NOVEL CALIBRATION METHOD FOR AN INFRARED THERMOGRAPHY SYSTEM APPLIED TO HEAT TRANSFER EXPERIMENTS IN HOT CHANNELS

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ABSTRACT

Heat transfer measurements in environments with highly non-uniform wall heat fluxes require high spatial resolution of the measured wall temperatures to capture the complex thermal situation. Infrared thermography systems provide the high spatial resolution, but not necessarily the thermal accuracy. Accounting for the specific optical arrangement they are typically calibrated in-situ by fitting a multi-parameter calibration function. The accuracy of the temperature mappings determined with the IR-equipment strongly depends on the temperature range covered by the provided temperature nodes. Therefore a novel robust in-situ calibration method is introduced, which does not require temperatures over the complete temperature range. The new setup is implemented experimentally, and reference measurements demonstrate the advantages of the new method.

INTRODUCTION

Infrared thermography enjoys more and more great popularity in various applications where high locally resolved temperature distributions are required (Carlomagno 2004). In generic film cooling experiments for gas turbine applications (Schulz 2000) the determination of the correlation between temperature and detected radiation is challenging. Radiation of hot infrared translucent windows, of hot gas and reflections of surrounding walls superimpose with the object signal. Since quantifying the essential radiative parameters is hard to accomplish, the common approach is to calibrate the thermography system in-situ with thermocouples embedded into the object surface. This procedure captures the unknowns and, therefore, guarantees high accuracy as long as temperature nodes cover the whole temperature range. In film cooling applications however, varying coolant mass flow rates change the temperature distribution on the test surface so that the lowest or highest temperature is not naturally covered. Furthermore the surface has to be coated with a high emissive paint, beneath which the thermocouples are placed. If 3d heat fluxes are present, the temperature on top of the coating cannot be determined with the adequate accuracy.

In the present work a novel calibration method is presented where the degree of freedom of the used calibration function is reduced by quantifying the relevant radiative parameters and by increasing the robustness of the thermography system to changes of operating conditions. Consequently, the more physical description allows an enhanced accuracy for extrapolated temperatures. The introduced method is in particular relevant for film cooling experiments run at steady state mode, where typical coolant to free stream density ratios are maintained by elevated free stream temperatures.

The following discussion is based on an InSb-IR-camera system applied to steady state film cooling experiments. The free stream is heated to 500K-550K. The optical access is established by a sapphire window which is heated to the same temperature.

RESULTS AND DISCUSSION

The basic principle of an infrared thermography system is to determine temperatures by measuring the IR-radiant power emitted from the object. Dependent on the spectral radiant emittance $W_{\lambda,b}$, the spectral emissivity $\varepsilon_{\lambda,obj}$, the spectral transmissivity τ_λ, the superimposing radiation $W_{\lambda,s}$ and the responsivity R_λ of the detector the detector signal can be expressed by

$$U_D \propto \int_0^\infty R_\lambda \left(\tau_\lambda \varepsilon_{\lambda,obj} W_{\lambda,b} + W_{\lambda,s}\right) d\lambda \tag{1}$$

The object signal is most significantly altered by the window which transmissivity varies with wavelength and bulk temperature. Fig. 1 shows the spectral transmissivity of sapphire at ambient and elevated temperatures.

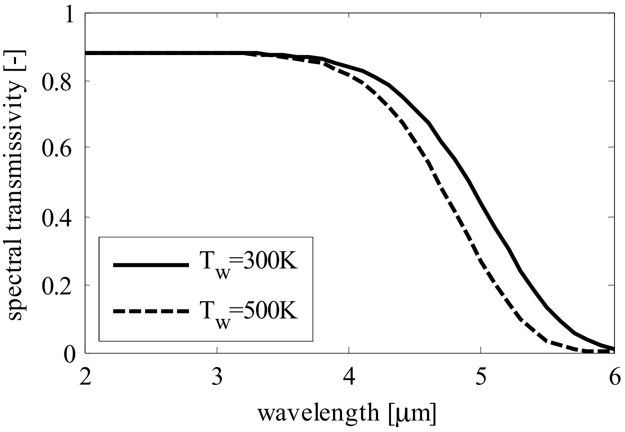


Fig. 1: Spectral transmissivity of sapphire (L=7mm) at different bulk temperatures

