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OPTICAL INVESTIGATION OF TRANSONIC WALL-JET FILM COOLING

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ABSTRACT

The evolution of increasing turbine inlet temperature has led to the necessity of full-coverage film cooling for the first turbine vane and blade. A new approach using high pressure steam injection cooling for transonic film cooling has been proposed by the authors. This paper presents first experimental results obtained under controlled conditions in a test model ejecting cooling air into air at atmospheric pressure thus enabling an experimental analysis of transonic film development under varying conditions.

Data obtained with digitally analysed speckle interferometry, shearography, holographic interferometry and schlieren techniques are presented to discuss the possible use of this type of film cooling for intense surface cooling.

INTRODUCTION

Increasing turbine inlet temperatures promise higher efficiency of steam and gas turbines when converting primary energy into electrical or mechanical energy. Combined cycles using steam and gas turbines reach efficiency of 54 to 55% . Beside high pressure ratios, high turbine inlet temperature is essential for efficiency improvement. Thus, several companies have already developed 1154^{o} and 1350^{o}C-class gas turbines (Amagasa et al., 1994) and high efficiency heavy-duty gas turbines with turbine inlet temperatures as high as 1500^{o}C are already under construction. Such high temperatures are far beyond the capabilities of metallic materials. Without cooling maximum average temperature could only be approximately 50% of modern turbine inlet temperature.

For better understanding of the effects taking place in the gas turbines airfoils with intense film cooling, large-scale computational analyses had been conducted and compared with experiments to understand the coolant jet and cross flow interaction in discrete-jet film cooling (e.g. Leylek and Zerkle, 1994; Bohn and Bonhoff, 1994). Additionally, the complex problem of predicting convection heat transfer in a turbine gas path is also a major research topic in the technical community (Simoneau and Simon, 1993). Significant progress has been made over the recent years in understanding the complex flow field interaction between film-hole flows and cross-stream regions. Film-hole length-to-diameter ratio, blowing ratio and injection angle turned out to be essential ingredients to understanding results of these interactions.

On the other hand, knowledge of `Coanda Effect´ in the transonic region has improved over the last years. This effect describes the bending of flows around surfaces and takes place only under certain conditions. Coanda ejectors have found many applications in industry varying from small fluid devices to reenergizing boundary layers on aircraft wings and jet flap devices (Fernholz, H. and Wille,R., 1971; Ameria and Dybbs, 1993). Several experiments with supersonic Coanda jets have been performed and published (Gregory-Smith and Gilchrist, 1987; Gilchrist and Gregory-Smith, 1988; Gregory-Smith and Hawkins, 1991; Gregory-Smith and Semior, 1994). In many of these experiments, a two-dimensional underexpanded jet has been blown over a convex Coanda surface and studied experimentally. The curved supersonic jet proved to have a complex shock cell structure with compression and expansion waves in the underexpanded core of the jet with an outer free shear layer of the jet and a boundary layer towards the Coanda surface. Ignoring the presence of the boundary layer, a plane wall-jet may be thought of as half a free jet. The Mach waves from the initial Prandtl-Meyer expansion are `reflected` at the wall and the free surface thus forming the cell like structure. At a certain pressure ratio between Coanda jet and main stream, the jet `breakaway´ from the surface but reattaches again when pressure is reduced. Some authors (Gilchrist and Gregory-Smith, 1988) also give guidance when the ´breakaway´ is likely to occur.

In steam injected gas turbine cogeneration systems steam at low temperature but high pressure is available (Satoh et al., 1991; Ishizuka and Suzuki, 1991) and the enhancement in power output by using this high pressured steam in various ways is already discussed (Ågren et al., 1994)

Since Coanda jets bend towards convex surfaces it has been suggested (Jericha, 1995) that its use might be considered for high temperature turbine blade film cooling. This experimental investigation presents results to determine the effects for film cooling of high temperature turbine blades, using cooling slits on the blade surface fed by slots with high pressure steam or air. Under certain geometrical conditions, the investigations indicates a uniform cooling of the surface and a film wall-jet `breakaway´ or `lift-off´ from the surface only at very high chamber pressure versus athmospheric pressure.

