PRESSURE SENSITIVE PAINT (PSP) AND TRANSIENT LIQUID CRYSTAL TECHNIQUE (TLC) FOR MEASUREMENTS OF FILM COOLING PERFORMANCES

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ABSTRACT

External film cooling on nozzle guide vanes and blades is an efficient way to protect turbine parts against hot gas temperatures (TIT). Numerical simulations are yet not accurate enough as they are not able to take into account the various parameters influencing the film-cooling performances. For these reasons experiments with accurate film cooling effectiveness measurement techniques are required. In this paper, a new measurement technique for the film-cooling performances is proposed. It is based on the use of the Transient Liquid Crystal technique (TLC) combined with the Pressure Sensitive Paint measurement technique (PSP). Experiments on a film-cooled flat plate are presented and the results of the new method are compared to the classical TLC technique using multiple experiments and a regression analysis. Reliable film-cooling performances are obtained with the new method.

INTRODUCTION

Modern gas turbines are becoming more efficient by working at higher gas temperatures. Therefore, extensive cooling of components such as turbine vanes, blades and/or platforms is absolutely necessary. Usually, a combination of internal and external cooling is employed. The latter consists in injecting cool air into small holes drilled on the surface in order to generate a so-called “cooling film”. Because of the importance of film cooling for turbine blade design, the subject has been extensively studied over the past 35 years (Goldstein 1971, Leontiev 1999). Film cooling investigations have been carried out on flat plate configurations (Forth et al. 1980 and Sinha et al. 1990) as well as on airfoil type flows (Ito et al. 1978, Takeishi et al. 1992 and Vogel 2002). Numerical methods and correlations have been developed to predict the adiabatic film cooling effectiveness and the increase in heat transfer coefficients. Several models can be found in literature and are used for specific applications only (Gard 1997 and Weigand et al. 1997). High uncertainties still persist for the local heat transfer coefficient and film cooling effectiveness and exact prediction of the resulting material temperature is difficult. For design purpose, it is of great importance to have detailed knowledge of film cooling performances -film cooling effectiveness and heat transfer coefficient- in complex flow situations such as film cooled turbine blades.

Transient liquid crystals (TLC) experiments can already provide good quality heat transfer results (e.g., Vedula et al., 1991). In order to be more accurate, a new approach presented in this paper consists of combining results of transient liquid crystals with pressure sensitive paint (PSP) measurements. Both techniques are based on optical measurements; hence, they are able to obtain results on the whole two–dimensional test surface.

The measurements sequence consists of two parts. The first part is performed with the PSP technique where the pressure sensitive paint is applied on the surface. The film cooling effectiveness is obtained. The second part is performed with the TLC technique, where the liquid crystal coating is applied on the test section. Combining the results of the two parts yields the heat transfer coefficient. By combining the data of the two experiments it is then possible to provide more accurate results of the film cooling performances.

NOMENCLATURE

BR [-]	blowing ratio
c_p [J/(kgK)]	specific heat at constant pressure

C [%]	oxygen concentration
D [m]	film cooling hole diameter
G [-]	gain factor
h [W/(m²K)]	convective heat transfer coefficient
I [lux]	fluorescence intensity
k [W/mK]	thermal conductivity
L [m]	wall thickness
p [Pa]	pressure
P [m]	pitch cooling holes
q [W/m²]	surface heat flux
T [K]	temperature
t [s]	time
x,y [m]	surface coordinates on the plate

Greek

α [m²/s]	thermal diffusivity $\alpha=k/(\rho\, c_p)$
η [-]	film cooling effectiveness
ρ [kg/m³]	density

Subscripts

0	initial condition (*t*=0)
air	air injection case
aw	adiabatic wall
f	film cooled
LC	liquid crystal
N2	nitrogen injection case
O2	oxygen
rg	recovery gas
tg	total gas
tc	total coolant
w	wall

TEST FACILITY

Experiments have been carried out in an open low speed wind tunnel as represented in Fig. 1. The air flow is generated by two fans mounted in series followed by a settling chamber and a convergent nozzle. The channel at the exit of the nozzle has a squared cross-section of 100 mm x 100 mm and a total length of 1500 mm. In order to have good optical access and low thermal conductivity, the walls of the channel were made out of Perspex.

