A STUDY OF THE INFLUENCE OF THE TIP-CLEARANCE OF AN AXIAL TURBINE ON THE TIP-LEAKAGE FLOW USING CFD TECHNIQUES

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Abstract. *The quantification of internal losses during the design of a turbomachine is necessary to identify the magnitudes of the secondary, shock, profile, and tip leakage losses. Tip clearance losses have strong influence on the turbomachine operation. Therefore, they require particular attention during the design process, when the gap should be conveniently set. In this work, the influence of the rotor tip clearance on the performance of a multistage axial flow turbine is evaluated by means of turbulent, viscous, 3D flow calculations, which is of great complexity, therefore requiring deep understanding of its physical behavior. Commercial CFD software was used for the design point study. The performance parameters turbine efficiency, mass flow and pressure ratios, for several tip clearances, is presented for a flat tip rotor blade. The results were compared with data available in the references.*

Keywords*: turbomachine, axial turbine, CFD, tip clearance, tip leakage*

1. INTRODUCTION

Since the 19th century the design concepts related to the gas turbines have been qualitatively understood, but the knowledge required for more efficient operation, improved performance and durability were available only recently. Such requirement motivated massive investment on the turbomachine design processes. Such massive investments over the years on the study of fluid mechanics and thermodynamic cycles, led to considerable improvement in both experimental and theoretical methods applied to the whole engines, as well as to their components. As a result, turbomachines currently may exceed 90 percent total-to-total efficiency. Performance improvement of various engine parameters are still possible, but major concern nowadays is pollutant emission. This has driven heavy investments in research aiming at achievement of high performance and low emissions.

The application of Computational Fluid Dynamics (CFD) to the propulsion system integration and aerodynamic improvement (Prat *et al*., 1997) is a particularly long and difficult task. Use of new CFD methods is widespread, helpful and powerful for the design of the whole propulsion system. Attention of researchers is focused on the design of aerodynamic shapes, using CFD-based methods, and sophisticated design and optimization algorithms.

Axial turbine flow is unsteady and highly three-dimensional. Small clearances on top of the rotor blades are necessary to prevent rubbing of the blades. Local pressure differences between pressure and suction sides of the blades cause undesirable leakage flow through the clearance gap, disturbing the main flow, with increase of losses. Therefore, it is necessary to know details about the most important phenomena like the secondary flows, the vortices in the tip region, the tip clearance flow blockage, the scrapping vortex, the tip leakage vortex, the boundary layer, the wakes flow to name some of much importance. Tip clearance, trailing vortices, secondary vortices and turbine endwall regions are presented and discussed. Figure 1 depicts some of such phenomena.

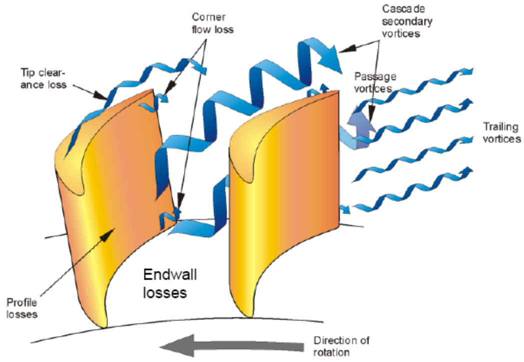

Figure 1. Schematic drawing showing tip clearance loss region (Japikse, 2009)

Although the phenomena that occur in this region have been studied extensively, during the preliminary design process a good understanding of the physical origin of the losses may be more valuable than a quantitative prediction. A flow schematic for the tip region of a turbine rotor blade is shown in Fig. 1. Detailed description of the physics involving internal flow of axial turbine can be found in Sjolander (1997), Tan (1997) and Mc Carter *et al.* (2000) and loss mechanisms in Denton (1993). The flow schematic for the region at the tip of a turbine rotor is shown in Fig. 2.

Estimation of losses can be made by several methods; the most recognized are the ones invented by Ainley & Mathieson (1951), Dunham & Came (1970) and Kacker & Okapuu (1982). Sources of losses are the friction on the profile, secondary and tip leakage, all considered independently. Better understanding of the tip leakage flow only begun in 1980's, with the introduction of flow calculation by means of three-dimensional Navier-Stokes in CFD codes.