EXPERIMENTAL MATERIALS AND METHODS

Test model

An experimental test model was built consisting of a pressure chamber fed by a metallic pipe and supplied from a 8 bar air supply via a pressure reducing valve at room temperature. The geometrical dimensions of this model are shown in Fig.1. Different shapes of the pressure chamber were used for these investigations with a uniform width of the exit slit. The chamber geometry has a cross-sectional change according to that of a Laval nozzle with the smallest diameter at the exit slit to provide an underexpandend jet. The stagnation pressure in the upstream flow was measured in the chamber and the flow discharged to atmospheric pressure. For reasons of comparison a pressure ratio R was defined as

$$R = \frac{p_a}{p_c} \qquad (1)$$

with p_a the atmospheric pressure and p_c the stagnation pressure inside the chamber.

Since the experiments were performed using optical techniques, acrylic glass was used as material for this model.

Laser-optical methods used for investigation

Three different types of optical techniques for flow visualisation and measurements has been used to investigate the pressure distribution inside the chamber, the flow conditions at the exit slot and the surface flow:

First, a speckle interferometry with reduced sensitivity for estimating the pressure distribution inside the chamber with different chamber geometries,

second, for the investigation of the air jet ejected from the slit, a schlieren and shearography setup has been used to visualize and measure the flow at different pressure ratios R; the direction of observation parallel to the exit slit.

And third, a holographic Interferometry for investigation of surface flow perpendicular to the slit also with different chamber geometries.

Fig.2 shows the optical setup for schlieren pictures (Fig.2a) and shearography (Fig.2b). The parts surrounded by the dotted line were exchangeable without alteration of the object operating under given conditions. Three types of schlieren filters had been used providing sensitivity in vertical, horizontal or all directions simultaneously. The shearography system was setup as a Mach-Zehnder interferometer with adjustable sensitivity for density gradients in vertical or horizontal direction. Details of the adjustment of this interferometer and the evaluation of the

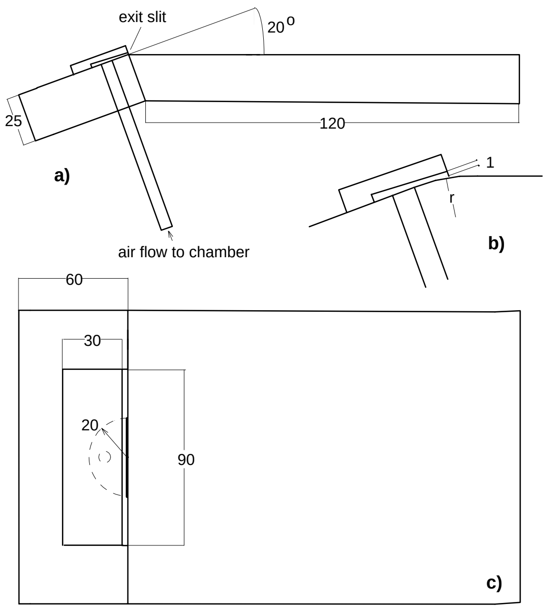

FIG.1 Test model for experimental investigation of transonic film cooling.. a) side view, b) detail of the cooling slit (r radius of curvature), c) top view

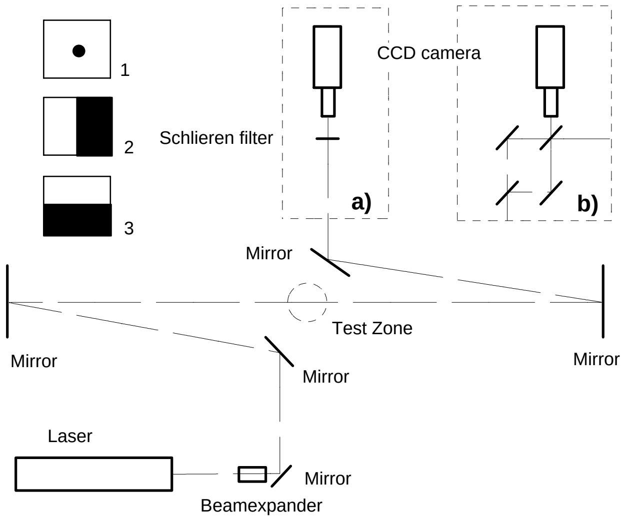

FIG.2 Optical system for a) schlieren pictures and b) shearography using a Helium-Neon laser and a CCD-type video camera

interferograms obtained with it are described in Pretzler et al. (1993). Both visualisation techniques are well covered in literature (Merzkirch, 1987; Meyer-Arendt, 1992)