The flat plate test section of L=25 mm thickness and 250 mm length covering the width of the channel (100 mm) was mounted into the bottom wall of the channel at 10 hydraulic diameters from the inlet. Introducing a small geometrical step at the start of the test section guaranteed a turbulent boundary layer. The test section is film-cooled by a row of five cylindrical holes, having an exit angle of 30° to the surface. The holes have a diameter of D=5 mm and the ratio between the holes length L_D and the diameter is L_D/D>3. The five holes are centered in the transversal (spanwise) direction of the channel with a pitch of P/D=3.5. The row in the longitudinal (streamwise) direction is located at 30 hole diameters after the start of the plate as shown in Fig. 2.

The plenum chamber for the coolant flow injection is mounted on the lower side of the test section. The coolant blowing ratio is adjusted by measuring the mass flow given by a graduated glass flow meter. The temperature of the coolant flow can be varied by an electrical heater tube. A by-pass vane allows the preconditioning of the flow before the transient test. The coolant flow temperature during the experiment is measured by a thermocouple inserted in the plenum chamber. Thermocouples located under the upper surface of the plate measure the initial surface temperature.

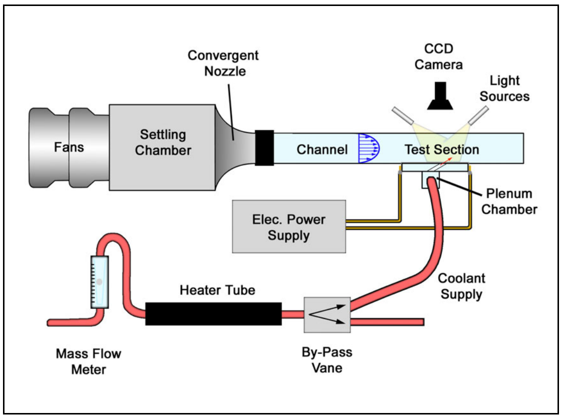

Fig. 1: Schematic drawing of the test facility.

Downstream of the cooling holes, a heater-foil of 20 µm thick nickel-chrome material was glued onto the surface. The foil has been connected to a power supply device through copper cables and bus bars mounted longitudinally to the plate forcing a transversal electrical current in the foil.

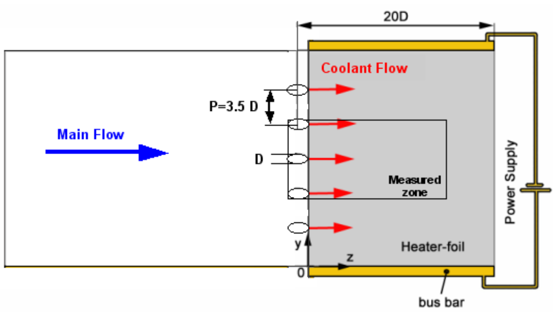

Fig. 2: Configuration of the Film cooled flat plate with heater-foils.

MEASUREMENT TECHNIQUES

Transient liquid crystal techniques

The transient measurement technique consists of monitoring the surface temperature evolution in time triggered by a heat pulse. In the present paper, the heat pulse is generated by an electric heater-foil on the surface (Vogel et al. 2002).

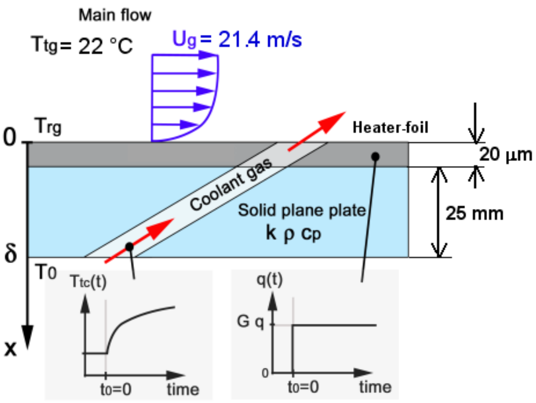

Fig. 3: Schematic drawing of the considered flat plate experiment.