The change of spectral transmissivity with temperature is significant in regions of high absorption. If the standard InSb-IR-system is used, integrating between λ_{min}=3μm to λ_{max}=5μm, a high radiation of the window and a reduced mean transmissivity is expected – the radiation-temperature dependence must be determined in-situ by fitting the 4 parameters r, b, f and U_{offset} of eq. 1 (Martiny 1996).

$$T_{obj} = \frac{b}{\ln\left(\frac{r}{U_D - U_{offset}} + f\right)} \qquad \textbf{(2)}$$

If the integration range is limited to λ_{max}=4.05μm by a short-pass filter, the system becomes less sensitive in respect to the operating temperature – the change of mean transmissivity can be reduced by that to 1.5%. This in turn allows calibrating the system at ambient temperatures. According to the applied calibration function (eq. 1) the remaining parameter to be fitted in-situ is U_{offset}, which comprises the radiation of the window, of the hot gas and reflections of the hot surroundings.

The advantages of the method are obvious. The number of free parameters could be reduced from 4 to 1. Since the spectral transmissivities are already captured, extrapolation of the calibration function is possible. In Fig. 2 six value pairs (TC1-TC6) of thermocouple temperatures and the corresponding interpolated detector signals are plotted which were acquired during a typical film cooling experiment at an elevated free stream temperature. The InSb-IR-system integrates up to λ_{max}=5μm. If the 4 parameters of eq. 2 are fitted to all nodes, the overall temperature deviation is RMS=0.32K. Skipping the value pairs TC1 and TC2 for calibration, the fitting is done with the remaining nodes TC3 to TC6. The overall error increases to RMS=5.1K.

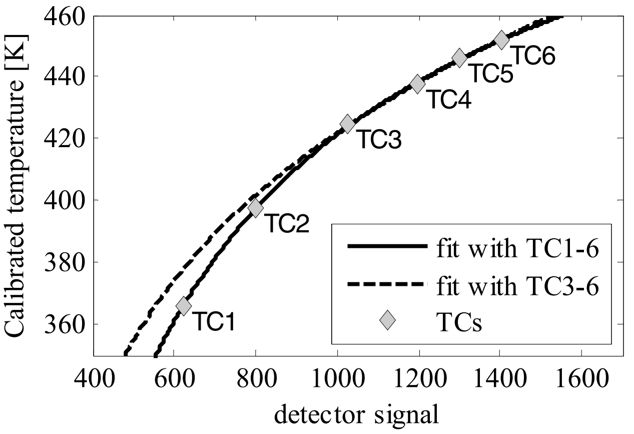


Fig. 2: 4 Parameter fitting, upper integration limit λ_{max}=5μm

Fig. 3 shows the result of the same test case, but applying the short-pass filter and the novel calibration method. If the single parameter is fitted to all value pairs (TC1 to TC6) the error of RMS=0.27K could be obtained. Fitting only with TC3 to TC6 the error merely increases to RMS=0.31K. Comparing the error with that of the 4 Parameter fitting (cp. Fig. 2) the improved accuracy of the new method for extrapolated temperatures could be verified.

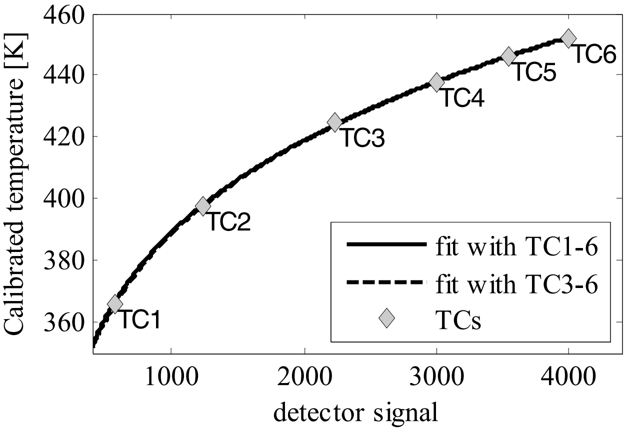
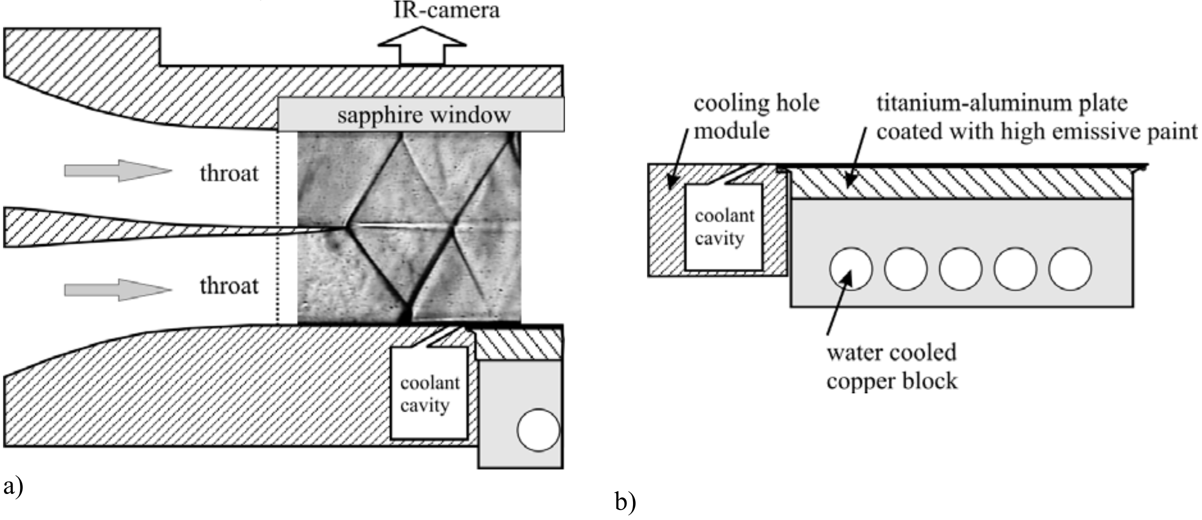