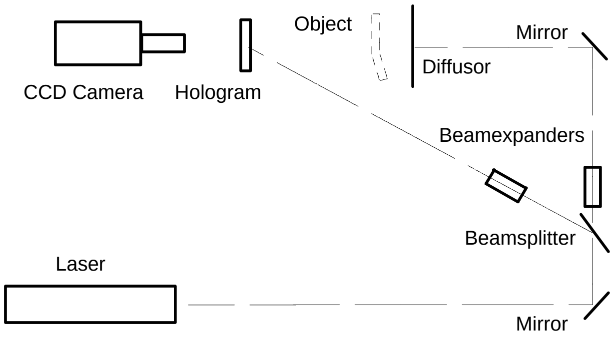

FIG.3 Optical system for holographic interferometry

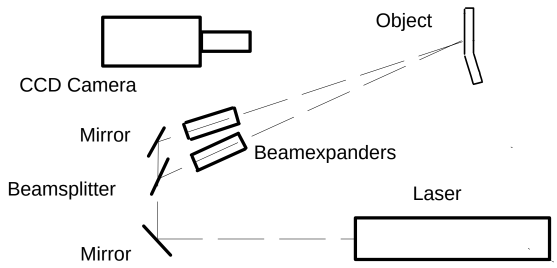

FIG.4 Optical system for speckle interferometry with reduced sensitivity

The setup for holographic interferometry is given in Fig. 3. Here the test model was penetrated in a direction perpendicular to the slit and the object surface to enable an observation of the coanda jet behind the exit slit. The flow itself as well as the change of thickness of the acrylic glass due to cooling by the underexpanded jet were measured. For better viewing conditions, a ground glass was inserted behind the object as diffuse scatter (Vest, 1979).

In order to compare the flow patterns behind the exit slit with the geometry of the pressure chamber, speckle interferometry had been used for estimating the pressure distribution inside the chamber. Because of the high pressure (high air density), a setup with reduced sensitivity had to be chosen (Fig.4; compare e.g.Jones and Wykes, 1983). Observation of the pressure chamber had been made possible by covering the chamber with an optical transparent material.

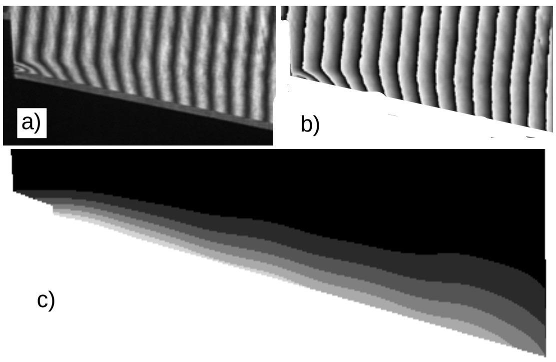

FIG.5 Digital evaluation of the interferograms. a) digitized interferogram, b) interference fringe phase shift modulo 2π after Fourier filtering and c) density distribution calculated from phase shift

Evaluation of the interferograms

Shearographic, holographic and speckle interferograms had been evaluated using a fast Fourier transform (FFT) technique proposed by Takeda et al. (1982). The intensity distribution in the interferogram is digitised (Fig,5a) first and then transformed by means of a fast Fourier transform therefore yielding a spatial frequency spectrum. The reason for a procedure like this can be explained by the intensity distribution i(x,y) in a interferogram (Fig.5a):

$$i(x,y) = i_0(x,y) + m(x,y) \cos (\phi(x,y)) \qquad (2)$$

where i_0 is low frequency background intensity, m is the modulation depth of the interferometer fringes and , most important of all, ϕ is the phase shift between the light waves interferometrically compared. This phase shift contains all the important information on pressure and temperature changes.