The case of a film-cooled flat plate with a single row of cooling holes as shown in Fig. 3 is considered. At t_0=0, a step change in the surface heat flux *q(t)* is generated by the heater-foil and at the same time coolant gas is injected at a constant blowing ratio but with a temperature evolution $T_{tc}(t)$. The heat flux and the coolant temperature vary as follows:

$$\begin{cases} q(t \le 0) = 0 \\ q(t > 0) = G\,q \end{cases} \tag{1}$$

and

$$T_{tc}(t) = a\,e^{bt} + ct + d\sqrt{t} \tag{2}$$

Where G stands for a gain with respect to a "reference" heat flux q, and a, b, c, d are constants fitting the measured temperature evolution.

The adiabatic wall temperature T_{aw} can be expressed in a dimensionless form, by the introduction of film cooling effectiveness:

$$\eta = \frac{T_{aw} - T_{rg}}{T_{tc} - T_{tg}} \tag{3}$$

As detailed in Vogel et al. 2002, the equation describing the temporal evolution of the surface Temperature during the transient test can be written as:

$$T_w(h_f, \eta, q) = A(h_f) + \eta B(h_f) + qC(h_f) \tag{4}$$

where:

$$A(h_f) = T_0 + \left(T_{rg} - T_0\right)\left[1 - e^{\beta^2} erfc(\beta)\right]$$

for $b \ge 0$

$$\begin{aligned} B(h_f) = {} & -T_{tg}\left[1 - e^{\beta^2} erfc(\beta)\right] + \\ & + \frac{h_f}{k}\left[\frac{a \cdot e^{b \cdot t}}{2}\left\{\frac{\sqrt{\alpha}}{\frac{h_f}{k}\sqrt{\alpha} + \sqrt{b}} erfc\left(-\sqrt{b \cdot t}\right) + \frac{\sqrt{\alpha}}{\frac{h_f}{k}\sqrt{\alpha} - \sqrt{b}} erfc\left(\sqrt{b \cdot t}\right)\right\} - \frac{\alpha\, a}{\frac{h_f}{k}\alpha - \frac{kb}{h_f}} e^{\beta^2} erfc(\beta)\right] - \\ & - \frac{h_f}{k}\left[\frac{c}{\alpha\left(\frac{h_f}{k}\right)^3}\left(e^{\beta^2} erfc(\beta) - \sum_{r=0}^{2} \frac{(-\beta)^r}{\Gamma\left(\frac{r}{2}+1\right)}\right)\right] + \\ & + \frac{h_f}{k}\left[\frac{d\sqrt{\pi}}{2\sqrt{\alpha}\left(\frac{h_f}{k}\right)^2}\left(e^{\beta^2} erfc(\beta) - \sum_{r=0}^{1} \frac{(-\beta)^r}{\Gamma\left(\frac{r}{2}+1\right)}\right)\right] \end{aligned}$$

when b<0, the term of *B(h_f)* in {} becomes:

$$\left\{\frac{\sqrt{\alpha}}{\frac{h_f}{k}\sqrt{\alpha} + \sqrt{b}} erfc\left(-\sqrt{bt}\right) + \frac{\sqrt{\alpha}}{\frac{h_f}{k}\sqrt{\alpha} - \sqrt{b}} erfc\left(\sqrt{bt}\right)\right\} = \left\{\frac{2\sqrt{\alpha}}{\left(\frac{h_f}{k}\right)^2 \alpha + b}\left(\frac{h_f}{k}\sqrt{\alpha} + 2\sqrt{\frac{-b}{\pi}}\left(\int_0^{\sqrt{-bt}} e^{t^2} dt\right)\right)\right\}$$

$$C(h_f) = \frac{G}{h_f}\left[1 - e^{\beta^2} erfc(\beta)\right]$$

and $\beta = \left(\frac{h_f}{k}\right)^2 \alpha\, t$

Γ is the gamma function and *erfc* is the complementary error function.