All such methodologies are relevant during the turbomachine design, although experimental tests are essential to calibrate the results and correctly predict the flow.

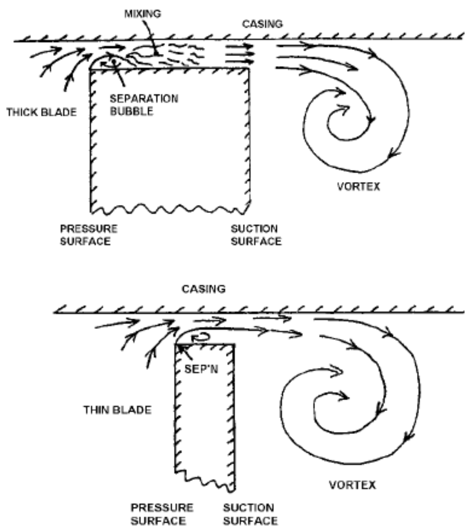

Figure 2. Representation of flows in the tip gap of an unshrouded blade (Denton, 1993)

During engine operation, the tip clearance in a turbine varies considerably due to the aeroelasticity, centrifugal and thermal loads of the rotor blades and casing. The position of the bearings defined by mechanical integration team has also influence due to the deformation of turbine axis of rotation. In aeronautical applications, the engines are lighter, thus responding more quickly to temperature changes, leading to a different pattern of variation during the change in operating point.

This work uses information collected from the report of Leach *et al.* (1982), about a four-stage axial turbine design, whose main turbine geometrical and operation characteristics are published. The aerodynamics and thermo-mechanical designs of the intermediate and low-pressure turbine are goal tasks for the performance improvement by the use of state-of-art leakage control concepts, low loss airfoil design, active clearance control and high strength and high temperature materials, for example. Being proprietary, experimental data of this turbine were not disclosed. The design mass-flow, efficiency and pressure ratio were used to reproduce the design parameters and to compare the calculations with results obtained from commercial software for design. The evaluation of tip-leakage flows based on tip-clearance variations using a computational fluid dynamics (CFD) was used by Anderson Jr. (1995) to predict the variations in pressure ratio, efficiency and mass flow for different gap clearances.

The grid generation and flow within the axial turbine were calculated using Concepts ETI's AxCent commercial CFD software.

2. LITERATURE REVIEW

Important studies on the tip clearance in turbomachines date from the 1960's and were based on experiments, correlations and models. Numerical studies and design modifications were introduced later and nowadays are being widely used for the investigation of tip clearance losses. Casing treatment and modifications, like circumferential grooves and slots, as well as blade pinched tip for compressors. Lu *et al.* (2006), Tomita and Barbosa (2007) and Williams (2009) contributed with studies on tip clearance influence on performance of turbomachines.

Tip desensitization, which is the alteration of the flow in the tip gap region aiming at reduction of the tip leakage flow and tip heat transfer coefficients, and geometric modifications of the blade tip (winglets and squealer-type geometries), in addition to casing treatment and casing recess, are being used to improve performance of turbomachines.

Saha *et al*. (2006) and Schabowski and Hodson (2007) analyze turbine rotor blade tip with squealer and winglet. The former describe a numerical study with and without pressure side winglet for a flat tip and full squealer and only suction side squealer tip. The latter investigate the impact of various combinations of squealer and winglet geometries on the turbine performance and the influence of the thickness of the squealers, using numerical and experimental results. Both concluded that winglet, squealers and their different blade tip shapes influence the flow pattern, therefore losses.

Krishnababu *et al.* (2009) published a numerical study to evaluate influence of different tip geometrics on the tip leakage flow and heat transfer, based on flat tip geometry and squealer type geometries, comparing two different tip clearance gaps. It was observed that, in comparison with the simple geometries, the squealer type geometrics are advantageous aerodynamically and for heat transfer, because they decrease leakage flow, and hence losses and average heat transfer at the tip. Harvey (2004) presents a thorough discussion about aerothermal implications of tip clearance, geometric modifications and treatments for shrouded and unshrouded blades.

