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# EFFECT OF THE TIP CLEARANCE ON THE CHARACTERISTICS OF A 1.5 COMPRESSOR STAGE WITH REGARD TO THE INDEXATION

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## ABSTRACT

Axial compressors have inherently unsteady flow fields because of relative motion between rotor and stator airfoils. This motion leads to viscous and potential interactions between blade rows. As the number of stages increases in turbomachines, the build up of convected wakes can lead to progressively more complex interactions. Variation in the relative circumferential position between stators or between rotors can change these interactions, leading to different unsteady forcing functions on airfoils and to different compressor efficiencies. Previous quasi-three-dimensional Navier-Stokes analysis showed that airfoil clocking can produce significant performance variations at the Mach numbers associated with an engine-operating environment. The potential benefit of airfoil clocking is an increase in stage efficiency. Depending on the turbulence model used, the variation of efficiency was on the order of 0.7% and 1.5% in the stage [ref. 3, ref. 1]. The losses in the second-stage stator passage appear to vary most as the airfoils are clocked. The 1.5 stage compressor used is made of an inlet guide vane (IGV), a rotor, and a stator. The indexing is performed between the IGV and the stator. In the absolute frame of reference downstream of the rotor, a bubble of loss issued from the interaction between the IGV-wake and the rotor tip clearance was measured in the tip region. In the hub region, the presence of the IGV-wake was found to have an influence on the extend of the stator hub clearance flow. Hence the indexing between the IGV and the stator will not only imply the positions of the IGV-wake at stator inlet, but also the here mentioned secondary flows.

## INTRODUCTION

The tip clearance is one of the most important source of losses axial compressors. A large amount of studies were performed concerning the effect of this tip gap on the characteristics of axial compressors and turbines. Experimental and numerical studies investigated the structure of the tip clearance using the latest measurement techniques and algorithms. However the prediction of the characteristics of compressors and turbines remains the main objective for turbomachine manufacturer. In parallel, few studies were done concerning the clocking (i.e. indexing) either through calculations or measurements. The published results mainly concerned the region at midspan and only the effect of the upstream stator wake on the following stator was investigated. A lack in information persists concerning the nature of the flow in the endwall regions.

An experimental investigation was performed, concerning the effect of the rotor tip clearance on the characteristics of a subsonic axial compressor stage. The measurements were performed on a 1.5 stage compressor composed of an Inlet Guide Vane followed by a rotor and a stator. Three different rotor tip clearances were investigated: 1.25%, 2.00%, and 4.00% of channel height. The stator hub clearance was kept constant at 1.25% channel height. The characteristics were determined by Temperature- and Aerodynamic probes measurements at inlet and exit of the compressor stage, over a pitch and from 10% to 90% of the channel height. Detailed Pitot measurements were performed in the same sections from 1% to 99% of the channel height and over one pitch with a step of 0.5 degree. In addition to the tip clearance effect, it was noticed that the IGV wake had an influence on the loss zones visualized at 0.84 stator chord length downstream the stator.

In order to emphasis the influence indexing on the effect of the tip clearance on the characteristics of an axial compressor stage, results from another study [ref. 13] will also be used.

## NOMENCLATURE

| | |
|---|---|
| cx | Axial velocity |
| h,H | Channel height [mm] |
| L | Chord [mm] |
| Lxstat | Axial stator chord [mm] |
| N | number of blade per row[] |
| Tc | Stagnation temperature [K] |
| t,τ | tip clearance [mm,%h] |
| u | tangential velocity of the rotor at midspan[m/s] |
| z | Radial coordinate [mm] |
| θstat | pitchwise position / pitchwise step [degree] |
| θstat | Stator pitch [degree] |

## TEST FACILITY AND MEASUREMENT EQUIPMENT

The compressor test facility of the LTT (Laboratoire de Thermique appliquée et de Turbomachines) is made up of an inlet guide vane (IGV), a rotor, and a stator. The rotor that is driven by an electric motor has a maximum velocity of 18000 rpm and the results presented in this paper were performed with a rotor velocity of 15’000 rpm. The test facility is a closed loop [Fig. 1] that enables the use of other gases than air. The temperature is held constant with the aid of heat exchangers in this study, the inlet stagnation temperature was 293K ± 0.2. The hub diameter is 160 mm and the channel height is 40 mm.