For the transient liquid crystal tests, narrow band thermo-chromic liquid crystals are applied on the surface. Cold light sources are used for the illumination of the test section. A 25 Hz color CCD camera mounted perpendicular to the flat plate records the color play of the liquid crystal coating. The time t_{LC} can be obtained by performing a data reduction of the hue signal (Camci et al. 1991 and Wang et al. 1994). The three unknowns q, h_f and η present in (4) are then solved by a multiple-regression analysis applied to typically eight to ten different transient experiments with identical aerodynamic and thermal conditions except for the coolant gas temperature (*a, b, c, d*) and the surface heat flux (G). This method has been used on a high-speed linear cascade by Vogel 2002 and proved to give reliable results. Thus, it will be considered as a reference measurements technique for comparison with the new measurement method combining PSP and TLC techniques. Note that in the present case, the test facility is working at low speed and no correlations or data were found in the literature for further validation of the new technique.

PSP techniques

Pressure sensitive paint techniques are based on oxygen-quenched photoluminescence. After being illuminated by a suitable light source, the PSP coating emits light which intensity depends on the oxygen partial pressure of the surrounding gas (Steiner 2000). PSP is sprayed on the surface and a pulsed high-pressure xenon lamp is used for the illumination. The light emission acquisition is done by a 1024x1024 scientific grade 16-bit CCD camera. Pressure measurements can be expressed as a function of the light emission I:

$$\frac{p_{O2}}{p_{ref}} = CA(T) + CB(T)\frac{I_{ref}}{I} + CC(T)\left(\frac{I_{ref}}{I}\right)^2 \quad (5)$$

Where I_{ref} is the intensity of the light emitted at the reference pressure p_{ref}. $CA(T)$, $CB(T)$ and $CC(T)$ are the calibration coefficients of the PSP. A second order polynomial function is used to describe the temperature dependence $CA(T) = a_0 + a_1{\cdot}T + a_2{\cdot}T^2$. These nine calibration coefficients can be obtained by calibrating the PSP at various pressures and temperatures.

The PSP technique can be used for two different applications:

1. Measurements of the pressure of a gas containing oxygen if the oxygen concentration is known, for instance air: $C = 21$ %.
2. Measurements of oxygen concentration if the pressure distribution of the gas is known.

Using the PSP measurement technique, film cooling effectiveness can be obtained by comparing the partial pressure of O_2 on the surface in a case with air injection and in a case with N_2 injection. During the PSP measurements, the power supply remains switched off and there is no electric current in the heater-foil.

A first test is performed with air injection and a PSP image is taken. As the concentration of O_2 in air is known (about 21 %), the static pressure on the surface, P_s can be obtained.

A second test is carried out at the same blowing ratio and flow conditions as the first test except that N_2 is injected instead of air. Since N_2 density is very close to air density, it is assumed that the static pressure on the surface in this second test is equal to the pressure measured in the first test (p_s). A PSP image is taken and, as the pressure distribution is known, the oxygen concentration on the N_2 film cooled surface can be obtained.

In the case of incompressible flows, according to the heat and mass transfer analogy, the local film cooling effectiveness can be expressed in terms of oxygen concentrations (Pederson et al. 1977 and Ito et al. 1978). If the coolant contains no oxygen, as it is the case with N_2 injection, the film cooling effectiveness becomes:

$$\eta(x,y) = 1 - \frac{C(x,y)}{C_\infty} \quad (6)$$

where $C(x,y)$ is the concentration of O_2 on the film cooled surface and C_∞ is the concentration of O_2 of the main flow. This method has been used by Zang et al. in 1999 on a film cooled turbine vane.

Yielding:

$C_\infty = 21\,\%$, $C = \dfrac{p_{O2,N2}}{P_s}$ and $p_s = \dfrac{p_{O2,air}}{0.21}$

$$\eta = 1 - \frac{p_{O2,N2}}{p_{O2,air}} \quad (7)$$

As the PSP is very sensitive to temperature variations, air and N_2 gas injections should preferably be made at the same temperature level as the mainstream temperature T_{tg}. At least care has to be taken for having the same injected gas temperature of air and of N_2.

PSP and TLC combination

Both methods described above for film cooling measurements contain disadvantages:

- The TLC technique needs multiple experiments which implies small variations in the coolant gas temperature and thus in the density ratio between coolant and mainstream. Moreover, carrying-out about ten different TLC tests, reducing the data of the video sequences and performing the regression analysis is rather time-consuming.

- The PSP technique provides only the film cooling effectiveness and gives no information about the heat transfer coefficient.

