality

Comparability and lighting independency is achieved by wavelet filtering and adaptively normalizing the signal histories before further evaluations as shown in Fig. 4. Applying this technique, local uncertainties can be reduced or multiple unknowns can be determined from a set of experiments at varying nondimensional temperature levels.

FLUID TEMPERATURE AND HEAT TRANSFER DISTRIBUTION

Heat transfer coefficients are evaluated according to Eq. 1 by using interpolated local fluid temperature histories. Here, an iterative technique based on the Laplace equation is used to interpolate arbitrary simply connected 2D regions with internal boundary conditions. As there are strong variations in fluid temperature and heat transfer coefficients, multiple experiments with different inlet temperatures should be performed to achieve TLC indications within a certain time interval for different regions. Effects on the uncertainty related to possible errors in liquid crystal thermography (Wiberg and Lior [2004]) will be considered.

CONCLUSIONS

State-of-the-art techniques and some novel techniques to perform transient heat transfer experiments in complex internal cooling systems have been presented in close and causal connection. They are qualified to assess and minimize the uncertainty of this measurement technique.

REFERENCES

Ekkad, S.V. and Han, J.C. [2000], A transient liquid crystal thermography technique for gas turbine heat transfer measurements. *Measurement Science and Technology*, 11, pp. 957–968.

Ireland, P.T. and Jones, T.V. [2000], Liquid crystal measurements of heat transfer and surface shear stress. *Measurement Science and Technology*, 11, pp. 969–986.

Poser, R., von Wolfersdorf, J. and Lutum, E. [2007], Advanced Evaluation of Transient Heat Transfer Experiments Using Thermochromic Liquid Crystals. *Proc. IMechE, Part A: J. Power and Energy*, 221, pp. 793-801.

Wiberg, R. and Lior, N. [2004], Errors in thermochromic liquid crystal thermometry. *Review of Scientific Instruments*, 75(9), pp. 2985-2994.