A POST PROCESSING PROCEDURE FOR THE EVALUATION OF ADIABATIC AND OVERALL EFFECTIVENESS OF EFFUSION COOLING GEOMETRIES

Bruno Facchini, Lorenzo Tarchi, Lorenzo Toni
Dipartimento di Energetica “S. Stecco”
Università degli Studi di Firenze
Via S. Marta, 3
50139 Firenze, Italy
+39 055 4796618
lorenzo.toni@htc.de.unifi.it

ABSTRACT

The measurement of adiabatic effectiveness of effusion cooling geometries is made complex by the presence of a relevant heat sink effect, due to both high porosity and length over diameter ratio, even if a very low conductivity material is employed in manufacturing test samples.

A full 3D FEM post-processing procedure has therefore been developed for a proper evaluation of the remainder and undesired thermal fluxes that are inevitably present during an effusion cooling experimental survey and that could easily invalidate adiabatic effectiveness measurements. Such procedure is based on a dual experiment performed on both a low and a high conductivity test sample representing the same cooling geometry. Overall effectiveness has been instead evaluated by means of the wall temperature distribution of the high conductivity plate only.

NOMENCLATURE

BR	Blowing Ratio ($\rho v_c / \rho v_{main}$)	*[-]*	**Subscripts**	
D	Cooling hole diameter	*[mm]*	ad	Adiabatic test
HTC	Heat transfer coefficient	*[W/(m²K)]*	aw	Adiabatic wall
k	Thermal conductivity	*[W/(mK)]*	c	Coolant
L	Hole length	*[mm]*	cond	Conductive test
Ma	Mach number	*[-]*	main	Main flow
q	Heat flux	*[W/m²]*	hole	Hole interior
S	Pitch	*[mm]*	in	Hole inlet
T	Temperature	*[°C]*	ov	Overall
v	Velocity	*[m/s]*	w	Wall
x	Abscissa along the plate	*[mm]*	x	Streamwise direction
y	Spanwise location	*[mm]*	y	Spanwise direction

Greeks

α	Cooling hole effusion angle	*[deg]*
η	Effectiveness	*[-]*
ρ	Density	*[kg/m³]*

INTRODUCTION

An improvement in overall efficiency and power output for gas turbines, whatever their application, can be achieved increasing firing temperature; an effective cooling scheme is then necessary to keep components safely below their melting points and, at the same time, to minimize the required coolant mass flow rate.

Effusion cooling (or full-coverage film-cooling), consisting of an array of closely spaced discrete film-cooling holes, is a very powerful way for the aforesaid requirements fulfillment. Even if this solution does not guarantee the excellent wall protection achievable with film-cooling, the most interesting aspect is the significant effect of wall cooling due to the heat removed by the passage of coolant inside the holes (Gustafsson [1], Arcangeli et al. [2]). In fact, such a huge number of small holes, uniformly distributed over the whole surface, permits a significant improvement in lowering wall temperature. From this point of view, effusion can be seen as an approximation of transpiration cooling through a porous wall, with a slight decrease in performance but without the same structural disadvantages and the real problems related to pores occlusion.

The major benefit related to the holes heat sink effect, turns into a problem when the adiabatic effectiveness of a given cooling scheme is to be evaluated. Indeed, the fact that no material can be identified as a literally adiabatic one, the significant porosity and the high holes length over diameter ratio, make experimental tests carried out on samples having a very low conductivity to suffer from conductive phenomena.

The aim of this paper is then to discuss a post-processing procedure for the obtaining of adiabatic effectiveness values from gathered experimental data.

Procedure has been developed and successfully tested on an effusion cooling array, with a feasible arrangement for a turbine endwall. As a matter of fact, due to its large area exposed to hot gas coming from the combustor, that are moreover moved towards it by secondary flows, and owing to the horseshoe vortex decreasing film cooling efficiency near the leading edge of the platform, the topic of endwall region cooling has recently come into great prominence.

RESULTS AND DISCUSSION

An experimental investigation has been set up for the evaluation, by means of a steady state TLC technique, of the adiabatic and overall effectiveness distributions, as defined in equations 1.1 and 1.2, of an effusion cooling array, representative of a HP stage turbine endwall.

$$\eta_{aw} = \frac{T_{main} - T_{aw}}{T_{main} - T_c} \qquad 1.1 \qquad\qquad \eta_{ov} = \frac{T_{main} - T_w}{T_{main} - T_{c,in}} \qquad 1.2$$

Chosen configuration is a flat plate with 98 holes having a diameter D = 1.40 mm, arranged in 15 staggered rows with equal spanwise and streamwise pitches ($S_x/D = S_y/D = 8.0$), a length to diameter ratio of 42.9 and an injection angle of 30 degrees. Experimental survey has concerned two different samples representing the same effusion cooling scheme, one made of quasi-adiabatic material (Poly Vinyl Chloride), the other realized in high conductivity material (AISI 410 stainless steel), whose thermal conductivity are, respectively, k_{ad} = 0.177 and k_{cond} = 24.9 W/(mK). Tests have been performed imposing a blowing ratio of 1.0 and setting the mainstream Mach number at 0.15. Regarding the employed test rig, a detailed description can be found in Facchini et al. [3].