A solution to get rid of the disadvantages of each method is to combine both of them and to perform the experiments in two parts. The first part using the PSP technique with pressure sensitive painting applied on the surface. This gives the film cooling effectiveness η as described above. For the second part of the method, liquid crystals are applied on the test section and only one transient test is performed. As the film cooling effectiveness is known from the PSP measurements only 2 unknowns remain in equation (4): q and h_f. The surface heat flux q can be numerically simulated. In the present case, the heater-foil is rectangular and contains no holes. Hence, the electric current in the foil is considered homogenous as well as the local surface heat flux. If the geometry of the heater-foil is more complex (curved boundaries or presence of cooling holes) q can be obtained using Joule's equation and a numerical simulation of the electric current distribution (Vogel 2002). Then, only the heat transfer coefficient h_f remains unknown in equation (4) and it can be solved with one TLC experiment only. Fig. 4 summarizes schematically the combination of the TLC and PSP methods.

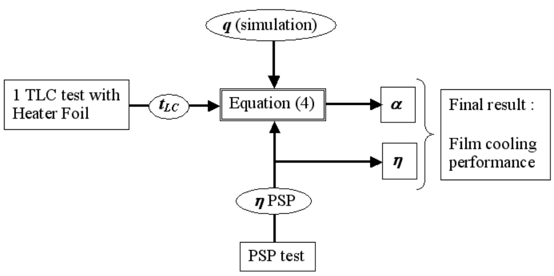

Fig. 4: PSP-TLC combination: method diagram

RESULTS AND DISCUSSION

Film cooling performance measurements have been performed with TLC and PSP techniques on the film-cooled flat plate for a main flow velocity of 21.4 m/s and total gas temperature of ~24°C. The initial temperature of the test surface was in the same range.

TLC with heater foils

Nine transient tests were carried out with the TLC technique for a blowing ratio set to 0.30. The three unknowns q, η and h_f were solved by the multiple regression analysis. More details concerning the description of the results are given in Vogel 2002.

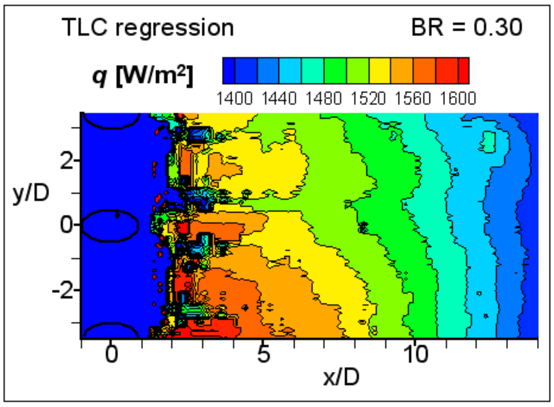

Fig. 5: Reference heat flux distribution obtained from the TLC multiple regression analysis.

The reference heat flux q obtained by the regression is presented in Fig. 5. The effective surface heat flux generation applied during each experiment is then the product of q by its gain factor G_i. Theoretically the heat flux should be homogenous on the surface, but the measured heat flux showed a gradient in the streamwise direction. This is certainly due to imperfect electric connections between the heater-foil and the bus bars.

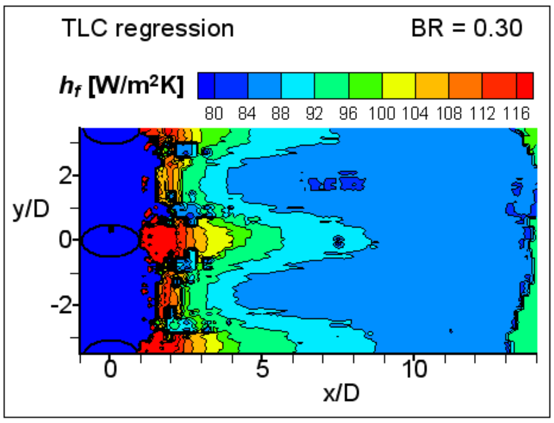

Fig. 6: Heat transfer coefficient distribution obtained from the TLC multiple regression analysis.

