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Measurement of local heat transfer coefficient on the endwall of a turbine blade cascade by liquid crystal thermography

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ABSTRACT

This paper presents convective heat transfer measurements on the endwall of a turbine blade cascade by means of the liquid crystal thermography. The measurement method is based on the heating, at uniform heat flux, of the endwall by means of an electronic circuit board. The heated region of the endwall surface exposed to the airflow is covered with a thermochromic liquid crystal coating. The colour map of the coating during a given test, featured by an assigned mass flow rate, is measured by using an image processing system. With a prescribed wall heat flux, the convective heat transfer coefficient is obtained, at every pixel location, from the measured temperature maps recorded at the steady-state. Heat transfer results, presented for the endwall of a high-pressure turbine cascade, have been obtained for different values of the Reynolds number. Regions of the endwall surface associated with high rates of heat transfer are well identified: the leading edge of blades, pressure and suction side corners, the blade wake and cascade throat. The spatially-resolved heat transfer measurements presented here could provide a useful baseline for a condition-specific, optimized endwall film-cooling solution that reduces overall heat transfer rates.

1. Introduction

Liquid crystal thermography has emerged as a reliable measurement tool for the determination of surface temperature distributions leading to convective heat transfer coefficients. The advantages of this technique are its flexibility, relative simplicity and low cost. Liquid crystal thermography correlates the colour response to temperature for a heated surface which has been treated with thermochromic liquid crystals (TLCs), complex organic substances that, at a particular temperature, selectively reflect incident light. The wavelength of the reflected light decreases with increasing temperature so that the colour changes from red, through the visible spectrum, to blue. The temperature-sensing ability arises from the molecular structure within the TLCs, which occurs within a temperature range corresponding to a transition between solid and liquid states. In this liquid crystal phase, molecules lose positional order (becoming fluid) but retain orientation order (retaining the optical properties of crystalline solids). The transitional temperature range is called bandwidth and it is conventionally intended as the temperature range between the red start and blue start temperature of the TLCs. There are two types of commercially available TLCs based on their bandwidths, namely narrow-band and wide-band. Narrow-band TLCs typically have bandwidths ranging from 0.5 to 4 °C, whereas wide-band TLCs typically have bandwidths ranging from 5 to 20 °C. Regardless of the type of TLCs, the exhibited colours can be calibrated to a particular temperature by performing a separate experiment.

Many investigators have contributed to the development and application of liquid crystal thermography ([1–8], among the others), making this experimental technique a powerful tool for the investigation of convective heat transfer. Experiments based on the use of TLCs can be classified into two categories: the steady method and the transient method. The steady method is based on the heating, with a prescribed heat flux, of the test surface; as thermal equilibrium is reached, the heat transfer coefficient on the surface can be mapped from a single TLC image. To overcome the problem of limited colour play range, the heat flux into the surface can be adjusted in order to move the colour band to different locations and so progressively map the heat transfer coefficient over the entire test section. In the transient method the temporal evolution of the surface temperature given by TLCs has to be analysed in conjunction with the solution of a transient heat conduction model penetrating to the wall substrate. For instance, if the test surface of a uniform initial temperature is suddenly exposed to a uniformly heated or cooled flow, the magnitude of

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Nomenclature

A	heat transfer surface area (m^2)
C	chord length (m)
C_x	axial chord length (m)
c_p	air specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	air thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Nu	Nusselt number = hC/k
Nu_{avg}	traverse-averaged Nusselt number
q_{conv}	convective heat flux ($W\,m^{-2}$)
q_{el}	electric input power per unit heat transfer surface area ($W\,m^{-2}$)
q_{cond}	conductive heat flux ($W\,m^{-2}$)
q_{rad}	radiative heat flux ($W\,m^{-2}$)
Re	Reynolds number = $U_{exit}C/\nu$
St	Stanton number = $h/(U_0 \rho c_p)$
T_{air}	air temperature (K)
T_{aw}	adiabatic wall temperature (K)
T_w	wall temperature (K)
U_o	mean inlet velocity ($m\,s^{-1}$)
U_{exit}	isentropic exit velocity ($m\,s^{-1}$)
x, y	axial and tangential coordinates (m)

Greek symbols

ν	air kinematic viscosity ($m^2\,s^{-1}$)
ρ	air density ($kg\,m^{-3}$)

the time-varying surface temperature is governed by transient heat conduction into a semi-infinite solid. The solution of the heat conduction problem coupled with the TLC measurements permits the determination of local heat transfer coefficient.