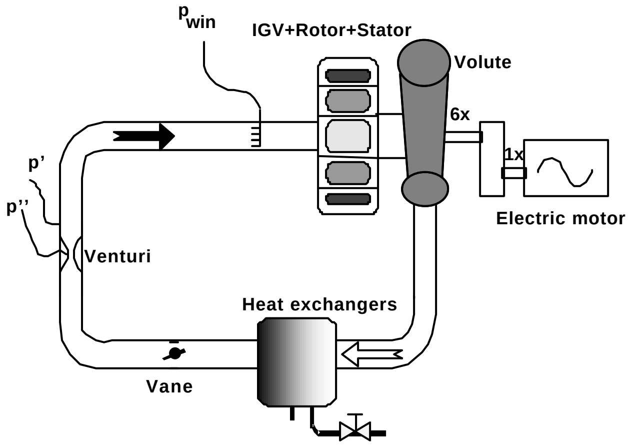

**Fig. 1** Closed loop axial compressor test facility

The variation of the tip clearance was performed using rotors with different diameters leading to tip clearances of 1.25 %, 2.00 % and 4.00 %of the channel height. The IGV is sealed at hub and tip and the stator has a hub clearance of t/h=1.25%. Pitchwise traverses are accomplished by rotating the IGV and the stator in unison past stationary probes mounted in radial actuators attached to the fixed tight chamber around the casing. The IGV and the stator are rotated with the aid of hydraulic cylinder. The indexation between the IGV and the stator is performed with a second hydraulic cylinder mounted between the IGV and the stator.

## TRAVERSE MEASUREMENTS

The characteristics of the compressor stage are determined with the aid of traverse measurements performed up- and downstream of the compressor stage. The measurement mesh has 23 points in the pitchwise direction and 9 points in the radial direction. The included measurement surface in each section goes from 10% to 90% of the span with a radial step of 10% of channel height. In the pitchwise direction, the measurements are done over 18 degrees, corresponding to the stator pitch. The pitchwise step is 1 degree except the first four degrees were the step was reduced to 0.5 degree due to the presence of the wake downstream of the IGV.

## THE PITOT PROBES

In order to have a detailed description of the loss zones for the different configurations of the compressor, measurements of the flow field were performed with cobra type Pitot probes on a refined mesh. These measurements were done in order to identify the secondary flows and to know their extent. The flow field is measured up- and downstream of the compressor stage, from 1% to 99% span and over a stator pitch (18 degree). Radial steps of 1% of the channel height are used except in the midspan region and in the pitchwise direction the measurements are done every 0.5 degree. Fig. 2 shows this measurement mesh having 2923 points per section. The Pitot tube had a diameter of 1 mm, which advantage was to reduce the wall effects on the probe.

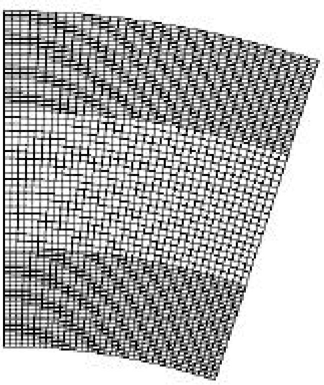

**Fig. 2** Detailed measurement mesh; 79x37 nodes.

## TRAVERSE MEASUREMENTS RESULTS

A very large amount of data are available in this study, but emphasis is put on the high loaded cases for the three tip clearances, listed in Table 1

| t/h | Test cases | $c_x/u$ |
|---|---|---|
| 1.25% | 004 | 0.427 |
| 2.00% | 104 | 0.421 |
| 4.00% | 051 | 0.440 |

**Table 1** High loaded cases for the three tip clearances.

Fig. 3 shows the stagnation pressure distribution 84.7% axial chord downstream of the stator trailing edge for the highest loaded test cases (Table 1). When the tip clearance is increased a core of stagnation pressure loss appears in the upper half of the channel in the stator wake region. It will be seen with the detailed Pitot measurements that this zone of low stagnation pressure is issued from the interaction between the IGV-wake and the rotor tip clearance flow. This will lead to a zone of loss downstream of the rotor and which location is constant in time in the absolute frame of reference (Fig. 6). This zone enters the stator close to the leading edge of the blade and hence will interact with the blade boundary layer.