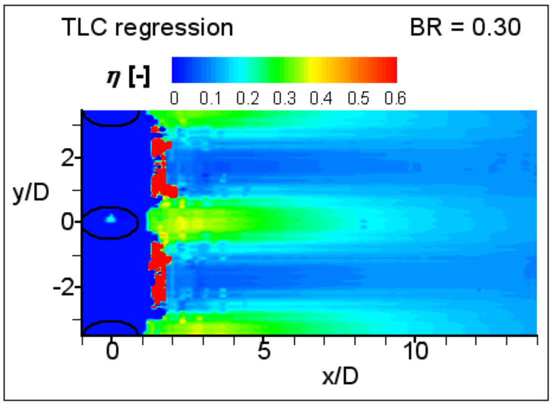

Fig. 7: Film cooling effectiveness distribution obtained from the TLC multiple regression analysis.

Fig. 6 shows the distribution of the heat transfer coefficient. There is a slight increase of h_f behind the cooling holes, which is a consequence of the increase in turbulence due to the cooling flow injection. It can be noted that, close to the downstream border of the foil ($x/D>13$), the results are not reliable because they have been influenced by a lack of t_{LC} signal detection during the multiple test experiments. The same remark is also valid for the region located just behind the cooling holes ($1<x/D<2.5$).

The film cooling effectiveness distribution is shown in Fig. 7. As expected, it reveals an increase of η behind the cooling holes.

It can be noticed that the results of the TLC technique with a multiple regression analysis are globally not very smooth. This is due to the noise present in the time signal (difficulty to detect t_{LC} from the evolution of the hue signal).

PSP results

Measurements were carried out with the PSP technique for five different blowing ratios (BR=0.07, 0.13, 0.26, 0.40, 0.53). Unfortunately the same blowing ratio as used for the TLC measurements (0.30) has not been tested. For each blowing ratio, two tests were performed, one with air injection and one with Nitrogen injection.

Fig. 8 compares the TLC and PSP spanwise averages of the film cooling effectiveness downstream of the cooling holes. Except close to the holes (x/D<1.5), the PSP results are smooth. They are coherent compared to typical trends found in the literature (Baldauf et al. 1997 and Drost et al. 1997). When the blowing ratio is increased the normal momentum of the coolant at the hole exit becomes higher and tends to drive the coolant away from the wall. As a result, the mixing with the mainstream is increased and the fraction of coolant remaining on the wall surface is reduced behind the holes. Consequently the film cooling effectiveness is also reduced. Further downstream the globally higher quantity of coolant produces a better film cooling effectiveness.

The results of the TLC method are also coherent with the trends found in the literature but contain more noise particularly behind the holes. As noted above this is due to the lack of t_{LC} signal detection in this region during the multiple test experiments. It should also be noticed that with the configuration used for the TLC measurements (Fig. 2), no signals can be measured between the holes since the upstream border of the heater-foil is located just downstream of the cooling row.

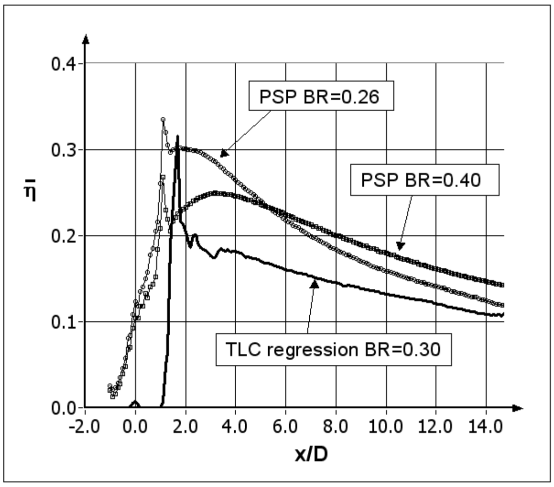

Fig. 8: Spanwise average of the film cooling effectiveness. TLC and PSP results comparison.

The difference between the TLC and PSP results is quite important. It is maximum close to the holes (about 30%) and decreases down to ~15% at $x/D \geq 10$.

The film cooling effectiveness distribution obtained with PSP is represented in Fig. 9. It shows an excellent signal to noise ratio. The resolution of 8 [pixel/mm^2] gives very detailed and smooth information on η. The results are in good agreement with the film cooling theory. At the hole exit, η=1 and between the holes, η=0. Downstream of the holes η decreases because of the mixing with the mainstream and becomes more and more homogenous in the spanwise direction as x/D increases. Note that the vertical line that can be seen at x/D = 1.4 is caused by the border of the 20µm thick heater-foil.