3. THE MULTISTAGE AXIAL FLOW TURBINE GEOMETRY

The axial turbine used for the analysis of the effects of variation of the tip clearance is a four-stage low pressure turbine, whose data were published by Leach *et al.* (1982). The design parameters are:

- Mass-flow: 31.85 kg/s;
- Rotational speed: 3902 rpm
- Inlet total pressure: 319.2 kPa
- Inlet total temperature: 1161 K
- Pressure ratio: 5.51
- Isentropic efficiency: 88.9 %

Figure 3 shows the CAD-generate 3D geometry of that turbine.

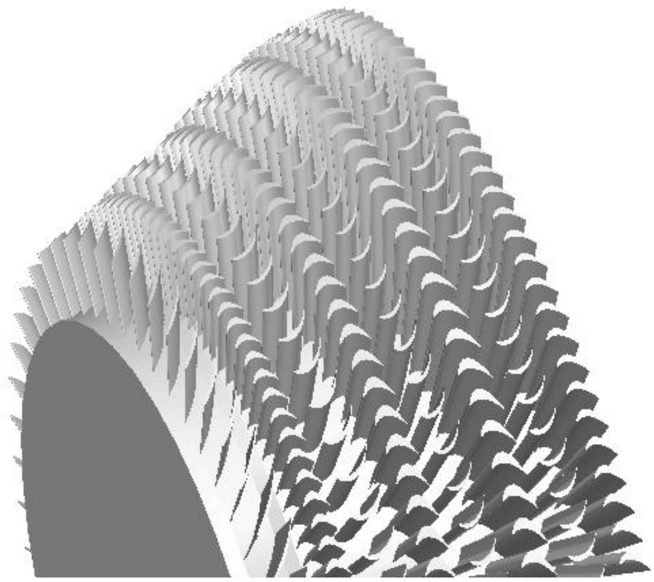

Figure 3. Four-stage axial turbine reconstructed from Leach *et al.* (1982).

The blade count for each row is shown in Table 1.

Table 1- Number of turbine blades for each row

STAGE	BLADE NUMBER	
	Stator	Rotor
1	54	120
2	72	96
3	84	100
4	108	122

This low pressure turbine drives the fan of an aeronautical gas turbine. Although the turbine details are not the scope of this work, and many of them are not described in the reference due to the proprietary information, it should be recognized that the design details and the loss models used for its design, and all the calibration settings, of fundamental importance, might not be the same as used in this work.

4. GRID GENERATION

The structured H-type grid was generated from the 3D geometry produced by CAD software, smoothed and refined to fulfill the requirements of the turbulence model used for the flow calculation. Several grids were tested, finishing with the one with 61 nodes spanwise, 33 nodes blade-to-blade and 1.144 nodes streamwise.

Figure 4 shows some details of one of the grids used in this work. For each blade tip clearance a grid was generated to take account of the different tip geometries.