In the frequency range all unwanted components (background noise etc.) can be filtered and only the sinusoidal fringe signal is reconstructed by an inverse Fourier transform. Finally the phase shift of this fringe signal can be computed by an inverse tangents operation using the imaginary and real part of the spectrum. The result (phase shift modulo 2π) of such an operation is shown in Fig.5b. After removal of the phase ambiguities (caused by the definition of tangents function) the phase shift of the light wave front produced by density (holography, speckle techniques) or density gradient (shearography) is shown in Fig.5c .

In holographic interferometry the laser light wave without flow (turned off) was stored holographically. After development of the holographic (photographic) plate this light wave was reconstructed again. The reconstructed light wave had then been compared interferometrically with the actual one penetrating the object in real-time. Both light waves interfered producing the interference pattern observed. The phase shift of the fringes is directly proportional to the time lag of the light wave penetrating the flow (caused by the change in density when switching the flow on) compared to the undisturbed light wave front.

Speckle interferometry uses the speckle effect for comparing two light wave fronts. (this speckle is the granulation seen when laser light illuminates a surface). The principle is the same as in holography and for that reason electronic speckle pattern interferometry (ESPI) is often called electronic holography. For both techniques the phase shift is proportional to density changes.

In contrast to holographic interferometry where the phase shift is linked to density changes, shearography phase shift is proportional to the density gradient in a plane perpendicular to the observation direction. The light wave trans-luminating the object is divided into two waves inside the interferometer and both waves are sheared against each other by a given amount. Thus, interference is produced by one light wave shifted against

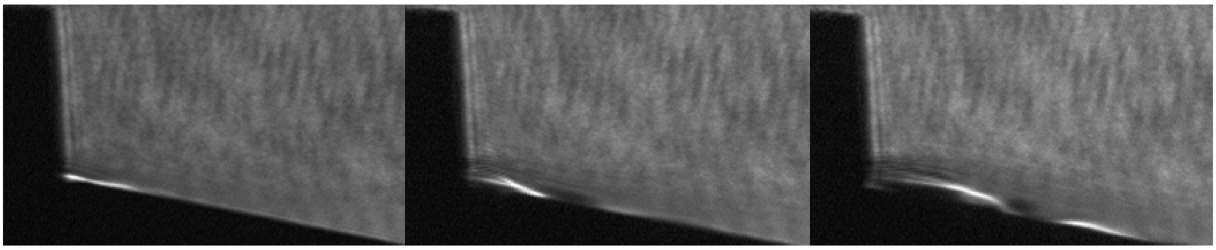

FIG.6. Schlieren pictures of coanda jet immediately after the exit slit. With a height of the exit slit of 1mm, the pressure ratios had been: R=0.47, 0.33 and 0.2 (from the left to the right respectively).

itself in a plane perpendicular to the observation direction. Therefore the difference in phase from one point of the light wave front to the neighbouring is detected. With the displacement (shear) known and sufficiently small, the phase shift detected is proportional to the first derivative of phase shift of the light wave front. This technique gives the possibility to adjust sensitivity of the optical system; a very important feature when close to shock waves with high density gradients.

RESULTS AND DISCUSSION

Investigation of jet `breakaway´

Experimental investigation of jet `breakaway´ was done using the test model shown in Fig.1a above. Keeping in mind, that a small ratio between slit width and radius of curvature requires a high chamber pressure for `breakaway´ (Gregory-Smith and Gilchrist, 1987, Fig.7) we started with a carefully smoothed surface from exit slit (1mm height) to model surface. The results are shown as schlieren pictures in Fig. 6 for pressure ratios of about R=0.47, 0.33 and 0.2 respectively. For these pictures a circular schlieren filter (1 in Fig.2 above) had been used, thus showing density gradients in both directions. With higher pressures inside the chamber, the shock cell structure of the coanda jet became more pronounced and grew in length.