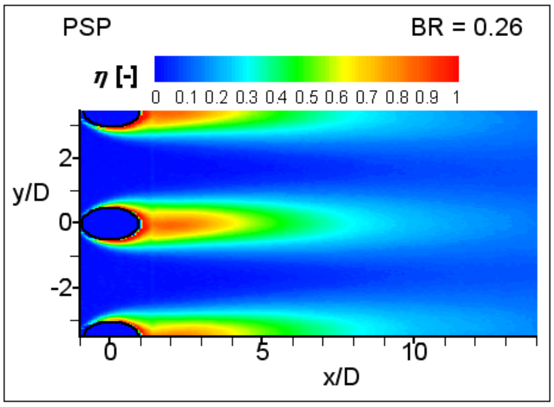

Fig. 9: Film cooling effectiveness distribution obtained by the PSP measurements.

PSP and TLC combination

As shown in Fig. 4 the single TLC test has to be combined with q and η in order to yield the heat transfer coefficient h_f.

	q	η
Case 1	From TLC regression	From TLC regression
Case 2	From TLC regression	From PSP measurements
Case 3	From simulation: q=1500 [W/m2]	From PSP measurements

Table 1: Variable combinations of the different cases.

In order to test the new method and to better understand how each of these two inputs (q and η) influences the calculation of h_f, three computation methods are used. The first computation is performed using the surface heat flux and the film cooling effectiveness obtained by the TLC regression. The second calculation is performed with η obtained by the PSP measurements. The third calculation is done using the surface heat flux resulting from a simulation. In the present case with a rectangular foil q is constant over the surface (q = 1500 [W/m^2]). Table 1 summarizes the three cases. Note that case 1 and 2 are taking into account the non-homogeneities of the surface heat flux due to imperfect electrical connections

The heat transfer coefficient calculated in case 1 is shown in Fig. 10 and proves to be very close to h_f obtained by the TLC regression. The difference is only about 1.5 +/- 1 %. This is in accordance to the fact that both input variables are coming from the TLC regression. This case can be considered as a proof of the regression analysis exactitude.

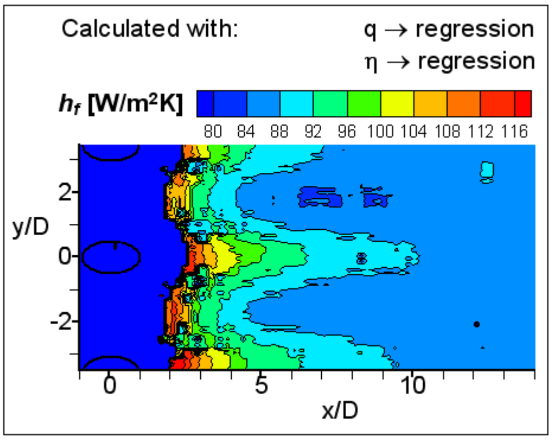

Fig. 10: Distribution of the heat transfer coefficient calculated in case 1.

The heat transfer coefficient obtained in case 2 shows also a very good agreement with the results of the TLC regression (Fig. 11). The difference is of the same order as in case 1, only about 1.5 +/- 1 %. In spite of the big difference between the film cooling effectiveness used in case 1 and 2 (about 25%), h_f from case 1 and case 2 are almost similar. It shows that η has minor influence on the heat transfer coefficient determination. This can be explained by the fact that the coolant temperature during the single TLC test chosen for these calculations was very close to the mainstream temperature. In such temperature conditions, the film cooling effectiveness had only very little influence on the evolution of the surface temperature. It is to note that if $T_{tg} \neq T_{tc}$ during the single TLC test, the error on h_f is in the same order as the error on η (about 25 % in the present instance).