Main features of steady and transient method are provided in several references, see for instance [2,5]. Despite the experimental difficulty to produce a uniform flux density, steady state methods are conceptually simpler and easier to be analysed than the transient methods, which require a more complicated image processing system (several image acquisitions per second are required to detect the time elapsed to locally attain a given temperature). Regardless of the technique (steady or transient) adopted to reconstruct the local heat transfer coefficient, TLC image processing in the 80s and 90s was typically based on visual detection to identify a single colour contour corresponding to a given isotherm. The advent of modern image capturing and processing systems has led to more efficient techniques based on hue-temperature relationship to interpret TLC images [3], thus enabling many isotherms to be simultaneously generated.

Heat transfer experiments in real turbine conditions involve very high instrumentation and operational costs; therefore, heat transfer coefficients are evaluated for low-temperature experiments and results are expressed in non-dimensional parameters (Nusselt, Reynolds, and Stanton numbers) and scaled to actual conditions. First experimental investigations of heat transfer in turbines made use of thin-foil heaters with thermocouples to provide local heat transfer measurements. The test surface is typically equipped with thin stainless-steel foil strips and with thermocouples soldered underneath the surface. As electrical power is delivered to the strips, a uniform heat flux applies to the surface and local heat transfer coefficients at the measurement points can be easily deduced from voltage, current and temperature readings. This standard technique was first employed by Blair [9] for measuring the heat transfer characteristics of the endwall surface of large scale turbine blade cascades and then by Graziani et al. [10] and Takeishi et al. [11], who extended the investigation to the airfoil surfaces.

Some problems involved in the heating foil/thermocouple techniques (heat losses, axial conduction effects, heat transfer coefficient measurements only in discrete points) have been overcome by the mass-transfer analogy technique. A naphthalene surface is cast on the test region and the mass is lost by sublimation during forced convection in analogy with the heat exchanged in heat-transfer experiments. The local mass-transfer coefficient is given by the rate of mass transfer per unit surface area, the local naphthalene vapour density and the density of naphthalene in the mainstream. The heat-mass transfer analogy states that Sherwood number (the dimensionless mass transfer coefficient) is analogous to Nusselt number and thus mass-transfer experiments can be performed to recover the local heat transfer characteristics over the whole region covered with the naphthalene coating. Goldstein and Spores [12] and Goldstein et al. [13] used this method to provide very accurate distributions of the local heat/mass transfer coefficients in a turbine blade endwall and in the near-endwall pressure and suction sides of a turbine blade, respectively.

Thermal imaging methods based on liquid crystal or infrared thermography are nowadays the most popular tools for heat transfer investigations in turbines. First examples of application of liquid crystal thermography to the study of gas turbine heat transfer are provided in [14–17], where the heat transfer coefficients for the endwall of a cascade and for turbine blade airfoils are deduced from a single-colour analysis. More recently, endwall heat transfer was typically investigated by using the infrared thermography as diagnostic tool [18–22]. The use of an infrared camera system requires the optical access to the endwall surface through a special window transparent to infrared radiation, whose costs are relatively high, especially in the case of large dimensions of the test surface to be viewed.

This paper presents the application of liquid crystal thermography, based on the hue analysis, to the study of heat transfer in the endwall region of a large scale turbine cascade. Liquid crystal thermography, in conjunction with the heating at uniform heat flux of the monitored surface, made it possible the determination of local heat transfer coefficient as post-processing output variable of a steady-state thermal experiment.

2. Experimental apparatus and procedure

A pre-packaged TLC sheet, provided by Hallcrest (type R30C5 W), was used for the present study. The TLC sheet consisted of a thin wide-band liquid crystal layer applied onto a thin clear Mylar film and backed with a black background paint and a pressure-sensitive adhesive; according to the producer specifications, the bandwidth is 5 °C, with red start at 30 °C and blue start at 35 °C.

2.1. The calibration experiment

The relationship between the colour and temperature of the thermosensitive TLCs was found by a calibration experiment. The calibration test was carried out by gradually heating an aluminium plate (110 mm × 300 mm × 5 mm) equipped with a plane heater attached to the back face and covered on the frontal face with a liquid crystal film identical to that used in the experiments. The