Numerical investigation of the influence of a hole imperfection on film cooling effectiveness

Fadéla Nemdili
Laboratoire de Mécanique Appliquée, Faculté de Génie-Mécanique
Université des Sciences et de la Technologie d'Oran, B.P. 1505 El-Mnaouar, Oran, Algeria
Email : turbo_fad@yahoo.fr

Abbès Azzi
Laboratoire de Mécanique Appliquée, Faculté de Génie-Mécanique
Université des Sciences et de la Technologie d'Oran, B.P. 1505 El-Mnaouar, Oran, Algeria
Email : abbesazzi@yahoo.fr

B. A. Jubran
Department of Aerospace Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada
Email: bjubran@ryerson.ca

Abstract

Purpose– This paper reports a numerical investigation of jet-cross flow interaction in the presence of imperfection inside the injection hole with application to film cooling of turbine blades.

Design/methodology/approach– The work includes the prediction of the thermal and hydrodynamic fields by solving the Reynolds Averaged Navier Stokes and energy equations using the finite volume method with a body-fitted hexahedral unstructured grid. The turbulence field is resolved by use of the k-epsilon turbulence Model.

Findings – The computational results show a dramatic and rapid decrease of the film cooling effectiveness when the obstruction is superior to 50%. It is found that when the obstruction is close to the exit hole, the thermal protection is significantly reduced.

Research limitations/implications – The present numerical investigation is simply directed towards a qualitative investigation of hole imperfection effects on film cooling.

Practical implications–The motivation comes from several industrial applications such as film cooling of gas turbine components and fuel injection. One of the main challenges of using film cooling is the blockage of holes by particles ingested by the engine during landing/take off or due to application of TBC or due to combustion particles as well as inaccuracies that result from drilling of holes.

Originality/value – The main goal of the present study is to conduct a numerical parametric investigation rather than reproducing the exact Jovanović's experimentation.

Keywords Film cooling, Parametric investigation, Hole imperfection, Jet in cross-flow
Paper type Research paper

Nomenclature

D,d	Hole and torus diameter
U	Velocity
Tu	Turbulence intensity
$BR = \rho_c U_c / \rho_\infty U_\infty$	Blowing ratio
$VR = U_c / U_\infty$	Velocity ratio
k	Turbulence kinetic energy

Greek

η	Effectiveness
$<\eta>$	Laterally averaged effectiveness
ε	Turbulence rate dissipation

Subscripts

c	Coolant conditions
∞	Streamwise conditions

Introduction

The jet-cross flow interaction is a well known problem and has been widely investigated by both numerical and experimental approaches. The motivation comes from several industrial applications such as film cooling of gas turbine components and fuel injection. Among many others, film cooling technique has been used for gas turbine blades for more than five decades. One of the main challenges of using film cooling is the blockage of holes by particles ingested by the engine during landing/take off or due to application of TBC or due to combustion particles as well as inaccuracies that result from drilling of holes. The shape and size of the hole, layout geometry, and injection angle, etc. are very critical deciding factors on film cooling effectiveness and heat transfer.

Imperfections in the holes may result from thermal barrier coating (TBC) which can detach from the surface and results in spallation (Sundram and Thole, 2007), particles ingestions during take off and landing and erosion, and/or corrosion on the turbine blades. Particles ingested in an engine could be dust, sand, fuel combustion residuals, volcanic ash, ice and salt (Sirs, 1994). Sirs (1994) and Sis (2007) reported that such dust ingestions may be significant, for example, for a helicopter operating in a sandy environment, the rate of dust ingestion could be in the range of 15 to 56 kg/hour. Imperfections may also be produced during manufacturing of the holes and refurbishing of the holes after long hours of flight. Film cooling injection holes have been made using two manufacturing techniques, namely Electro Discharge Machining (EDM) and Laser Drilling (DL). EDM is well suited for small size holes and offers consistency and necessary finish quality. The shortcomings are mainly recast layer, micro-cracking and only used for conductive material (Tolinski, 2006). Laser drilling has recently been extensively used in drilling of film cooling holes due to its cost and speed which makes it ideal for large volume production (Sizov, 2007). However, it tends to be crude and may lead to defects in injection holes which affect the film cooling protection of gas turbine blades (Jovanović, 2006)

Jovanović (2006) experimentally investigated the effect of discrete hole imperfection on film cooling effectiveness and heat transfer. The hole used in this experiment is simple cylindrical holes at an angle where the imperfections are generated to mimic inaccuracies that are generated by means of laser drilling and often discrete and have a toroidal shape. It was reported that such inaccuracies might be relatively big with a length scale of a quarter of the hole diameter (Jovanović, 2006). Inaccuracies can results from applying TBC to the film cooled blades (Sundram and Thole, 2007). Jovanović *et al.* (2006) reported the effect of discrete imperfection inside a short perpendicular hole and found that an additional vortex is generated due to imperfection which in turn changes the film cooling effectiveness.

Sizov (2007) reported the effects of three types of inaccuracies due to laser drilling on film cooling effectiveness. The inaccuracies consist of imperfections in the length of a hole with different cross sectional shapes and sizes. He defined the so-called blockage area and stated that in real laser drilled holes the blockage could mount to 30%. It was found that the shape of inaccuracies has little influence on the injection flow characteristics while the size of the imperfections has a very strong influence on film cooling at small and moderate velocity ratios.

Bunker (2000) investigated the partial blockage of film cooling holes and found that an exit area blockage of 15% resulted in a decrease of 30% in film cooling effectiveness in the vicinity of the holes. Sundaram and Thole (2007) and Na *et al.* (2006) investigated the effect of partially film cooling hole blockage due to TBC and particle ingestions on film cooling effectiveness and reported that deposits near the hole exit may sometimes lead to improvement of the cooling effectiveness while partial hole blockage tends to reduce the cooling protection of the blade.

Kuk *et al.* (1994) investigated the effect of micro particles in film cooling from a single hole and concluded that blockage can be avoided by changing the angle of the injection hole.

To the best of the author's knowledge it seems that there is little work on the effect of hole imperfection due to inaccuracies of the manufacturing methods, refurbishing of the holes after long hours of flight, thermal barrier coating (TBC), and erosion, and/or corrosion on the turbine blades, on film cooling effectiveness and heat transfer. This paper presents a computational parametric study on the effects of imperfections based on Jovanović's experimental work (Jovanović *et al.*, 2006).

It is well known that a film cooling mathematical model based on statistical turbulence models and using RANS equations is limited in its capability to reproduce exactly the complex vortex and thermal fields occurring in the vicinity of a jet in cross flow. Especially, the k-epsilon turbulence model is reputed to underestimate the lateral spreading of the jet and also not suited to reproduce the extreme anisotropic distribution of turbulent stress (Azzi and Lakehal, 2002). So, the lateral averaged adiabatic film cooling effectiveness is always underpredicted, particularly for high blowing ratio cases. Taking this into consideration, the present numerical investigation is simply directed towards a qualitative investigation of hole imperfection effects on film cooling. The main goal of the present study is to conduct a numerical parametric investigation rather than reproducing the exact Jovanovic's experimentation.