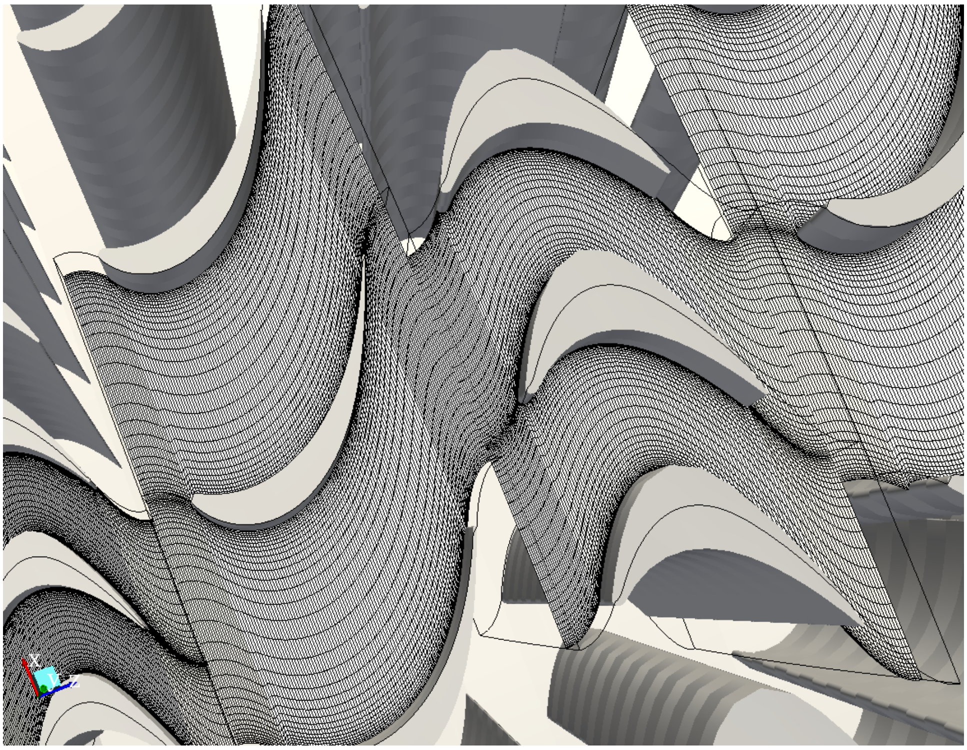

Figure 4 - Generated grid for second stage

5. BOUNDARY CONDITIONS AND NUMERICAL IMPLEMENTATION

The boundary conditions are:

- At inlet: total conditions (pressure and temperature);
- At outlet: static pressure with radial equilibrium;
- At the inter blade positions: periodicity;
- At the walls: non-slip;
- At the spaces between consecutive rows: mixing-plane averages.

The flow was modeled using a system of equations made of the conservation equations, the turbulence model equation of Spalart and Allmaras (1992), equation of perfect gas with variable properties, as indicated below.

- Mass conservation:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.\left(\rho u_i\right) = 0 \tag{1}$$

- Momentum:

$$\frac{\partial\left(\rho u_i\right)}{\partial t} + \vec{\nabla}.\left[\left(\rho u_i u_i\right) - \vec{\vec{\sigma}} - \vec{\vec{\tau}}\right] = 0 \tag{2}$$

- Energy:

$$\frac{\partial\left(\rho e_t\right)}{\partial t} + \vec{\nabla}\cdot\left[\left(\rho e_t u_i\right) - \left(\vec{\vec{\sigma}} + \vec{\vec{\tau}}\right)u_i - \vec{q}\right] = 0 \tag{3}$$

The spatial discretization was based on Liou's (1996) third-order Advection Upstream Splitting Method ($AUSM^+$), which uses a cell interface Mach number based on characteristic speeds from the neighboring cells.

The spatial integration was carried out in an explicit time-marching scheme.

The time integration was performed using a second-order four-step Runge-Kutta scheme and Upwind extrapolation for the convective inviscid fluxes.

The effects of turbulence were simulated using the Spalart and Allmaras (1992) one-equation turbulence model for the transport of the modified eddy-viscosity, indicated below.

$$\frac{D\tilde{v}}{Dt} = C_{b1}(1 - f_{t2})\tilde{S}\tilde{v} + \frac{1}{\sigma}\left[\nabla.\left((v+\tilde{v})\nabla\tilde{v}\right) + C_{b2}(\nabla\tilde{v})^2\right] - \left[C_{w1}f_{w1} - \frac{Cb1}{K^2}f_{t2}\right]\left[\frac{\tilde{v}}{d}\right] + f_{t1}\Delta U^2 \quad (4)$$

where:

$$vt = \tilde{v}f_{v1}; \quad f_{v1} = \frac{\chi 3}{\chi 3 + C_v 1^3}; \quad \chi = \frac{\tilde{v}}{v}$$

$$\tilde{S} = S + \frac{\tilde{v}}{K^2 d^2} f_{v2}; \quad f_{v2} = 1 - \frac{\chi}{1 + \chi\ f_{v1}}$$

