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Optical convective heat transfer measurements using infrared thermography and frequency domain phosphor thermometry

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ABSTRACT

A novel technique for spatially resolved heat transfer measurements is proposed. Utilizing its transmissive properties the temperature distributions at the upper and lower surface of an acrylic glass plate mounted on a heated copper surface are measured. Infrared thermography is employed to determine the external wall temperature. The temperature at the interface between acrylic glass and copper base plate is measured with a thermographic phosphor. The temperature dependent phosphorescence lifetime of the applied $Cr^{3+}:Al_2O_3$ (ruby) powder is assessed using frequency-domain processing of high-speed camera recordings. The measured temperature boundary conditions are used to perform a finite element computation of the conductive heat flux that is imposed by an electric heater. The heat transfer coefficient distribution is corrected iteratively to compensate lateral conduction errors. The newly developed technique is validated by means of jet impingement heat transfer measurements and compared to numerical results and data available in the literature.

1. Introduction

Knowledge of the local heat transfer is essential for the design and further development of gas turbine components like film cooled walls [1]. The heat flux is commonly described by the heat transfer coefficient h (1), which comprises of the heat flux q, the wall temperature T_w and a driving or reference temperature T_r.

$$q = h(T_r - T_w) \tag{1}$$

In general the main flow temperature T_∞ is used as a driving temperature, while for film cooled surfaces the adiabatic wall temperature T_{aw} and for jet impingement the jet temperature T_j are applied. The complex flow field at an actively cooled surface leads to strong spatial variations of the heat transfer and hence requires highly resolved two-dimensional measurements.

Heat transfer coefficients can either be determined through surface temperature measurements or a mass-transfer analogy (e.g. [2]). An extensive overview of heat transfer measurement techniques including exemplary applications is provided in [1]. In the past decades several spatially resolved optical temperature measurement techniques have been developed. Infrared thermography is a straightforward approach since the thermal radiation emitted by the test surface is detected and transformed into a temperature reading. A comprehensive review of the fundamental physics and various applications is provided in [3]. Alternative techniques take advantage of the temperature dependence of optical properties of some materials. Cholesteric liquid crystals are organic substances that selectively reflect different colors depending on their temperature [4,5]. There are narrow band formulas that perform a full color change from blue to red within a temperature range of one Kelvin. Broadband liquid crystals can cover temperature ranges of about 20 K. Temperature sensitive paints (TSP) and thermographic phosphors utilize a process called thermal quenching that affects the light emission of optically active molecules. In case of TSP organic luminescent molecules embedded in a polymer binder are excited by an UV light source and emit a red-shifted fluorescence signal whose intensity decreases with increasing temperature. Details about the technique and an extensive discussion of sources of error and necessary corrections are provided in [6,7].

Different from TSP, thermographic phosphors are crystalline inorganic materials that are doped with transition metals or rare earth elements. After a UV excitation the intensity as well as the decay lifetime of the phosphorescence are temperature dependent. In contrast to liquid crystals and TSP, thermographic phosphors are inert and chemically stable, which is why they are often used for high temperature applications [8,9]. The large number of available phosphors covers a wide temperature range [10]. The good temperature sensitivity and signal intensity make them an attractive alternative to the aforementioned techniques. The phosphor temperature can either be measured with an intensity based or a lifetime based strategy. Since absolute intensity measurements

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Nomenclature

D	nozzle diameter (m)
f	frequency (Hz)
h	heat transfer coefficient (W/(m^2 K))
I	intensity (–)
k	thermal conductivity (W/(m K))
l	distance nozzle – surface (m)
n	index variable (–)
Nu	Nusselt number based on nozzle diameter D (–)
Nu_0	stagnation point Nusselt number (–)
$\overline{Nu}$	spatially averaged Nusselt number (–)
r	radius (m)
Re	Reynolds number (–)
t	plate thickness (m)
t	time (s)
T	temperature (K)
q	heat flux (W/m^2)
v	velocity (m/s)
x, y, z	Cartesian coordinates (m)
λ	wave length (m)
ϕ	phase shift (–)
τ	lifetime (s)
τ	transmissivity (–)
Ω	angular frequency (1/s)