Turbulence and mathematical models

The simulations were performed using the CFX 10.0 software from ANSYS, Inc. In the solver package, the solution of the Reynolds Averaged Navier-Stokes Equations is obtained by using finite volume method with a body-fitted structured grid. A cell-centered layout is employed in which the pressure, turbulence and velocity unknowns share the same location. The momentum and continuity equations are coupled through a pressure correction scheme and several implicit first and second order accurate schemes that are implemented for the space and time discretizations. In the present computation, convection terms written in convective form are discretized with a third order upwind-biased scheme.

The turbulence closure is done with the help of the standard k-epsilon turbulence model (Launder *et al.*, 1975) coupled with scalable wall function strategy. The major discrepancy of the standard wall function approach is its dependence on the nearest point to the wall. It is shown that refining the near wall mesh does not give a unique solution of increasing accuracy (Crotjans and Menter, 1998). The problem of inconsistencies in the wall-function in the case of fine meshes is overcome with the use of the scalable wall function formulation developed by CFX group. The basic idea behind the scalable wall-function approach is to limit the value used in the logarithmic formulation by a lower value of $\tilde{y}^* = max\left(y^*, 11.06\right)$. Where the value 11.06 is the intersection between the logarithmic and the linear near wall profile. The computed $\tilde{y}^*$ is therefore not allowed to fall below this limit. Therefore, all mesh points are outside the viscous sublayer and all fine mesh inconsistencies are avoided. This approach allows the use of scalable wall function on arbitrarily fine meshes.

A second improvement added in the CFX formulation is the use of an alternative velocity scale, u^* in the logarithmic region:

$$u^* = C_\mu^{1/4} k^{1/2} \tag{1}$$

As it is well known in turbulent flow, k never goes to zero value, so u^* does not go to zero if U_t goes to zero. Based on this definition, the following explicit equation for u_τ can be obtained:

$$u_\tau = \frac{U_t}{\frac{1}{k}\log\left(\tilde{y}^*\right) + C} \tag{2}$$

The absolute value of the wall shear stress τ_ω, is then obtained from:

$$\tau_\omega = \rho u^* u_\tau \tag{3}$$

Test case description

Two geometrical configurations which have been studied experimentally by Jovanović *et al.* (2006) are reproduced here. In the first configuration, the jet was injected perpendicularly into the cross flow through the cylindrical hole with a diameter D=64 mm (Fig. 1(A)). According to the experimental setup, a short hole was used; the length over the diameter of the hole was 1D. For computational purpose, a plenum is added to the computational domain. This case is noted as perfect case (P) and it is used here for comparison purpose. The second configuration is similar to the perfect case with an inner-torus (IT). The imperfection is assumed to have the shape as a melt injection (Von Allmen and Blatter, 1995). Therefore, a half torus was chosen to simulate the imperfection. Although the imperfection can occur anywhere during the drilling process, in the present investigation it was chosen to be placed one torus diameter inside the hole (Fig. 1 (B)). The torus diameter was 16 mm (d=D/4). This is of the same order of magnitude as the imperfection produced during the drilling process. Table 1 shows the flow conditions of the three velocity ratios considered.

Table 1: Mainstream velocity versus the velocity ratio.

	$U_\infty (mm/s)$	δ/D	Perfect VR	Inner-Torus VR
1	120	0.30	(P1) 0.54	(IT1) 0.54
2	190	0.21	(P2) 0.34	(IT2) 0.34
3	330	0.16	(P3) 0.20	(IT3) 0.20

Geometry and computational domain

The computational domain presented in Figure 2, is composed of a single row of cylindrical perpendicular hole. The lateral spacing of holes is fixed to 3D. Where D is 64 mm and stands for the hole diameter. The hole length-to-diameter ratio is 1. The computational domain extends from the inflow plane to 29D in the streamwise direction and from the bottom of the flat plate to 8D in the vertical direction. In the spanwise direction, the domain extends from a plane through the middle of the hole to a plane at 1.5D in the middle between two injection holes, and symmetry conditions are imposed on these planes. The no lateral inclination of the jet, allows the consideration of only half of the flow domain.

For a maximum inlet boundary condition precision, a plenum part is integrated in the computational domain, while the approaching mainstream boundary layer was taken to be fully developed using the power-law approximation $U_{in} = U \times (y/\delta)^{1/7}$ where δ is the boundary layer thickness given in Table 1. At mainstream inlet, uniform distributions are specified for k and ε, corresponding to $Tu = 1\%$ and $\mu_t/\mu = 30$, while at the plenum the turbulence intensity is set of $Tu = 10\%$ and the length scale of $k^{3/2}/\varepsilon = 0.3D$. Table 1, summarizes the mainstream velocity for the three cases considered in the present study, which match those done by Jovanović *et al.* (2006) in their experimental measurements. The injection flow velocity is computed according to the velocity ratio values, while the outflow boundary condition is set at constant zero relative pressure. Scalable wall function, which is a powerful tool in CFX code, is applied by default at all wall boundaries. All walls are considered as adiabatic and a temperature difference of 6° between the main stream and the plenum is considered.

Preliminary computational tests lead to an optimized grid, composed of nearly half million elements. The grids are highly refined near the walls and use the well known O grid strategy to well describe the vicinity of the hole injection. The quality of the computational grid is highly improved in the sense of aspect ratio and skewness by use of the O grid strategy cited above. Figure 3 shows the three main parts of (P) case. All grids are generated by use of the ICEM grid generation tool from ANSYS, Inc.

Results and discussion

The first validation of the predicted results consists of comparing the centreline adiabatic film cooling effectiveness with the measurements of Jovanović *et al.* (2006). On Figure 4, the centreline values are plotted for both perfect (P) and inner torus (IT) cases and for three different velocity ratios. Left panel is for the experimental measurements done by Jovanović *et al.* (2006) and right panel is for present numerical computation. One common feature is the monotonically streamwise decrease of film cooling effectiveness and hence, less thermal protection when increasing the velocity ratio. Note that since the density is assumed to be constant the blowing ratio is strictly equivalent to the velocity ratio. The presence of the hole imperfection (inner torus obstacle) accelerates the jet, promotes the jet lift-off phenomenon and results on lower values of film cooling effectiveness. Computational data are in good agreement with experimental measurements especially for low blowing ratio and are under estimated for high blowing ratios, which is a known behaviour of computations done by eddy viscosity turbulence models. When looking at the experimental data, one can see that for the lowest velocity ratio (P3) the centreline effectiveness is maximum at the near field and decrease monotonically when going to the far field. This is explained by the fact that the cold jet is continuously attached to the flat plate. For the intermediate velocity ratio (P2) the centreline effectiveness is lower than that for the lower velocity ratio in the near field and higher in the far field. This is probably an indication that the cold jet lift off and reattach at approximately x/D=4. Finally for the highest velocity ratio (P1) the trend of centreline effectiveness indicates that the jet lift off totally without a possibility of reattaching to the wall. These details are not reproduced by the numerical data due to the limited capability of the present turbulence model. Nevertheless, the global trend is well reproduced, namely for the same geometry, the effectiveness decreases when the velocity ratio increases and also decreases for the same velocity ratio when adding the hole perturbation. The same features are shown on Figure 5, when comparing the experimental and computational results of the so called laterally averaged adiabatic film cooling effectiveness $<\eta>$ defined by:

$$\langle\eta\rangle = \frac{1}{L}\int \eta\, dz \quad ; \qquad \eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \tag{4}$$

where T_{aw} stands for adiabatic wall temperature, T_∞ for mainstream temperature and T_c for cold jet temperature. L is the spanwise distance from -0.5D until 0.5D.Figure 6 shows the non-dimensionalized vertical velocity on the center plane and through the hole jet. Due to the short hole length, the velocity profile is not fully developed and shows a peak moving towards the lee side. The imperfection accelerates the jet and promotes a small negative region in the vicinity of the leading edge of the hole. The penetration of the cross flow in the hole near this region is proportional to the velocity ratio. Note that in the experimental data given by Jovanović *et al.* (2006), the inward mean-flow near the leading edge is more pronounced than it is for numerical results. This is due probably to a need for a higher resolution in this critical part of the domain.

Figure 7, shows the effectiveness contours on the flat plate as well as the secondary velocity vectors on three spanwise plans. Results are shown for both the lowest and the highest velocity ratios (VR = 0.20 and 0.54). The perfect cases are compared to the inner torus cases. The well known Counter-rotating Vortex Pair (CVP) structure is well reproduced and the flow field shows a net acceleration in both the right and the left side of the jet. At similar velocity ratio, the CVP in inner torus cases is stronger and in a higher vertical position. This situation explains the effect of the CVP on pulling down the mainstream hot gas and consequently destroys the thermal protection. The strength and the elevation position of the CVP are the two deterministic parameters of the effectiveness. The more elevated and stronger is the CVP, the less is the thermal effectiveness. Such conclusions are largely discuted and documented by researchers in film cooling field and particularly by Jovanović *et al.* (2008). The main conclusion is that the presence of the imperfection decreases the lateral spreading of the jet and results in lower values of the laterally averaged film cooling effectiveness. Increasing the velocity ratio leads to the jet lift off phenomenon and the effectiveness goes to lower values.

Influence of imperfection size

The influence of the percentage of the hole obstruction is investigated by use of three inner torus having three different sizes. The three cases are noted respectively 23.44%, 43.75% and 60.94%. The forth case is naturally the perfect hole which will be noted 0% obstruction. The same blowing ratio is used for all four cases, which is the intermediate one (BR=0.34). Figure 8 shows the geometry for the four test cases.

Figure 9, shows the effectiveness contours on the flat plate as well as the secondary velocity vectors on three spanwise plans. Results are shown for the intermediate velocity ratio (VR = 0.34) and the four cases 0 %, 23.44%, 43.75% and 60.94% respectively. It is seen that when the imperfection size growth the jet is accelerated and the lift off phenomenon take place. The centres of the two counter rotating vortices moves far from the flat plate and some hot gas can enter into the injection hole. As consequence, the thermal protection is seriously reduced. Film cooling effectiveness contours of the four cases are represented on Figure10. It is clear from the figure that the flat plate protection is dramatically decreased when the obstruction changes from 23.44% to 43.75%. This finding confirms what is explained previously by the 3D figures. The area averaged film cooling effectiveness over the flat plate is computed for the four cases and represented on Figure11. The results show that when the obstruction grows over 50% of the hole area, significant reduction in the film cooling occurs.

Influence of imperfection position into the hole

The effect of the imperfection position is investigated by keeping the 23.44% case and varying its position inside the hole. Four cases are computed and showed by Figure12. The inner torus is moved from top to bottom and the cases are called respectively L1, L2, L3 and L4. The perfect case (P) is represented for comparison purpose. Effectiveness contours on the flat plate as well as secondary flow on three spanwise plans are presented on Figure13. Results show that when the imperfection is too close to the hole exit, the thermal protection is reduced. When the imperfection is far from the hole exit, the cold jet can easily recover its developed behaviour and the thermal protection is practically unaffected.

This is confirmed by figure14, which represents the area averaged film cooling effectiveness computed over the flat plate for the five cases. It is shown that when the imperfection is placed far from the hole exit (L1) the area averaged film cooling effectiveness is affected by approximately 10% from that of perfect case. The diminution passes to about 20% when mobbing to L2 case and so on.

Conclusions

Numerical investigation of the presence of inner torus imperfection inside the hole injection is done with the help of the well stabilized CFX code from ANSYS Inc. The k-eps turbulence model coupled with scalable wall strategy is applied with success to highlight the main features of the presence of such imperfection. For comparison purpose, the perfect case is also done. Three different velocity ratios are investigated and both flow and thermal fields are presented. Finally, numerical results showing the influence of the imperfection size and position on the film cooling effectiveness is presented. The main conclusion is that the presence of imperfection leads to a decrease in the adiabatic film cooling effectiveness in the same manner to that obtained when the velocity ratio is increased. From the parametric study, it is shown that for 50% of hole obstruction with a position less than one diameter to the hole exit can reduce seriously the thermal protection of the blade. To avoid thermal protection deterioration, it is advised to keep the imperfection size as small as possible and far away from the hole exit.