Fig. 3: 1 Parameter fitting, upper integration limit λ_{max}=4.05µm

The novel method is now applied to a film cooling experiment at highly non-uniform wall heat fluxes (Fig. 4). A cooling film is established by inclined cylindrical holes. A coated titanium-aluminum test plate is cooled at the bottom surface enhancing the conductive heat flux. Top and bottom of the test plate are instrumented with thermocouples embedded flush with the metal surface. The upper surface is coated with high emissive paint at low thermal conductivity.



a)

b)

Fig. 4 a) transonic test section b) heat transfer module

Fig. 5 exemplarily shows the detector signal for a selected operating condition. The thermocouple positions are marked by the crosses.

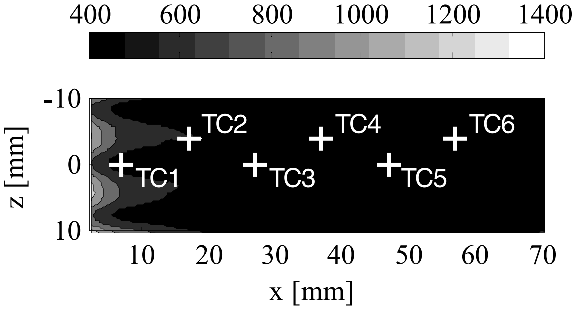


Fig. 5: Detector signal values at high heat flux variations

To verify the calibrated temperature distribution a 3d-heat flux calculation is performed modeling the test plate with the coating. Calculated temperatures below the coating at the thermocouple positions are compared to the corresponding thermocouple values. As shown in Fig. 6 the overall error is RMS=1.23 K. The effect of the 3d-heat fluxes near the cooling holes is impressively shown by additionally plotting the temperatures on top of the coating, determined with a simple 1d-heat flux approximation.

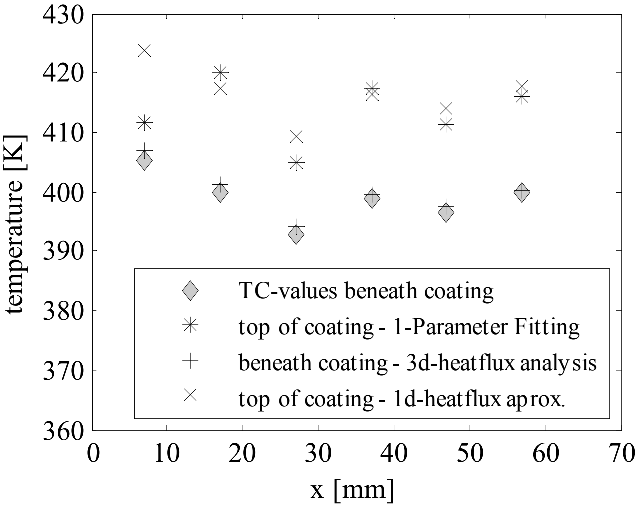


Fig. 6: Temperature data showing the validity of novel method

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