Figure 1a shows the raw bidimensional effectiveness distribution obtained for the PVC sample, abscissa x/S_x = 0 corresponds to first hole axis. The evident non zero effectiveness values even upstream the first row and the halos surrounding the holes, meaning the subsistence of a heat sink effect inside them, are a clear consequence of the aforesaid issues.

A further post-processing of measurements we are in possession of, is thus required for an appropriate and thorough evaluation of heat conduction through the plate. A full 3D FEM procedure has hence been developed to post-process the gathered experimental data and then to get the adiabatic effectiveness values. It is an iterative procedure that consists of two subsequent steps: the first (*adiabatic step*) to be carried out on the adiabatic sample, in a similar way to that reported in Brauckmann and Wolfersdorf [4], the following on the conductive one (*conductive step*).

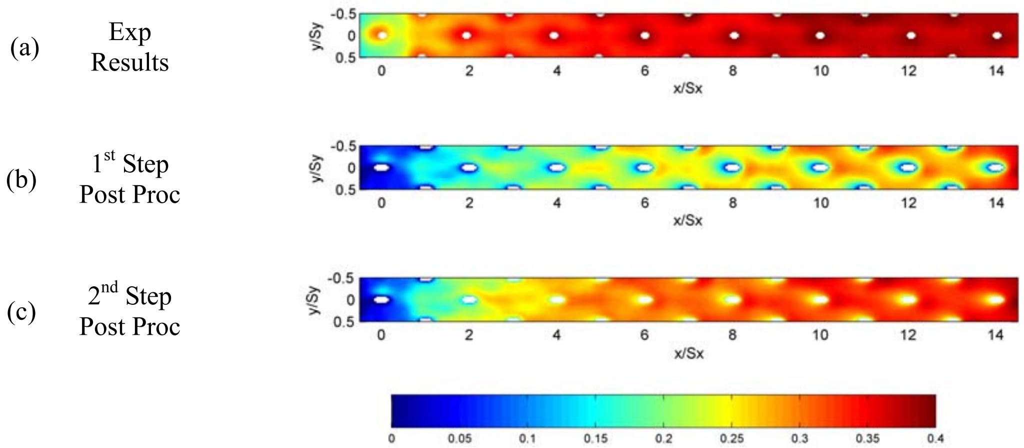

Fig. 1: Effectiveness Map – PVC Sample

Adiabatic Step Post-Processing

The objective of the adiabatic step post-processing is the evaluation of the thermal fluxes across the plate, that clearly wouldn't be present in an ideal adiabatic case, and the obtaining of a consistent value of heat transfer coefficients of both mainstream flow and holes interior. Coolant temperature rise, that is reported as it flows through the holes, is evaluated as well. Steady state FEM calculations were performed using the commercial code ANSYS®11. A spanwise pitch width periodical section of the tested geometry has been meshed with 200000 elements, imposing adiabatic boundary conditions upstream and downstream the plate; sample housing has been modeled too.

Boundary conditions on the FEM model were imposed as follows:

- Hot gas side: TLC experimental map (T_{wall}) imposed as wall temperature.
- Holes interior: a convective load is applied. HTC_{hole} evaluated via a proper correlation for turbulent flows and T_{hole} deriving from measured values inside the plenum. Air temperature rise inside each hole was taken into account implementing an iterative procedure.
- Coolant side: a convective load is applied. Heat transfer coefficient was fixed at 5.0 W/m^2K and coolant temperature deriving from measured values inside the plenum. Anyway, this thermal load has a very low influence on the final result as the temperature difference between coolant and surface is negligible.

In order to reckon the adiabatic wall temperature and then the adiabatic effectiveness, an HTC_{main} value is necessary as well. A transient test has then been performed in the same hot gas flow conditions of the effectiveness test but without coolant injection being not possible having the same temperature step on both flows. This measurement provided an HTC_{main} value (indicated as HTC_{main0}) that can be properly applied upstream the first hole only: actually, during an effectiveness test, coolant injections lead to a significant heat transfer variation, whose certain increase is not evaluated at all during the transient test. HTC_{main} value will then be checked once again during the conductive step.