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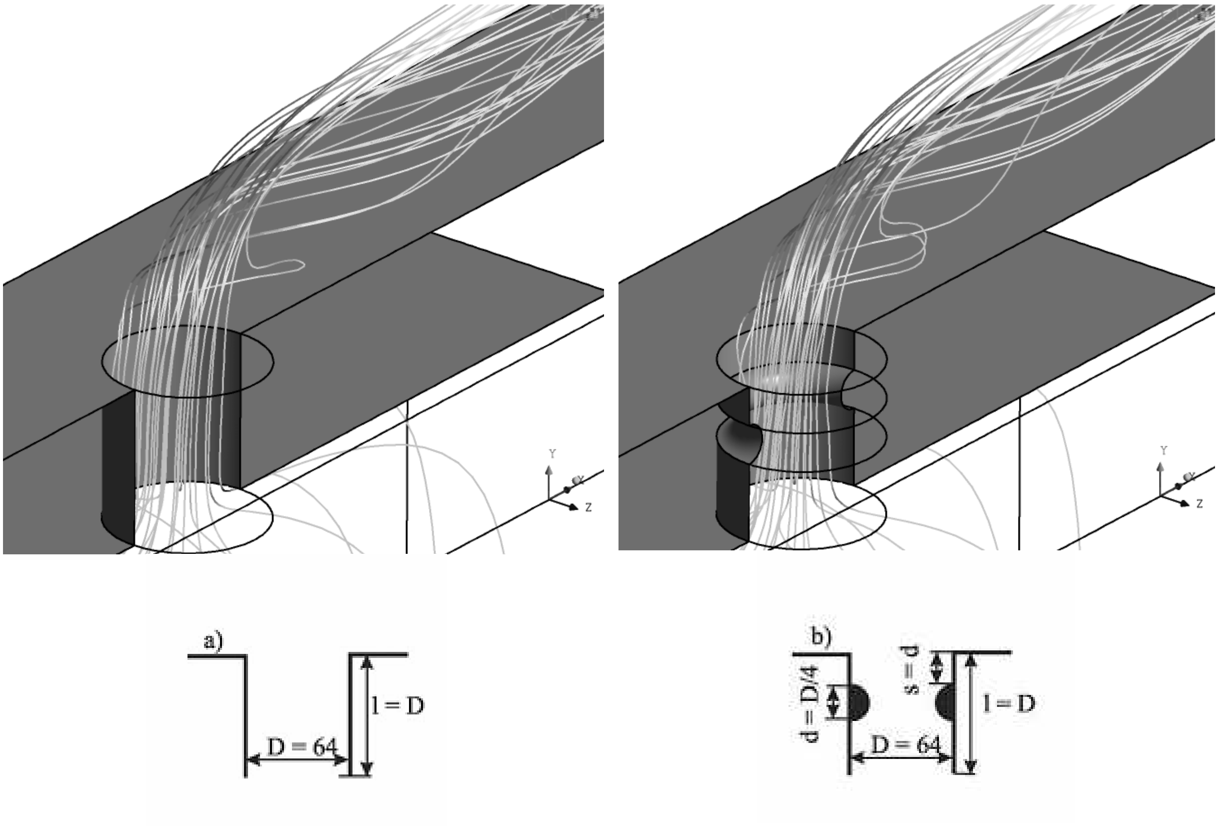


Figure 1. Geometries of the test cases holes, (a) Perfect hole (P), (b) Inner torus hole (IT)

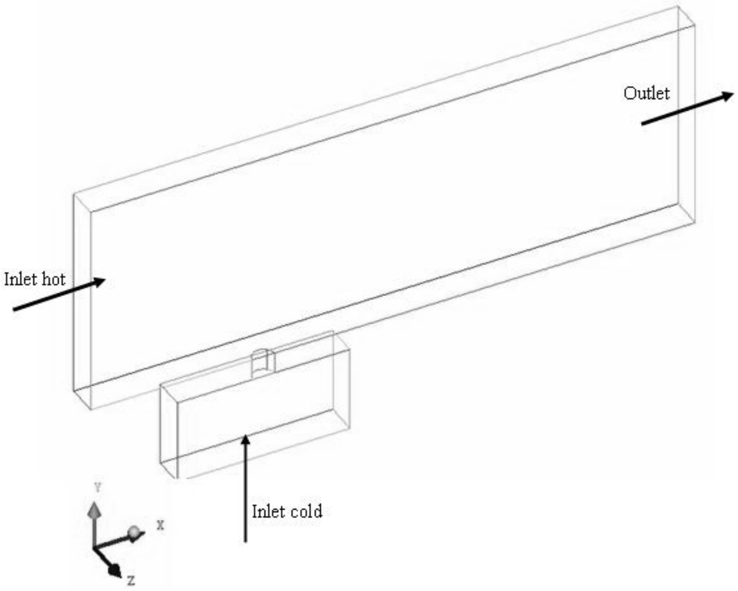


Figure 2. Computational domain

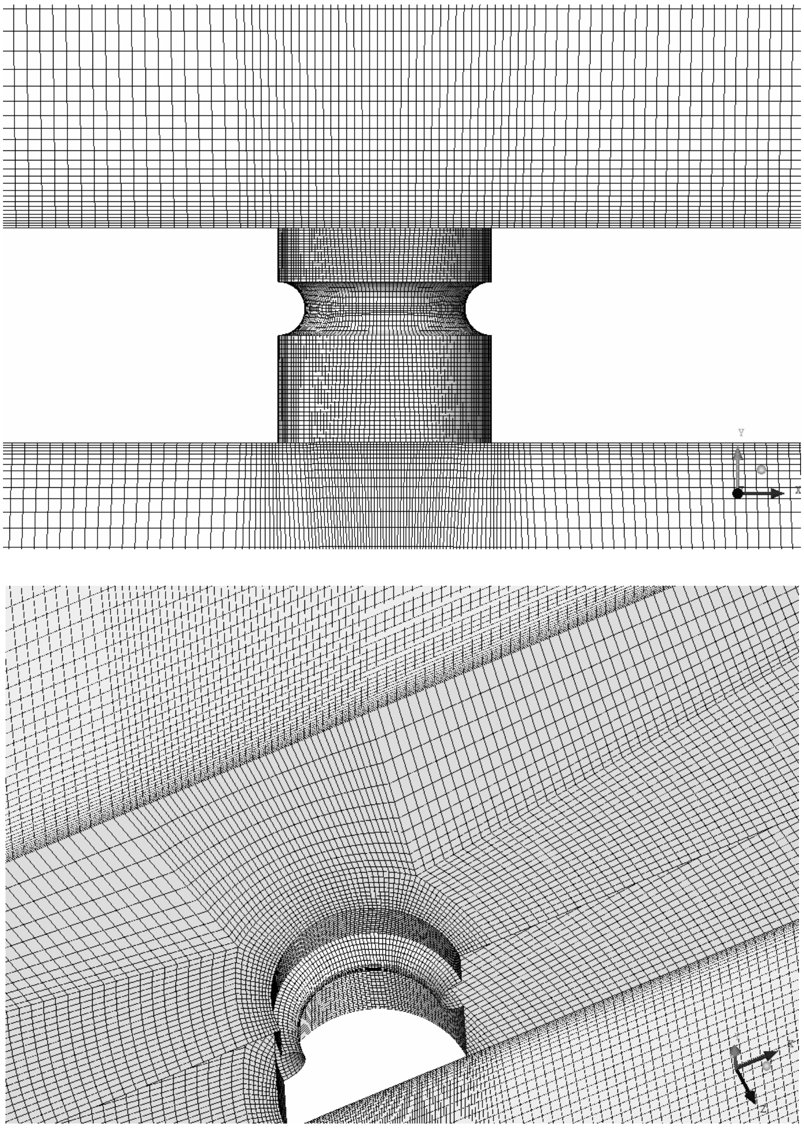


Figure 3. Computational grid, (Inner torus hole (IT))