If, on the other hand, the exit slit for film cooling was turning into the downstream objects surface with a too small radius of curvature r (compare Fig.1), a `breakaway´ was observed already at lower chamber pressures. This is shown in Fig. 7 at pressure ratios of R=0.4, 0.33 and 0.25. At a pressure ratio of R=0.33 a recirculation zone was clearly observable leading to a ´flip off´of the coanda jet with increasing chamber pressure. Again reducing the chamber pressure a hysteresis effect took place before the jet attached again.

Once turned towards the model surface the jet showed slightly increasing turbulent oscillations at the outer free shear layer. To get a first idea of the dimensions of this effect shearograms had been made of the flow with two different model-headings and different pressure ratios. Two results are given in Figs. 8. and 9.: a) the side views of the model are shown, clearly indicating the chamber hood also seen in the interferograms (Figs.8 and 9 b) and in the schlieren pictures (Fig.6,). The results of the evaluation of the shearographic interferograms (Figs 8 and 9 c) are given in terms of density and not density gradient. This was made possible

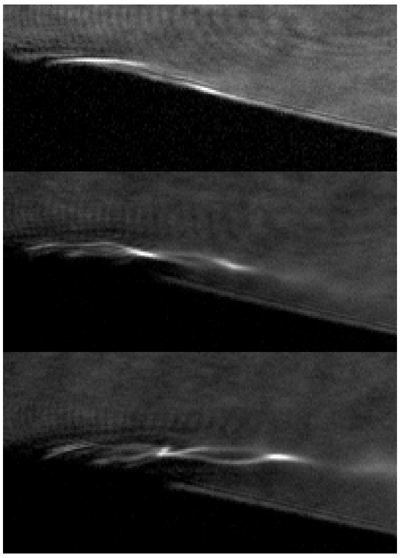

FIG.7. Investigation of `breakaway´ with slot surface turning into the downstream surface with a too small radius of curvature (Fig.1b). Exit slit height was 1 mm, pressure ratios R=0.4, 0.33 and 0.25 from the upper to the lower.

by integration along the shear direction. Lighter areas indicate higher density. The pressure ratios are R=0.33 in Fig.8 and R=0.31 in Fig.9. When changing the pressure ratio from R=0.33 to R=0.25, the thickness of the coanda film increased by less than 10% in the case of the plane heading and no more than 60% if the flow turned 80^{o} when the curved heading was used. All densities obtained in this experiment were integral values along the line of observation.

To get more detailed information on the lateral extension of the flow over the surface, holographic and speckle techniques had been used with an direction of observation perpendicular to the surface of the model.

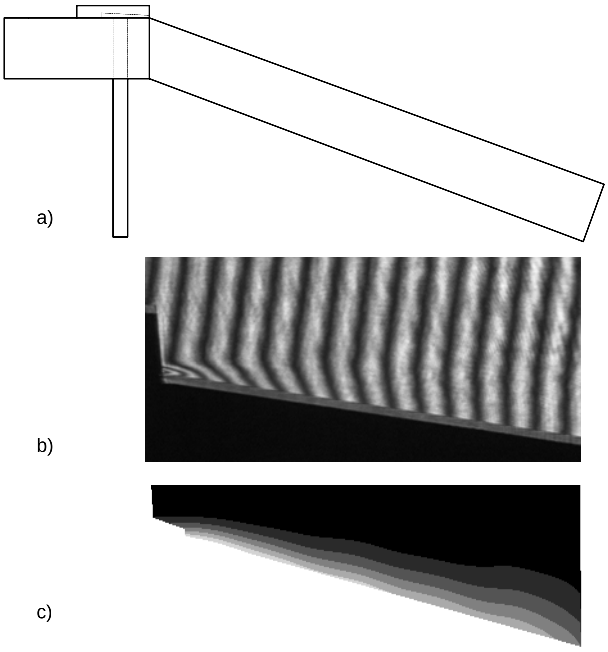

FIG.8. Interferogram (shearogram) of the flow along the surface of the test model using the plane head-piece and a pressure ratio of 0.33. a) side view of the model, b) shearogram, c) density distribution (lighter areas indicate higher density)