It's hence possible to reckon the bidimensional distribution of the thermal fluxes on the test surface, having the same spatial resolution of the assigned T_{wall} map. Then, adiabatic wall temperature can be calculated as:

$$T_{aw}^{I} = T_{wall} + \frac{\dot{q}}{HTC_{main}} \qquad 1.3$$

that can be employed in Eq.1.1 for the evaluation of adiabatic effectiveness. As denoted by the superscript, such results are to be refined: actually they will be among the input data of the subsequent conductive step.

The bidimensional distribution depicted in Fig. 1b and the blue line in Fig. 2, show the results obtained following the adiabatic post-processing. Let's focus on the region upstream the first injection (i.e. $x/S_x < 0$) where heat sink is the only effect accountable for $\eta \neq 0$. As clearly shown by the aforementioned figures, assumptions made on HTC_{hole} (which is actually the only value not been measured, but evaluated through correlations) appear consistent, leading to null values before the first row.

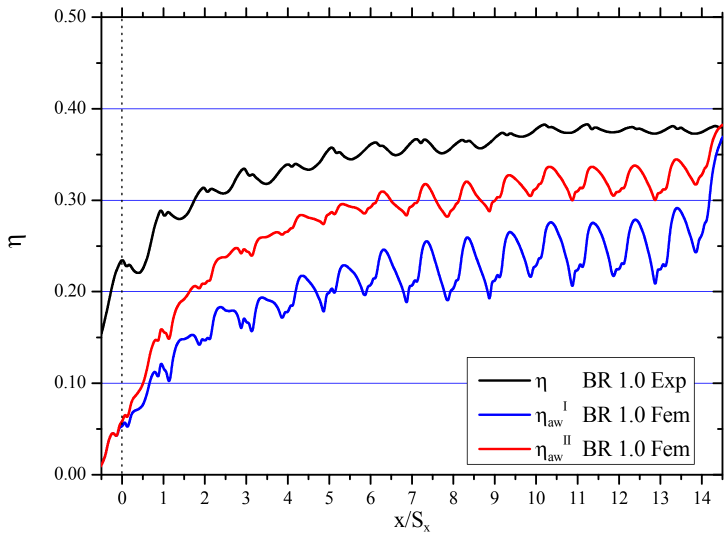

Fig. 2: Spanwise Averaged Effectiveness

Conductive Step Post-Processing

Results deriving from adiabatic step post-processing, namely adiabatic effectiveness distribution and mainstream heat transfer coefficient, are employed within the conductive step of the global post-processing procedure (Fig. 3). They are indeed initialization data, being their values to be revised by means of an iterative calculation.

- Conductive FEM calculation is initialized with η^i_{aw} and HTC_{main0} from adiabatic step and with measured mainstream and coolant temperatures.
- FEM simulation provides a wall temperature distribution to be compared with performed measurements.
- In case, HTC_{main} is revised; changes in heat transfer parameters obviously affect adiabatic effectiveness as well.
- The new η^{i+1}_{aw} is used to re-initialize ANSYS® run.
- Convergence is achieved when the maximum error on wall temperature is below measurement uncertainty range $\Delta_{meas} = \pm 0.5$K.
- η_{aw} and HTC_{main} are finally got.

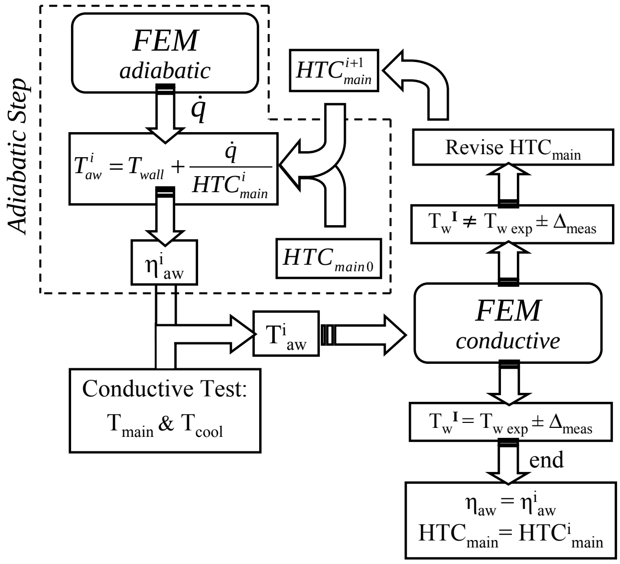

Fig. 3: Iterative Procedure

Experimental results deriving from conductive test are plotted in Fig. 4 using the overall efficiency definition (Eq. 1.2). Besides spanwise averaged η_{ov} values obtained by means of TLC, Fig. 4 collects the ones measured through a set of seven T-type thermocouples housed in dead holes 1 mm below the cooled surface.