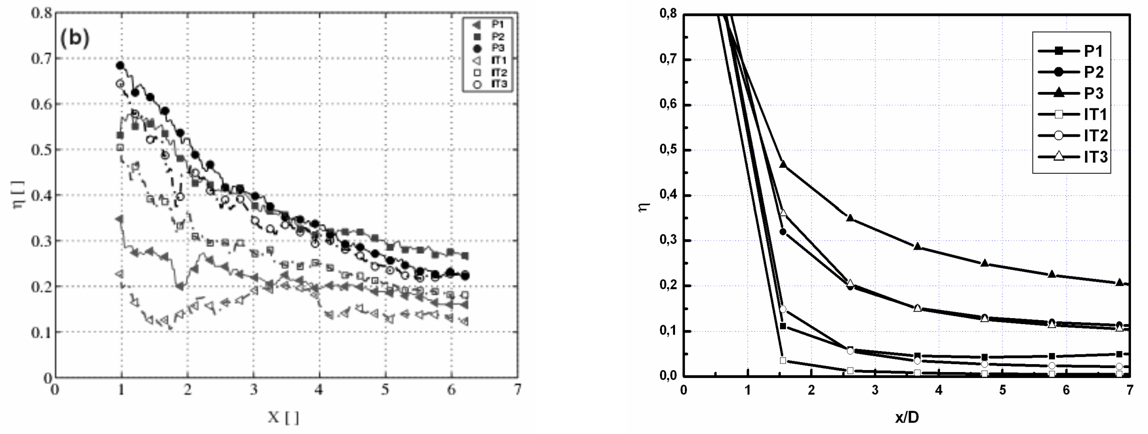


Figure 4. Centerline adiabatic film cooling effectiveness,
left: experimental measurements (Jovanović et al., 2006), right: present numerical data

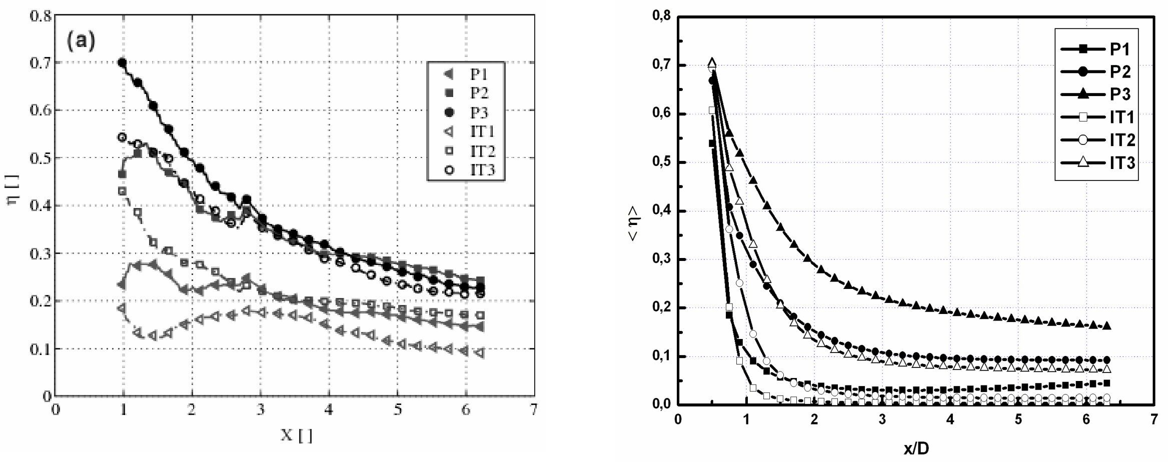


Figure 5. Laterally averaged adiabatic film cooling effectiveness,
left: experimental measurements (Jovanović et al., 2006), right: present numerical data

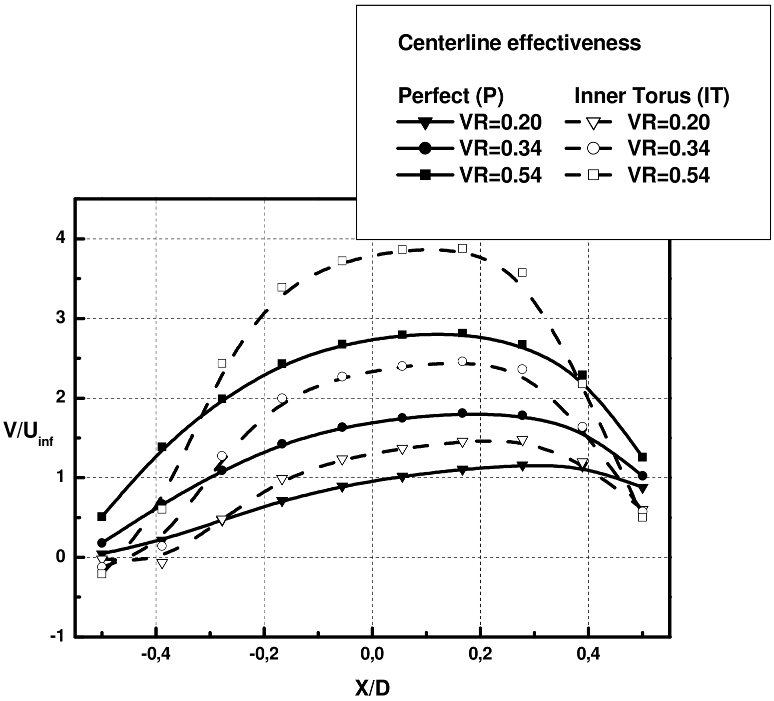
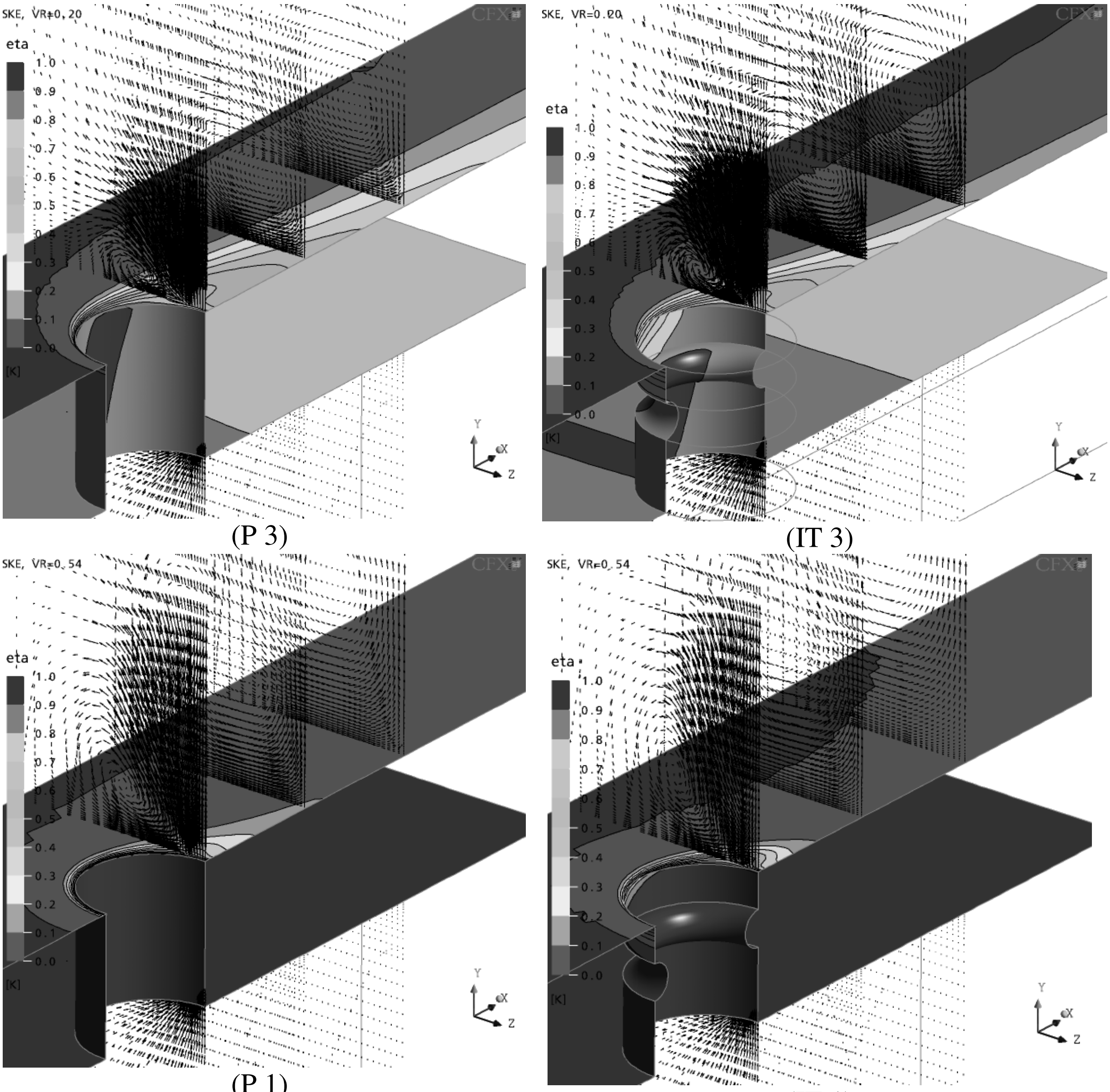