$$f_{w1} = g\left[\frac{1 + C_{w3}^6}{g^6 + C_{w3}^6}\right]; \quad g = r + C_{w2}(r^6 - r); \quad r = \frac{\tilde{v}}{\tilde{S}K^2 d^2}$$

$$f_{t2} = C_{t3}\exp\left(-C_{t4}\chi^2\right)$$

$$f_{t1} = C_{t1} gt \exp\left(-C_{t2}\frac{w_t^{\ 2}}{\Delta U^2}\left[d^2 + g_t^{\ 2} d_t^{\ 2}\right]\right); \quad g_t = \min\left(\frac{0.1\Delta U}{w_t \Delta x_t}\right)$$

$$C_{b1} = 0.1355\,; \sigma = 2/3\,; C_{b2} = 0.622\,; K = 0.41$$

$$C_{w1} = C_{b1}/K + (1 + C_{b2})/\sigma$$

$$C_{w2} = 0.3; C_{w3} = 2;\ C_{v1} = 7.1\,; C_{t1} = 1\,; C_{t2} = 2\,; C_{t3} = 1.1\,; C_{t4} = 2$$

The flow is considered fully turbulent; hence all transition terms in the turbulence model are turned-off.

The simulations were carried out using the following Courant Numbers: 1.3 (simulation without tip clearance) and 0.55 (simulations with tip gap) to account for numerical stability. Acceleration of numerical convergence was achieved by implicit residual smoothing, variable time-step and multigrid. At every other loop the calculations of turbulence were performed during time integration.

6. TIP CLEARANCES SELECTION

The baseline was set with a turbine without tip clearance. Three other tip clearances configurations were, for all rotors: a) 1.5%; b) 2.0% of the rotor blade height; c) configuration with different tip clearance as shown in Tab. 2.

Table 2. Values of the gaps at the rotor blade for case c)

	FIRST CASE	SECOND CASE	THIRD CASE	FOURTH CASE
ROTOR	TIP GAP (%)	TIP GAP (%)	TIP GAP (%)	TIP GAP (%)
1	0.0	1.5	2.0	1.5
2	0.0	1.5	2.0	1.6
3	0.0	1.5	2.0	1.8
4	0.0	1.5	2.0	2.0

7. CFD RESULTS

The CFD simulations were made at the turbine design condition.

Sjolander (1997) refers to the fact that, although the gap is little, the tip leakage flow has large effect on the aerodynamics of the turbomachine. Small variation of the gap causes considerable decrease of the machine efficiency, therefore increasing the fuel consumption and the consequent the operating costs.

According to Sjolander (1997) and Krishnababu *et al*. (2009), in an unshrouded turbine, the tip gap is of the order 1% - 2% of blade height, though manufacturing tolerances, centrifugal expansion, and dissimilarity between the thermal loading of the blade row and casing lead to a variation in the clearance during the operating cycle.

During the calculations, the numerical residues and the mass-flow were monitored. The numerical residues and mass flow history are shown in Figures 4 and 5. Table 3 shows the results of the design using 2D code and 3D CFD calculations, for the tip clearances chosen. It can be observed that the efficiency predicted using 2D code is higher compared with the predicted using CFD. This could be originated by the choice of the loss correlation models used in the meanline and streamlines design techniques. The predicted efficiency of 89% may be overestimated.

Table 3. Comparison of results from CFD and meanline/streamlines

	Mass Flow (kg/s)	**Pressure Ratio**	**Efficiency (%)**	**Design Tool**
Original Design	31.85	5.51	89.0	1D and 2D
Baseline	32.49	5.34	84.7	3D
1.5% gap	32.60	5.27	83.6	3D
2% gap	32.73	5.22	81.6	3D
Various gaps	32.67	5.23	81.8	3D