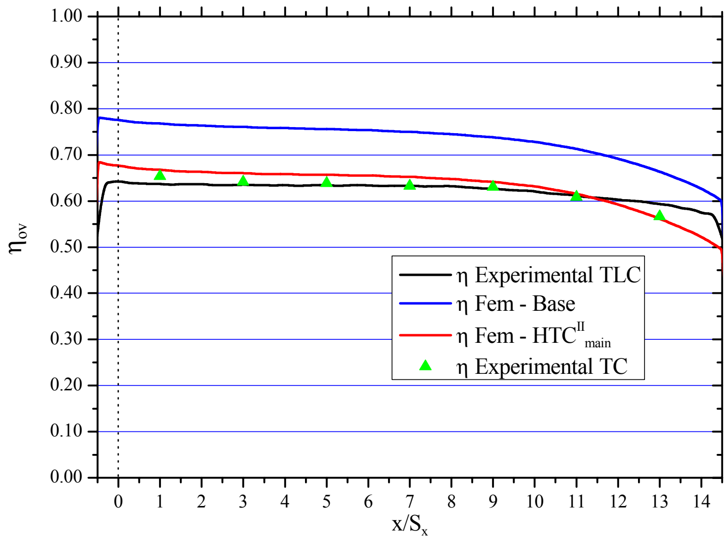

Fig. 4: Spanwise Averaged Overall Effectiveness

Looking at the plotted data, the agreement between the measurements got via the two different techniques (i.e. TLC and thermocouples) is absolutely displayed; differences arising for $x/S_x > 13$ are ascribable to an inadequate TLC illumination of the final region of a so wide test plate. The blue line in Fig. 4 represents the overall effectiveness predicted by FEM calculation initialized with the adiabatic step output. The underestimation of wall temperature after the first iteration is blatant, and there is hence the need of operating a correction on HTC_{main} for the following run: in particular it has to be increased. The possibility of lowering HTC_{hole} has been considered, but not adopted at all, as upstream the first injection a zero spanwise averaged effectiveness has been obtained within the adiabatic step by means of smooth duct correlations.

Hot gas side heat transfer coefficient has therefore been enhanced: it has been maintained unchanged, and consequently equal to the value previously measured with transient test without film injection (HTC_{main0}), upstream the first row, then linearly increased up to 100% more up to the fifth hole and then kept constant (Fig. 5). Such a variation does not amaze at all: as can be found for example in Han et al. [5], in Baldauf et al. [6] and Sen et al. [7], a 15% heat transfer coefficient increase is wholly plausible in the first diameters downstream a single row of film cooling holes.

Moreover, Kelly and Bogard [8], even though the full coverage configuration they analyzed had different geometrical features, found, in the fully developed region, a 60-80% HTC augmentation with respect to the values obtained without film injection.

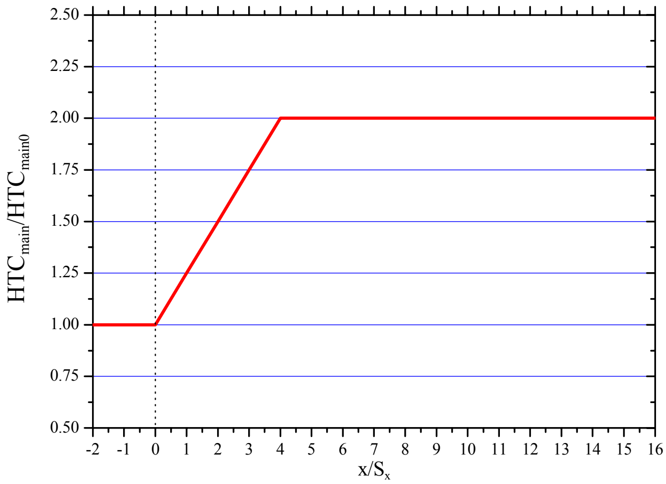

Fig. 5: Mainstream Flow Heat Transfer Coefficient Increase

When setting the shape of HTC_{main}/HTC_{main0} the most logical choice was to adopt an effectiveness-like trend, thus reaching a sort of asymptote after five-six rows, with an about 15% row-by-row literature confirmed increase. With such a law, roughly applied as a spanwise averaged trend, the adiabatic effectiveness distribution deriving from the adiabatic step has been updated and has become the map depicted in Fig. 1c (also represented by the red η^{II}_{aw} line in Fig. 2). FEM calculation has hence been re-initialized with the just obtained η^{II}_{aw} and HTC^{II}_{main}: predicted wall temperature now falls in the ±0.5K error band and convergence is achieved; the updated overall effectiveness plot is shown in Fig. 4.

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