Available online at www.sciencedirect.com

ScienceDirect

Experimental Thermal and Fluid Science 31 (2007) 381–389

Experimental Thermal and Fluid Science

www.elsevier.com/locate/etfs

Method for analysis of showerhead film cooling experiments on highly curved surfaces

G. Wagner [a,*], E. Schneider [a], J. von Wolfersdorf [b], P. Ott [a], B. Weigand [b]

[a] *Laboratoire de Thermique Appliquée et de Turbomachines (LTT), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

[b] *Institute of Aerospace Thermodynamics (ITLR), University of Stuttgart, D-70569 Stuttgart, Germany*

Received 9 July 2005; accepted 18 May 2006

Abstract

The transient liquid crystal technique has been extensively used for measuring the heat transfer characteristics in gas turbine applications. Thereby, the time evolution of the surface temperature is usually evaluated using the model of a semi-infinite flat plate. For experiments on cylinders, Wagner et al. [G. Wagner, M. Kotulla, P. Ott, B. Weigand, J. von Wolfersdorf, The transient liquid crystal technique: influence of surface curvature and finite wall thickness, ASME Paper GT2004-53553, 2004] showed, that curvature and finite thickness effects can have an influence on the obtained heat transfer coefficients. The aim of this study is to develop a time effective data reduction method that accounts for curvature and that is applicable to film cooling experiments with time varying adiabatic wall temperatures. To verify this method, transient liquid crystal experiments have been carried out on a blunt body model with showerhead film cooling. The experimental data was evaluated with the traditional semi-infinite flat plate approach and with the curvature correction using regression analysis.

Keywords: Transient method; Liquid crystals; Curvature; Film cooling

1. Introduction

The leading edge of an airfoil is exposed to the hot gas flow with very high heat transfer. Therefore this region is very often protected by using several film cooling rows. This cooling scheme – showerhead cooling – can have a variety of arrangements regarding hole angles to the surface, spacings between the holes, number of rows or hole shapes. Many studies have addressed these parameters with the aim to obtain detailed information of heat transfer and film cooling on the full surface, e.g. Mehendale et al. [2], Witteveld et al. [3], Polanka et al. [4] among others. Transient film cooling experiments using Thermochromic Liquid Crystals (TLC) have been performed in this context by e.g. Ekkad et al. [5], Reiss and Bölcs [6], Hoffs et al. [7]. Usually for data reduction purposes, the assumption of a flat surface has been made. Curvature effects can have an influence on the obtained results as shown by Wagner et al. [1] from investigations on a hollow cylinder model. The aim of this study is, to extend this work to a film cooled situation and showing the effect of surface curvature in this application.

2. Experimental set-up

The showerhead cooling experiments were carried out on a symmetric triangular model located in the middle of a rectangular channel. A continuously running compressor supplies the facility with air at $T_g = 50\,°C$ with an incoming Mach number of 0.26 and a Reynolds number based on the leading edge diameter of 6.07×10^4. The dimensions

* Corresponding author. Tel.: +41 (0)21 693 35 39; fax: +41 (0)21 693 35 02.

E-mail addresses: guillaume.wagner@epfl.ch (G. Wagner), itlr@itlr.uni-stuttgart.de (J. von Wolfersdorf).

0894-1777/$ - see front matter
doi:10.1016/j.expthermflusci.2006.05.006

Nomenclature

Bi	Biot number [–]
c	specific heat capacity [J/kg K]
d	hole diameter [m]
D	leading edge diameter [m]
h	heat transfer coefficient [W/m^2 K]
J	number of time steps in the Duhamel superposition method [–]
k	thermal conductivity [W/m K]
K	number of experimental parameters [–]
N	number of experiments used for the regression [–]
Nu	Nusselt number [–]
Ma	Mach number [–]
P	span-wise pitch [–]
$\dot{q}$	heat flux [W/m^2]
R	radius of curvature [m]
Re	Reynolds number [–]
s	coordinate from stagnation point [m]
t	time [s]
T	temperature [°C]

Greek symbols

α	thermal diffusivity [m^2/s]
δ	wall thickness [m]
Φ	overall cooling effectiveness [–]
γ	span-wise exit angle [°]
η	film cooling effectiveness [–]
φ	stream-wise exit angle [°]
θ	row location [°]
Θ	dimensionless temperature [–]
ρ	density [kg/m^3]
σ	curvature parameter [–]
τ	dimensionless time [–]

Subscripts

aw	adiabatic wall
c	coolant
D	based on leading edge diameter
f	film cooled
fp	flat plate
g	hot gas
i	initial
j	time step index
k	experimental parameters index
R	based on radius of curvature
w	wall
0	non-film cooled
δ	based on wall thickness
n	experiments index

Superscript

n	experiments index

of the flow section are 340×99 mm^2 (Fig. 1). As described in Fig. 2, the Perspex test model has two rows of cylindrical cooling holes. CO_2 is used as coolant resulting in a density ratio of about 1.7 at a blowing ratio of 2.2. The sidewall of the test facility is equipped with 5 Perspex windows for optical access. Four miniature 25 Hz color CCD cameras were placed around the model and eight cold light sources were used to obtain a homogenous illumination of the test section.

As shown in Fig. 1, a pneumatic insertion mechanism with a pre-conditioning box was used to generate the transient experiment. During the pre-conditioning period, the Perspex model is removed from the main flow channel and cooled in the pre-conditioning box with impinging jets of cold air. The coolant flow is by-passed and its mass flow rate and temperature level are adjusted. The temperature of the test model is measured by 10 thermocouples. When the model has reached the desired temperature level (T_i

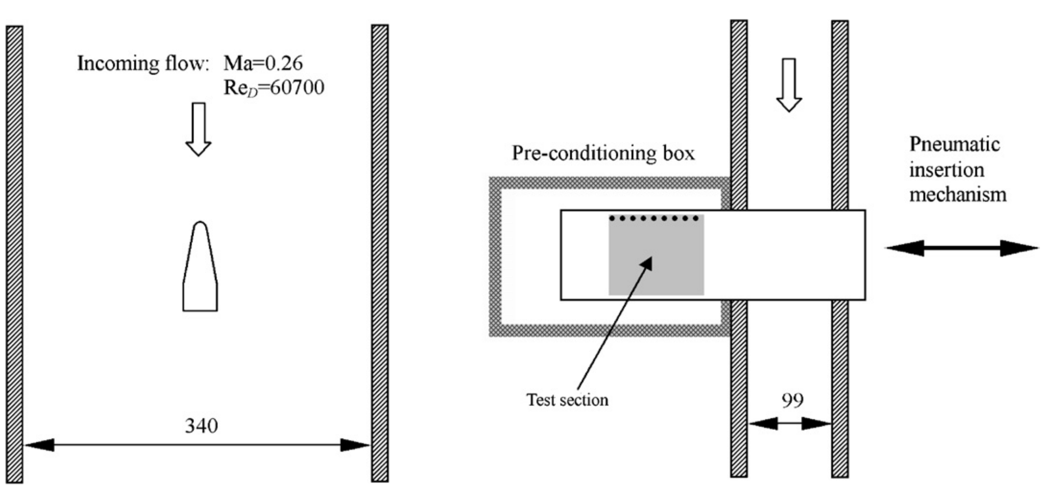

Fig. 1. Test facility with rapid insertion mechanism.