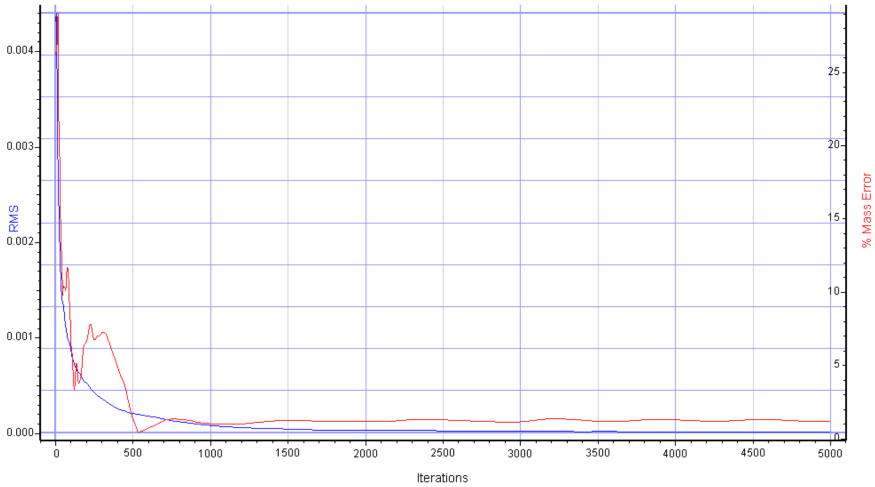

Figure 5. Numerical residues decay during 5,000 iterations (simulation without tip gap).

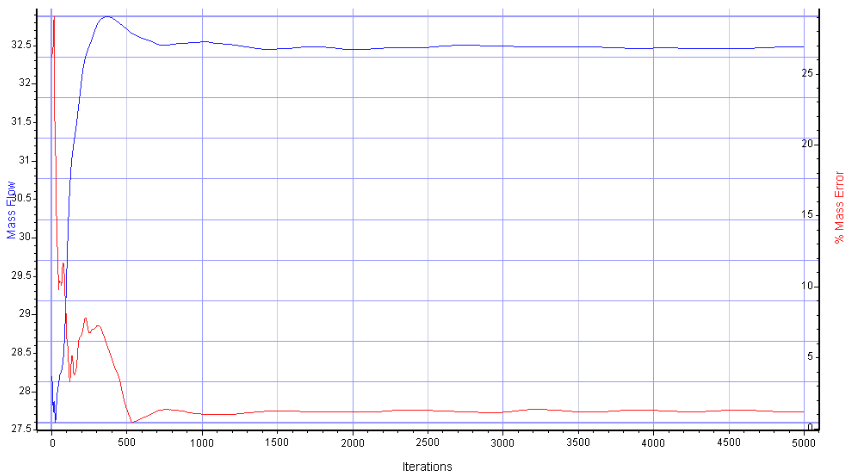

Figure 6. Mass-flow calculations during 5,000 iterations (simulation without tip gap).

Figure 7shows the static pressure and Fig. 8 the Mach number distribution along the axial turbine channel for the rotor without tip gap. The graphs show the distribution of total pressure along the blade span for each rotor.