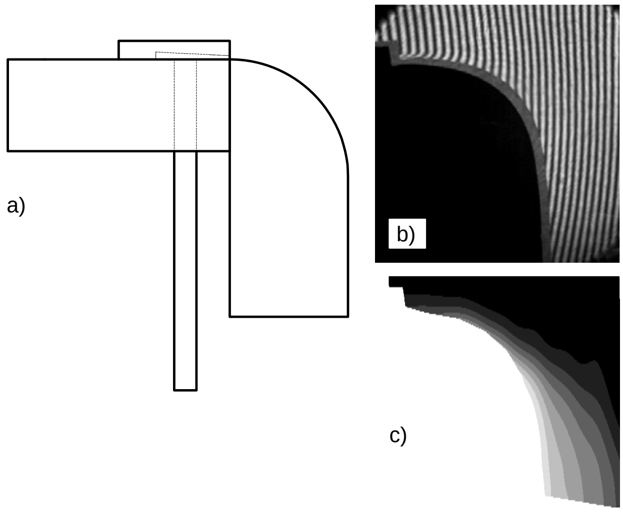

FIG. 9. Interferogram (shearogram) of the flow along the surface of the test model using the curved head-piece and a pressure ratio of 0.31
a) side view of the model, b) shearogram, c) density distribution (lighter areas indicate higher density)

Fig. 10 compares the pressure distribution inside the chamber. This pressure distribution was obtained using speckle interferometry, with reduced sensitivity, as shown in Fig.4. Since the height of the chamber is known, the integral phase shift (caused by the density change inside the chamber when turning the flow on) can be reduced to a local density distribution assuming a similar distribution in all heights. With the known temperature of the air (23^{o}C, measured inside the chamber) pressure was estimated for differently shaped chamber geometries. Two results are shown in Fig.10 a. and b. While a circular geometry led to a pressure decrease radially outward from the metallic pipe feeding the chamber, a geometry with straighten edges produced a more uniform pressure distribution at the exit slit (Fig.10.b). Those results were also confirmed by first numerical calculation performed in the subsonic region with the flow analysis program FIRE (FIRE is a software program developed by AVL, O´Connor, 1992).

The chamber geometry also had very important effect on the surface film that is it influences the position of the shock so that the film outside the chamber is unevenly distorted. This was observed when holographic techniques were used to investigate the jet expanding over the surface. Real time holographic interferometry (first exposure without the jet compared to the situation when the jet was operated under different conditions) indicated a slightly rippled but uniform spreading of the film over the surface in case of the chamber with straighten edges. The circular geometry investigated resulted in a more or less non-uniform distribution. For a more clear presentation of the results,

FIG 10. Pressure distribution inside the chamber for a) circular shaped and b) chamber with straighten edges. Light areas indicate high pressure zones. Stagnation pressure in the metallic pipe feeding the chamber had been 2 bar in both cases.