Figure 6. non-dimensionalized vertical velocity along the center plane in the vicinity of hole injection



(P 3) (IT 3)

(P 1) (IT 1)

Figure 7. Effectiveness contours on the flat plate and velocity vectors on three spanwise plans,

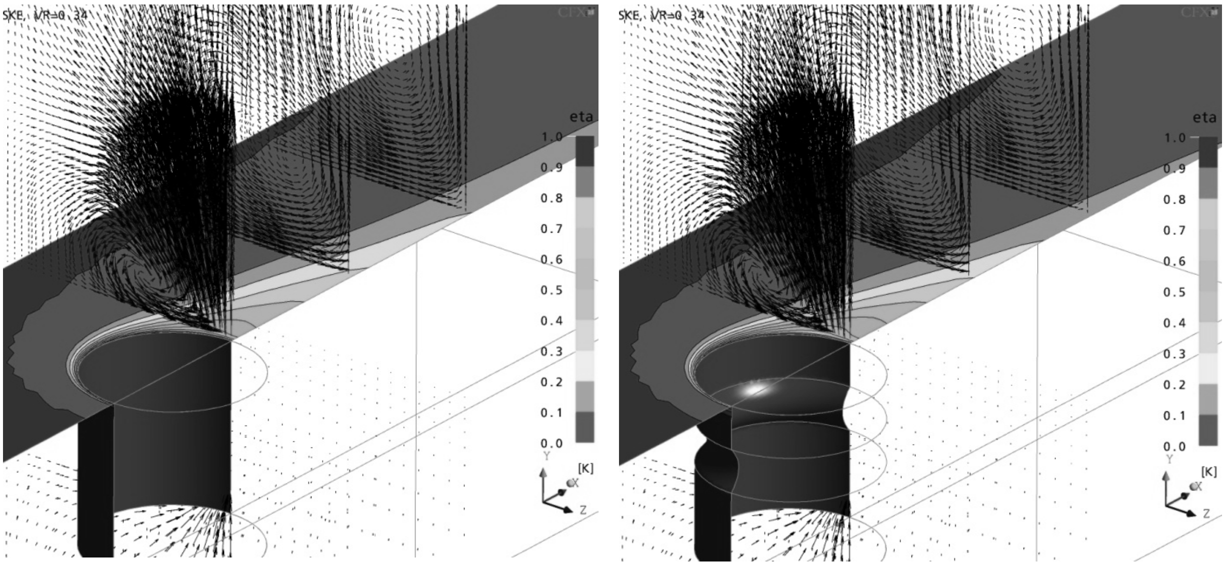
(P), 0% obstruction

(IT), 23.44% obstruction

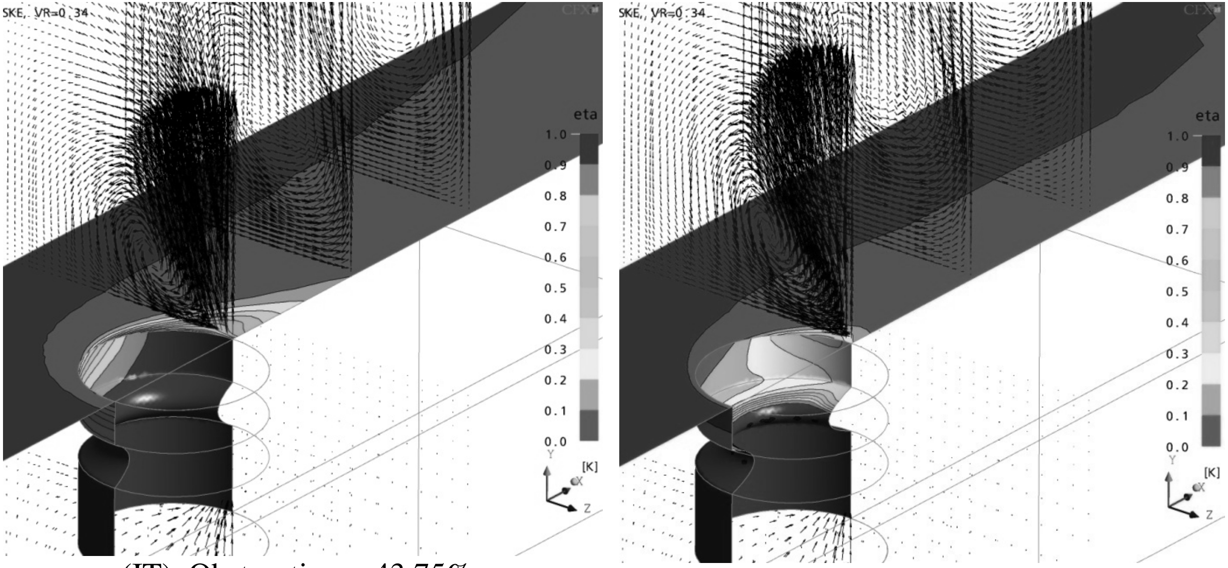
(IT), 43.75% obstruction

(IT), 60.94% obstruction

Figure 8. Geometries of the test cases holes, versus % of obstruction