Subscripts

aw	adiabatic wall
em	emission
i	interface
j	jet
w	wall
r	reference
src	source

Abbreviations

CFD	computational fluid dynamics
FEM	finite element method
FFT	fast Fourier transform
IR	infrared
LED	light emitting diode
PMMA	poly(methyl methylacrylate)
PMT	photo multiplier tube
TBC	thermal barrier coating
TSP	temperature sensitive paint
UV	ultra violet

are prone to errors originating from spatial or temporal variations of the illumination, coating thickness and tracer concentration, the intensity ratio of two spectral emission bands is usually used. The emission is imaged through narrow bandpass filters and the measured intensities are divided by each other. Based on a previously acquired calibration curve the ratio can be converted to temperature. This approach requires a phosphor with two sufficiently strong emission bands that feature different temperature sensitivities. Furthermore, two cameras or a stereoscope are needed to simultaneously record the two images. Lifetime based measurements can be conducted in the time- or frequency-domain. For the time-domain approach the phosphor is excited by a short pulse which is followed by an exponential decay of the phosphorescence intensity. If the decay is sampled with a high frame rate camera the lifetime can be determined by fitting a model decay curve, see [11]. In case of the frequency domain approach the phase shift between a sinusoidal excitation signal and the phosphor response is utilized to measure the lifetime [12]. A comparison between the intensity and lifetime based techniques showing the superiority of the lifetime approach is provided in [13]. Compared to all the optical techniques described above the lifetime based approach, especially the frequency domain method, is less sensitive to variations of the viewing angle or distance, fluctuations and non-uniformities of the excitation, spatial variations in the coating thickness or tracer concentration and finally non-linearities of the detection system. The temporal resolution is limited by the lifetime of the phosphor and several periods have to be recorded if the phase shift shall be measured with a good accuracy. The bandpass filter of the detector has to be selected carefully since the method is very sensitive to interference with non-phase-shifted light.

Independent from the temperature measurement techniques, the methods for measuring heat transfer coefficients can be divided in two main categories: steady state and transient techniques [14]. Transient techniques are usually based on the assumption of a one-dimensional heat flux into a semi-infinite wall. The conductive heat flux is calculated from the surface temperature history after a step change of the flow temperature, which can be created in short duration facilities or by sudden heating of the main flow [5]. In contrast to transient approaches steady state techniques require a stationary heat flux through the surface, i.e. heat has to be supplied or removed at the back of the test plate. If Joule effect heating is used to generate the heat flux (e.g. [15]), the electrical power input is a measure of the supplied heat. However, conduction losses and non-uniformities of the heat flux distribution have to be corrected. If convective cooling or heating of the specimens backside is used, the heat flux can be determined calorically or from a calculation of the steady state heat conduction [16]. In the simplest one-dimensional case the calculation of the stationary conductive heat flux requires a second temperature measurement at the rear side of the test surface. Because of the limited access and design constrains in test facilities the backside temperature is often measured with thermocouples. Support structures with a high thermal conductivity can be used to equalize the temperature distribution and create an almost isothermal temperature boundary condition at the bottom of the test plate. However, the thermocouple measurements are at discrete locations and do not offer the high spatial resolution of optical measurement techniques that can be applied at the external surface.

In present study a new approach for measuring the conductive heat flux at a flat plate surface is introduced. The heat transfer coefficient calculation including an iterative correction of lateral conduction errors is explained, followed by a description of the applied measurement and data reduction techniques. Special emphasis is placed on the frequency domain phosphor thermometry approach for measuring two-dimensional temperature distributions. Finally, the new technique is employed for a jet impingement heat transfer study and validated against numerical and literature data.

2. Measurements principle

2.1. Heat flux

In case of one-dimensional conduction the heat flux can be calculated from Fourier's law:

$$q_z = -k\frac{dT}{dz} \tag{2}$$