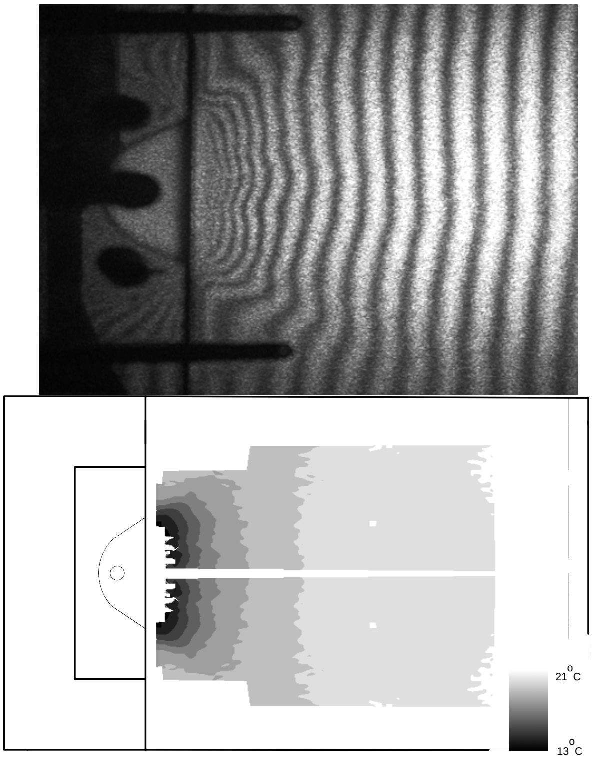

FIG.11 Holographic interferogram of the test model with the chamber straightened edges (upper picture) and phase map of the interferogram placed in the ground view of the test model (lower picture). The interferogram results from the cooling of the acrylic glass by the underexpanded flow within 60 seconds and a pressure ratio R=0.33. Dark areas indicate high acrylic glass shrinkage (low surface temperatures).

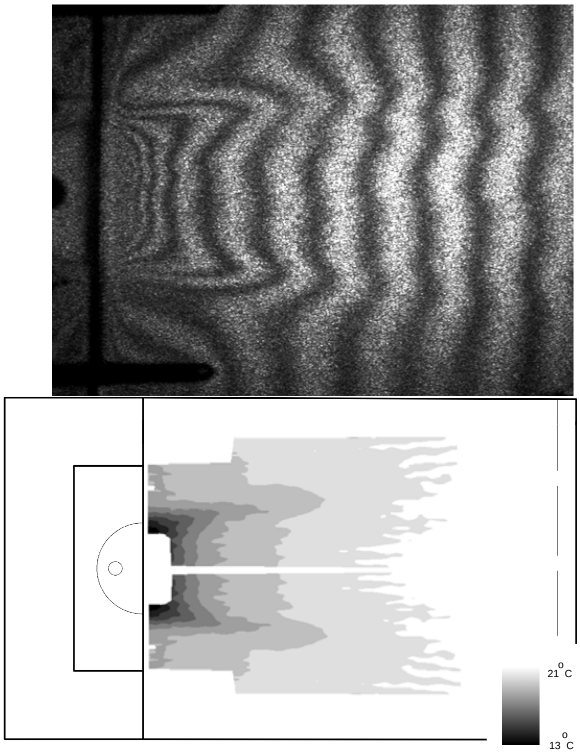

FIG.12 Holographic interferogram of the test model with the circular chamber (upper picture) and phase map of the interferogram placed in the ground view of the test model (lower picture). The interferogram results from the cooling of the acrylic glass by the underexpanded flow within 60 seconds (R=0.33). Dark areas indicate high Acrylic glass shrinkage (low surface temperatures).

two interferograms, one for the straighten chamber (Fig.11) and one for the circular one (Fig.12) show the holographically detected shrinkage of the acrylic glass surface due to cooling by the underexpanded jet within 60 seconds. The real time fringe system was adjusted parallel before the measurement (finite fringe system) so that the bending of the fringes indicate the shrinkage of the acrylic glass. The phase-maps beneath the interferograms give contour maps of the cooling of the surface and are presented in the appropriate position in the ground view of the model. In this evaluation areas too high fringe density or too little fringe contrast was masked. Whereas in Fig.11, the jet emerges completely uniform from the slit, the circular chamber produces a less uniform flow with clearly pronounced cooling properties along the edges of the chamber and less than average in the middle. This indicates the importance of proper chamber design for a uniform cooling of the surface, and shows the possibility of producing a uniform flow bent toward the surface with an easy-to-manufacture chamber geometry.

CONCLUSION

Preliminary results on the test model (Fig.1) has shown that Coanda effect can take place in the range of pressure ratios of R=0.4 to R=0.2 together with uniform cooling of the surface if several conditions are observed. Most important is the construction and manufacturing of a smooth contour between pressure chamber and surface and the tuning of the chamber geometry to achieve a uniform pressure distribution along the film ejection slit. With respect to future application to turbine blade cooling, it is also important that beside geometrical consideration in the design of the film holes an appropriate pressure ratio is assured.

FUTURE WORK

In this paper a model ejecting cooling air into air at athmospheric pressure was used for a first experimental analysis. In the next step a cooling experiment is planned using the transonic cascade at the Institute of Thermal Turbomachinery and Machine Dynamics supplied from a 3MW compressor station. In this experiment the influence of crossflow, the blowing ratios and the cooling effectiveness will be investigated.