(P), Obstruction = 0% (IT), Obstruction = 23.44%



(IT), Obstruction = 43.75% (IT), Obstruction = 60.94%

Figure 9. Effectiveness contours on the flat plate and velocity vectors on three spanwise plans for BR = 0.34

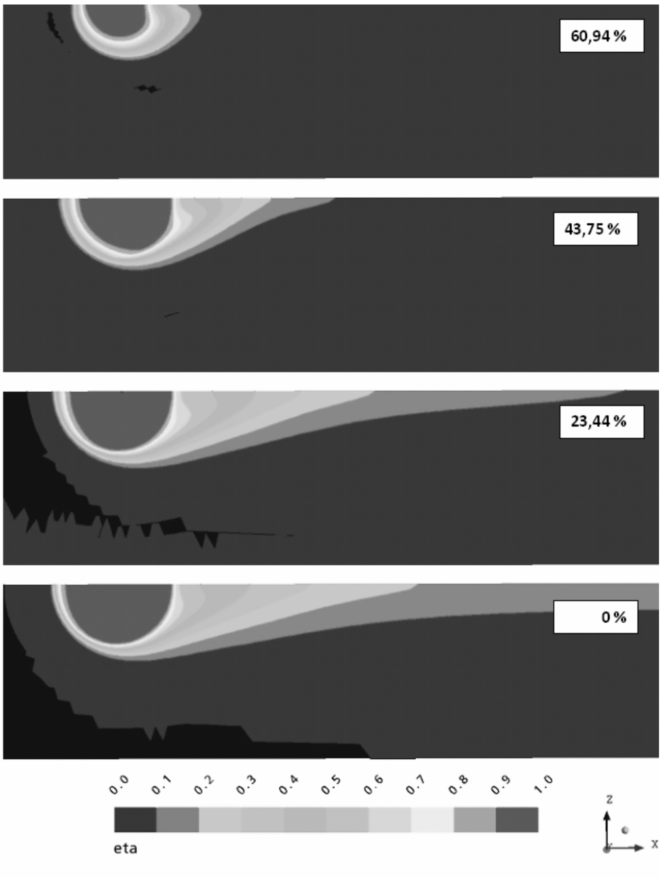


Figure 10. Film cooling effectiveness versus % of obstruction

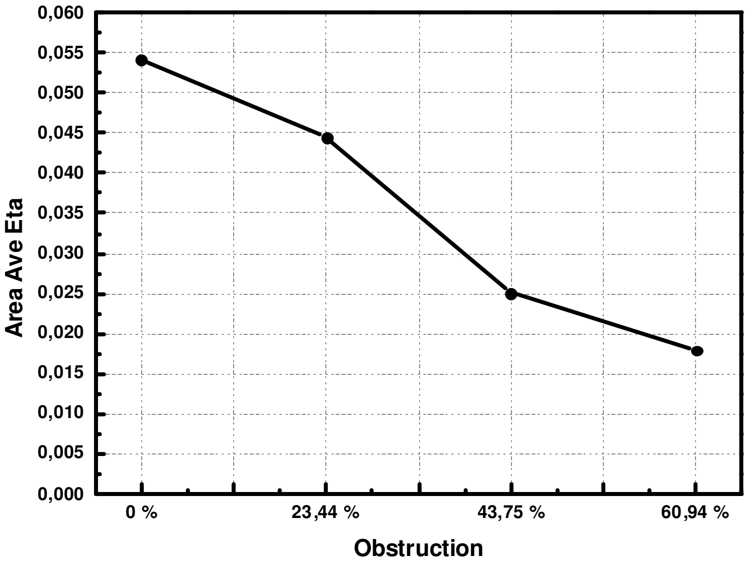
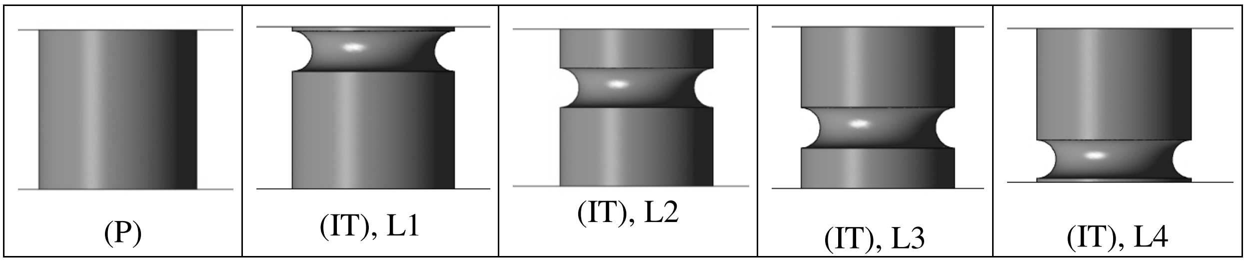
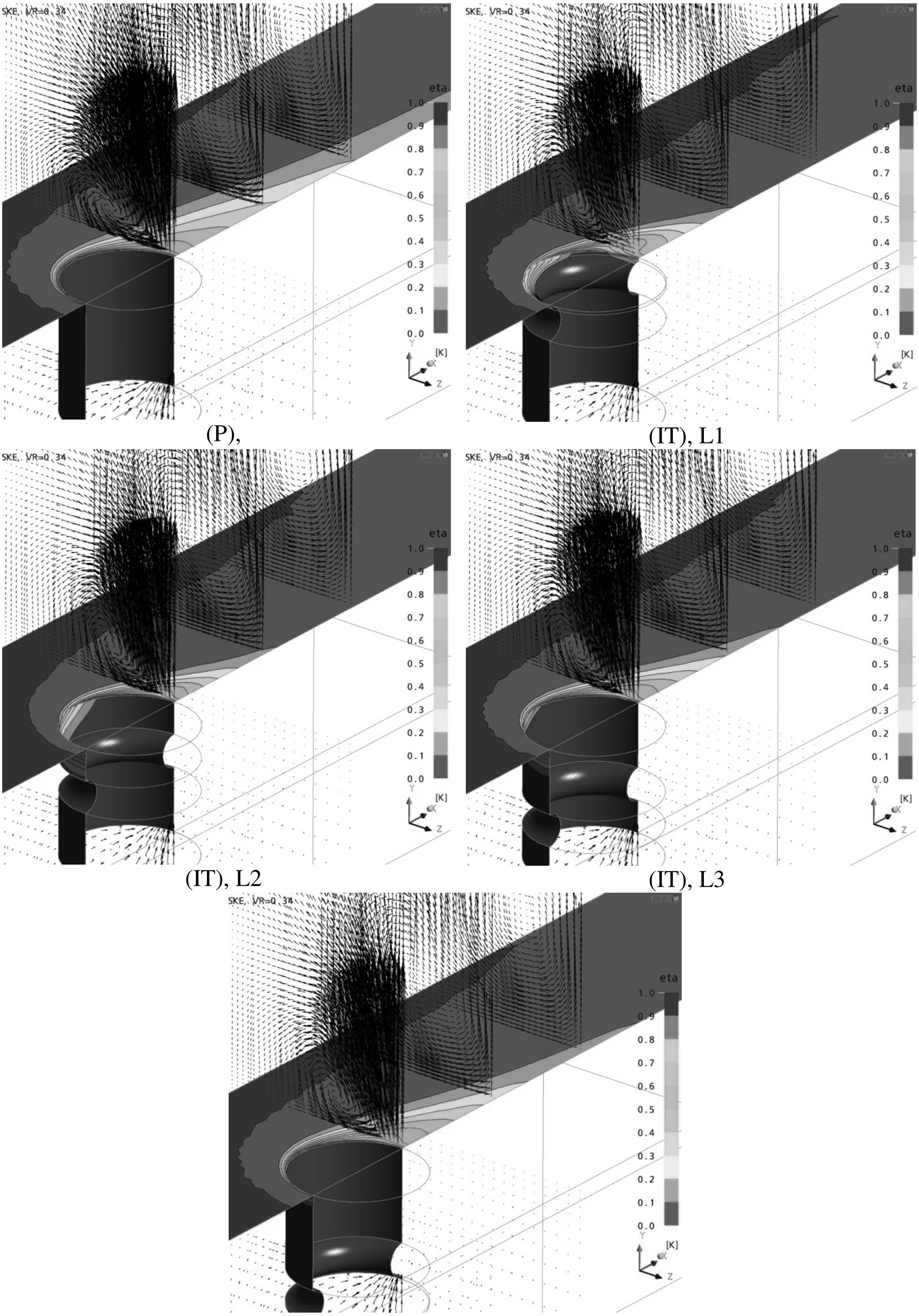