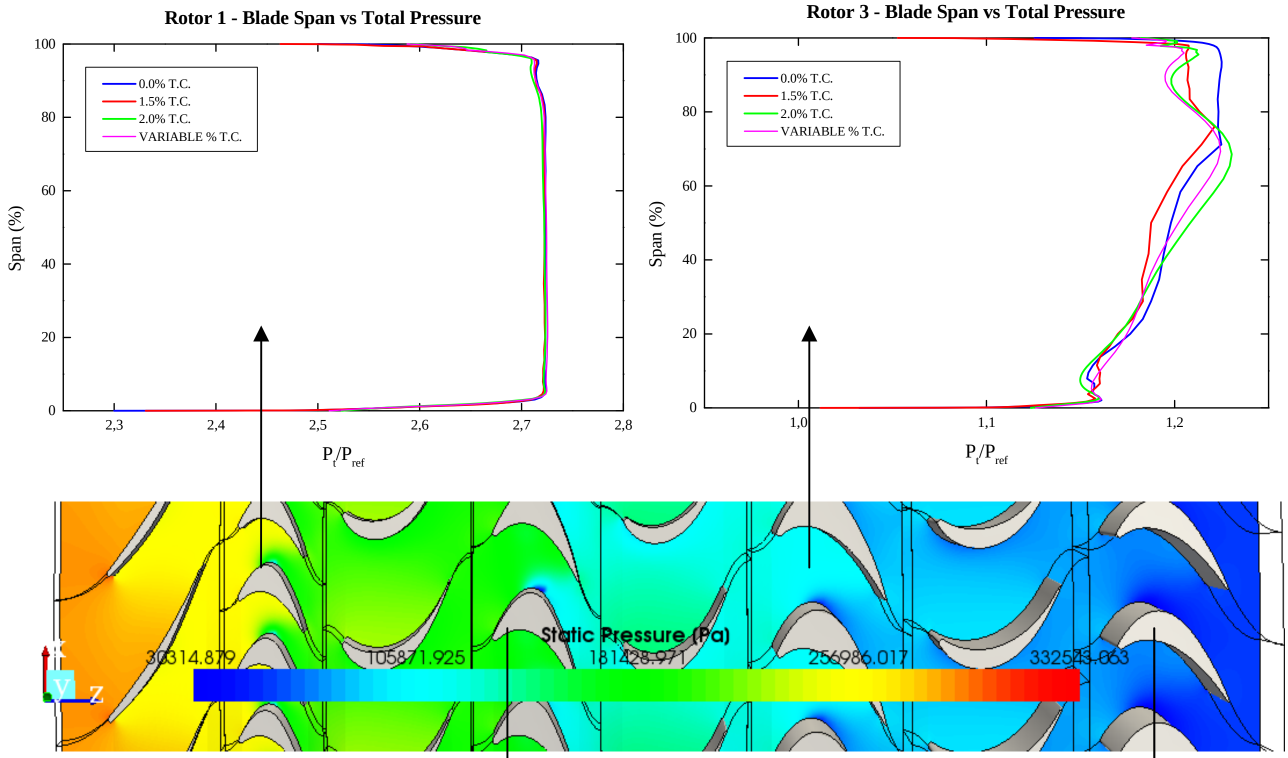

Figure 7. Static pressure contours at 90% of blade span.