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REFERENCES

Ågren, N.D., Frutschi, H.U. and Svedberg, G.;"A parametric study of steam injected gas turbine with steam injector", ASME COGEN TURBO POWER´94, Vol 9, pp 177-184

Amagase,S., Shimomura,K., Kadawaki,M., Takeishi,K., Kawai, H., Aoki,S. and Aoyama,K., 1994, "Study on the turbine vane and blade for a 1500^{o}C class industrial gas turbine", *Journal of Engineering for Gas Turbines and Power*, Vol. 116, pp 597-604

Ameria, M. and Dybbs, A., 1993, "Coanda ejector - why it works", *Proceedings of the SPIE*, Vol 2052, pp 289-296

Bohn, B. and Bohnhoff, B., 1994, " Berechnung der Kühlungs- und Störungswirkung eines filmgekühlten transonisch durchströmten Turbinengitters mit diabaten Wänden", *VDI-Bericht*, Nr. 1109

Fernholz, A. and Wille, R., 1971, " Grenzschichten und Wandstrahlen an stark gekrümmten Wänden (COANDA-Effekt)", *DLR Forschungsbericht*, FB71-46

Gilchrist, A.R. and Gregory-Smith, D.G. , 1988, "Compressible Coanda wall jet: predictions of jet structure and comparision with experiment", *International journal of Heat and Fluid Flow*, Vol.9, pp 286-295

Gregory-Smith D.G. and A.R.Gilchrist, 1987, "The compressible Coanda wall jet - an experimental study of jet structure and breakaway", *Heat and Fluid Flow*, Vol. 8, pp 156-164

Gregory-Smith D.G. and Hawkins,M., 1991, "The development of an axisymmetric curved turbulent wall jet", *International Journal of Heat and Fluid Flow*, Vol.12, pp 323-330

Gregory-Smith, D.G. and Senoir P., 1994, " The effects of base steps and axisymmetry on supersonic jets over coanda surfaces", *International Journal Heat and Fluid Flow*, Vol.15, pp 291-298.

Ishizuka,T. and Suzuki, A., "Steam injection aeroderivative gas turbine, its modification design and operation experience", 19th CIMAC 1991, paper G15

Jericha, H., Sanz, W., Woisetschläger, J and Fesharaki, M., 1995, "CO_2-Retention Capability of CH_4/O_2-Fired Graz Cycle", *Proceedings CIMAC 95,* in press

Jones, R. and Wykes, C., 1983, "Holographic and Speckle Interferometry", Cambridge University Press, Cambridge, pp 153-163

Leylek, J.H. and Zerkle, R.D., 1994, "Discrete-Jet Film Cooling: A comparison of computational results with experiments", *Journal of Turbomachinery*, Vol.116, pp 358-368

Merzkirch, W., 1987, "Flow Visualization", Academic Press, Orlando

Meyer-Arendt, J.R., 1992, "Selected papers on Schlieren Optics", *SPIE - The International Society for Optical Engineers Milestone Series*, MS 61

O´Connor, L., 1992, "Computational Fluid Dynamics; giving a boost to engine design", *ASME Mechanical Engineering*, Vol. 114, pp 44-51

Pretzler, G., Jäger, H. and Neger, T., 1993, " High-accuracy differential interferometry for the investigation of phase objects", *Measurement in Science and Technolgy*, Vol.4, pp 337-346

Satoh,T., Watanabe,A. and Kajita,S., "Development and operation of Cheng cycle steam injected gas turbine cogeneration system", 19th CIMAC 1991, paper G22

Simoneau R.J. and Simon F.F, 1993, "Progress towards understanding and predicting heat transfer in the turbine gas path", *International Journal of Heat and Fluid Flow*, Vol.14, pp 106-127

Takeda, M., Ina, H. and Kobayashi, S., 1982 "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry", *Journal of the Optical Society of America*, Vol.72, pp 156-167

Vest, C.M., 1979, "Holographic interferometry", John Wiley & Sons, New York, pp 264-295