Figure 11. Area averaged film cooling effectiveness versus % of obstruction



(P) (IT), L1 (IT), L2 (IT), L3 (IT), L4

Figure 12. Geometries of the test cases holes, obstruction position



(P),

(IT), L1

(IT), L2

(IT), L3

(IT), L4

Figure 13. Effectiveness contours on the flat plate and velocity vectors on three spanwise

plans for BR = 0.34

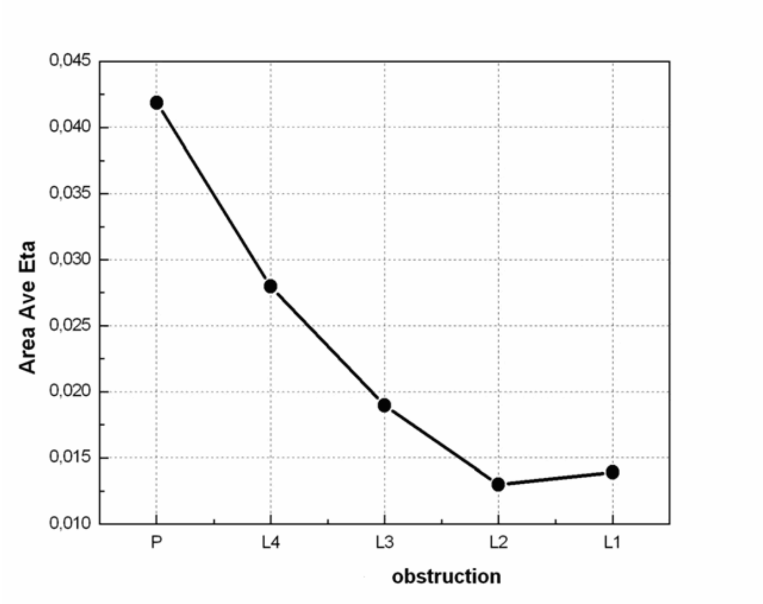


Figure 14. Area averaged film cooling effectiveness, obstruction position

Authors' information

Fadéla Nemdili
Laboratoire de Mécanique Appliquée, Faculté de Génie-Mécanique
Université des Sciences et de la Technologie d'Oran, B.P. 1505 El-Mnaouar, Oran, Algeria
Email : turbo_fad@yahoo.fr

Brief Professional biography :

Fadéla Nemdili is a lecturer at USTO University, Algeria. She received her Ph.D. thesis in 2008 from USTO University, Algeria. She is working on film cooling computations.

Abbès Azzi
Laboratoire de Mécanique Appliquée, Faculté de Génie-Mécanique
Université des Sciences et de la Technologie d'Oran, B.P. 1505 El-Mnaouar, Oran, Algeria
Email : abbesazzi@yahoo.fr

Brief Professional biography:

Abbès Azzi is Mechanical Engineer with a background of computational heat transfer and turbulence modelling. He received his Ph.D. in 2002 from USTO University working on film cooling computation in collaboration with ETH Zurich. He spent one year Post doctoral research on Large Eddy Simulation with the group of Pr. Lesieur at Grenoble, France. He work as Professor and researcher at USTO University, Algeria

B. A. Jubran
Department of Aerospace Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada
Email: bjubran@ryerson.ca

Brief Professional biography:

Bassam Jubran was educated at Cardiff University (formally University of Wales), Britain, graduating in 1980 with B.Sc. Honours degree in Mechanical Engineering. He obtained a PhD, also from the University of Wales, in 1984. He is currently a Professor of Thermo-Fluid Engineering at Ryerson University, a member of the Professional Engineers of Ontario, and the American Institute of Aeronautics and Astronautics (AIAA). Professor Jubran served as Editor-in-Chief of the Journal of Engineering Research, and he is currently on the editorial boards of the International Journal of Low Carbon Technologies, and the International Journal of Mathematics in Engineering, Science and Aerospace. He received the Hisham Hijjawi Award in the field of Energy and Informatics, 1997 and the Shoman Award for Young Arab Scientists (Engineering Sciences), 1994. Dr. Jubran has published more than 90 refereed Journal papers and over 35 conference proceedings papers.