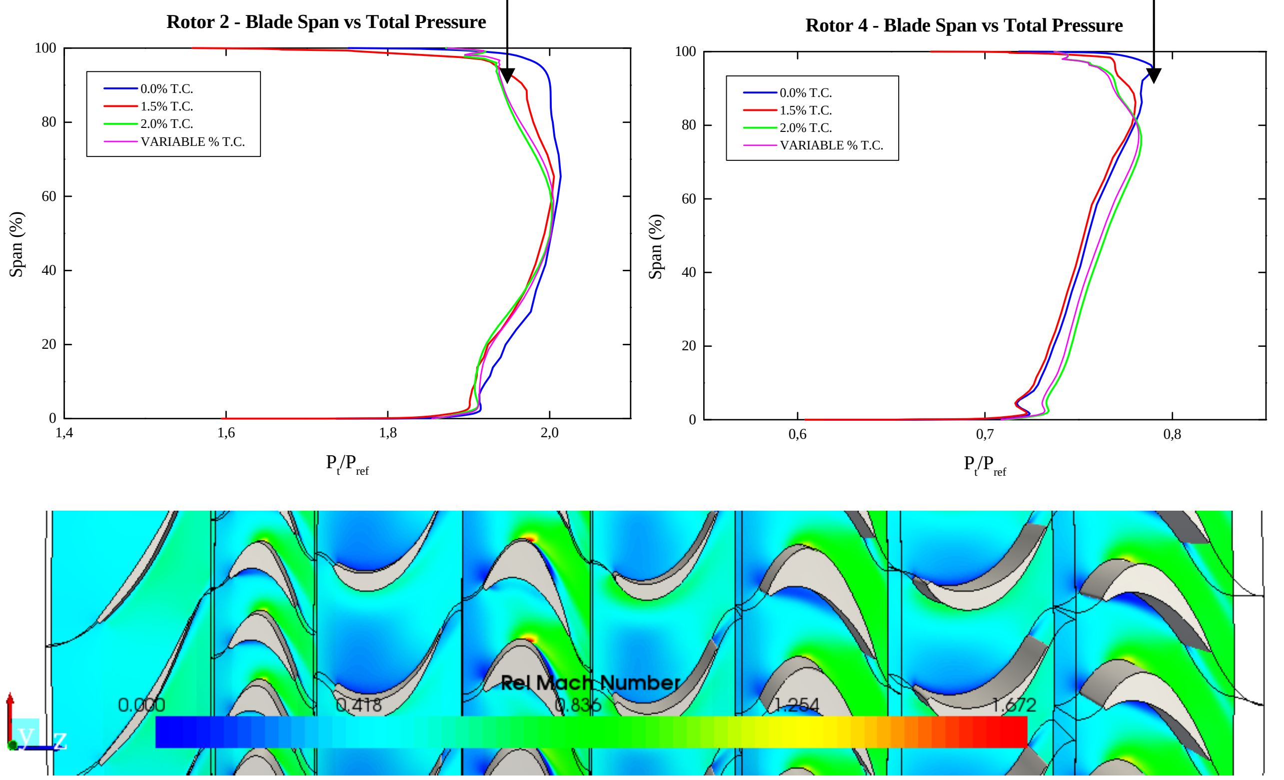

Figure 8. Mach number contours at 90% of blade span.

The leakage flow at the gap region does not participate in the energy transfer process. Hence, the secondary losses should increase for high values of tip gap and the efficiency and expansion ratio should decrease.

8. DISCUSSION AND CONCLUSION

CFD simulations of flows in multistage turbomachines require fine grids. The complexity of the flow makes more difficult the calculations, especially when different flow regimes (subsonic and supersonic) appear in the blade passage. This would require special numerical methods in order to make the solver robust. In this work, a variable time-step, implicit residual smoothing and multigrid techniques were used to improve convergence. It was observed in several cases tested, using Courant number higher than 1.0, that the numerical solutions diverged during the flow calculations for rotors with tip gap, while the solution was smoothly achieved if no tip gap was considered. Also, for several cases considering around 1% tip clearance, divergence occurred if a third-order spatial discretization scheme was used, even if the calculations started with first-order discretization and substituted for a third-order scheme after stabilization of the mass-flow. For all those cases the grid was refined appropriately. For some of the cases, preconditioning was used to take account of flows in large speed range and to enhancing the numerical robustness in regions of low Mach number, but no convergence was achieved, despite the use of a second-order centered scheme with non-linear artificial viscosity to avoid numerical instabilities in regions with high gradients as in the shock waves. Mass flow oscillated in these cases, but no divergence was observed, independently of the grid size.

The results from CFD calculations show clearly the influence of the tip clearance and its gap values on the efficiency and pressure ratio of a low pressure multistage axial flow turbine. A very high difference of 3.1% in efficiency was found if the first and the third cases of Table 3 are compared. This is a large difference that would cause significant drop in the engine thermal efficiency. Evaluation of the turbine tip gap influence on efficiency as early as during the turbine design phase, is of much importance. Variations of tip clearances due to rubbings during aircraft maneuvers, the wearing of the engine bearings and the mechanical deformation of the whole engine must be taken into account at that stage.

As a plus of the results obtained in this research, the boundary conditions for the stress analysis could be better defined from the pressure and temperature distributions on the blade and casings surfaces.

Unfortunately, no published experimental data of the turbine studied in this work were found in the literature, perhaps because they are proprietary. The conclusions drawn from the results are in agreement with what could be expected, what indicates the validity of the study. Moreover, the efficiencies calculated from the CFD data are more realistic than the ones from the 1D and 2D models.

The methodology used to predict the turbine efficiency using CFD calculations can be used in conjunction with high-fidelity design-analysis computer programs, in the same direction as the methodologies used for the design of new generation of low emission and quiet gas turbines, as indicated by Konstantinos *et al.* (2011). Small improvement on engine performance means great reduction in engine operational cost, thus better share of the market.

9. ACKNOWLEDGEMENTS

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