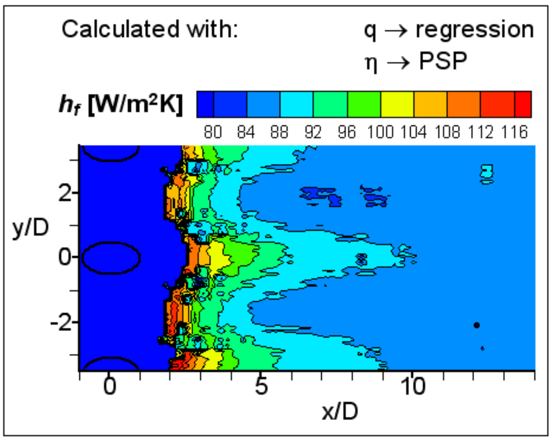

Fig. 11: Distribution of the heat transfer coefficient calculated in case 2.

This result is of primary importance. The error in the determination of η and the error in the determination of h_f are separated one from another. The inaccuracy on η is only due to the PSP method and the inaccuracy on h_f is only due to the TLC method as long as the single TLC test is done with the condition $T_{tg} \approx T_{tc}$.

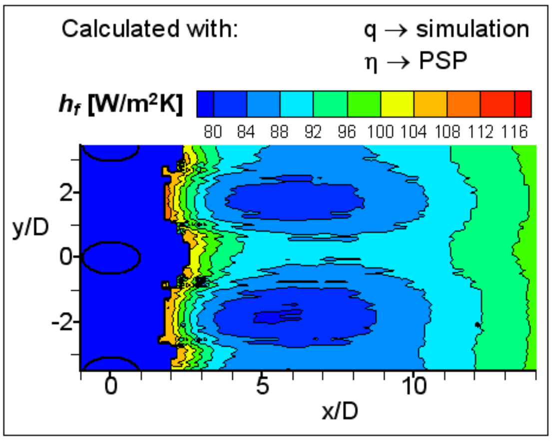

Fig. 12: Distribution of the heat transfer coefficient calculated in case 3.

In case 3 the surface heat flux used as input is given by a computed simulation based on an analytical solution. The heat transfer coefficient obtained is represented in Fig. 12. In comparison with the cases 1 and 2, case 3 shows a much bigger difference with the results given by the TLC regression (more than 10% in some regions). This can be explained by the fact that the q distribution is not homogenous on the surface during the heater -foil test. Indeed, Fig 4 shows that q actually varies between 1400 and 1600 [W/m$_2$].

This last case illustrates the importance of the accuracy of predicting q. If the surface heat flux cannot be simulated with enough precision, the error on h_f can become drastically high.

CONCLUSIONS

In this paper a new method for determining the film cooling effectiveness and heat transfer coefficient is proposed. This method consists in combining the transient liquid crystal (TLC) technique and the pressure sensitive paint (PSP) technique. This new method has been applied on a film cooled flat plate. Results were compared to the classical TLC technique using multiple experiments and a regression analysis.

The film cooling effectiveness obtained with the new method showed good agreement with the trends given in the literature. However there were high discrepancies noted between the results of the new method and the TLC regression.

Concerning the determination of the heat transfer coefficient, the surface heat flux induced by the heater foil must be accurately known. If not, the error on the heat transfer coefficient can become drastically high.

Having the coolant temperature during the single TLC test equal to the mainstream temperature eliminates the influence of the film cooling effectiveness on the determination of the heat transfer coefficient. Thus, with the present method, the heat transfer coefficient could be determined with a higher accuracy than with the regression analysis.

The advantage of the presented approach is the need of only two experiments for the local determination of the global film-cooling performances. Moreover, compared to other transient liquid crystal techniques, where it is necessary to perform multiple experiments with some small variations in the coolant temperature, the measurement approach proposed here is more accurate as only one coolant gas temperature is used, thus respecting a constant density ratio.

FUTURE WORK

As observed in Fig. 8, there is a noticeable difference between the film cooling effectiveness obtained with the TLC regression and the PSP results. The film cooling effectiveness obtained with the TLC regression (BR=0.30) should be located between the two PSP curves (BR=0.26 and 0.40). Further investigations are needed to understand this difference and to find out which method is more reliable.

In order to avoid the difficulties encountered for the predictions of the surface heat flux, alternative solutions to the heater-foils should be used for the generation of the transient test. First, heater grids could be mounted in the main flow for producing a step change in the mainstream temperature. For film cooling measurements on blade models, a rapid insertion mechanism could be used allowing the insertion of a preconditioned model into a hot main flow.

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