The distribution of the entropy rise through the compressor stage (Fig. 4) indicates that the zone of high loss in stagnation pressure has a strong entropy rise due to shear phenomena of the different secondary flows. The flow leaking over the tip of the blade increases the entropy rise, and drops the stagnation pressure. One of the most detrimental effect of the leakage flow is that this low energy fluid is accompanied by an increased outlet flow angle. The consequence will be an increased incidence on the following blade row that will become critical when the loading is increased, causing earlier separation.

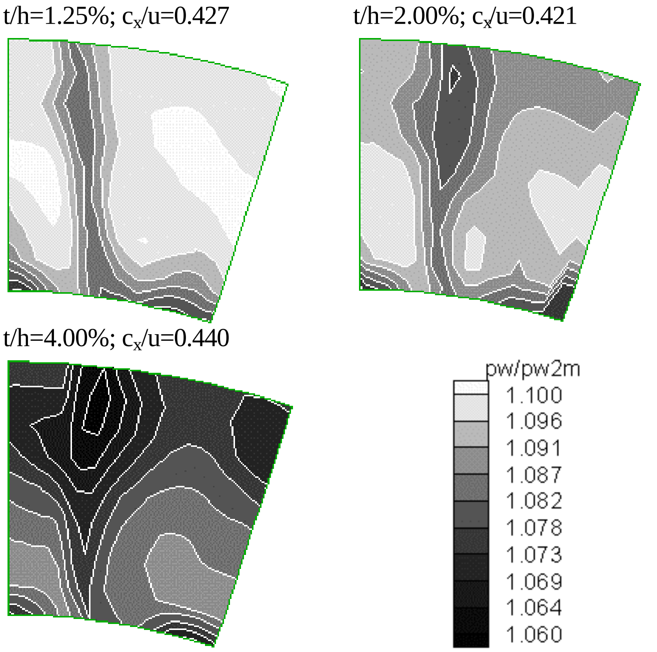

**Fig. 3** Distribution of the stage stagnation pressure ratio measured 84.7% axial chord downstream of the stator for the three tip clearances and for the high loaded cases

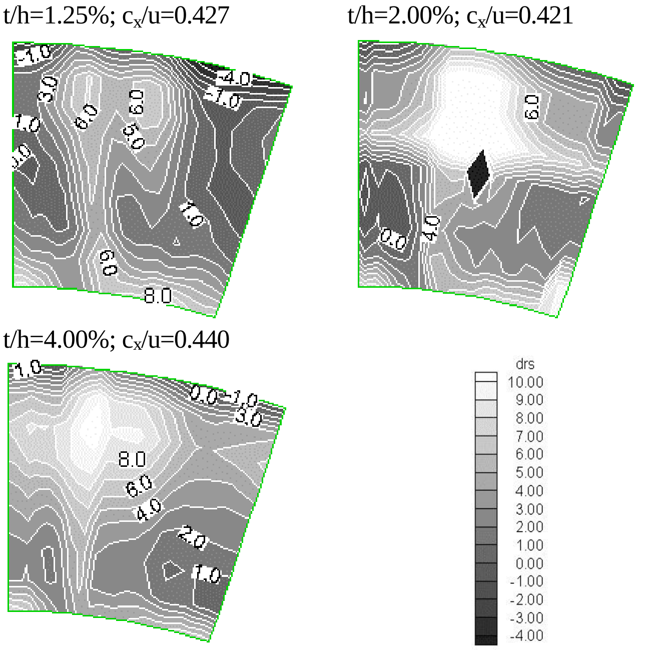

**Fig. 4** Local entropy rise through the compressor stage measured 84.7% axial chord downstream of the stator for the three tip clearances and for the high loaded cases

Fig. 5 shows the flow angle downstream of the stator row, for the three studied tip clearances and for the here presented cases (high loaded). As the tip clearance is increased, large flow angles appear in the casing region close to the wake. Flow angles up to 42 degrees are measures whereas the design flow angle at nominal conditions given by the constructor is 29 degree. When increasing the tip clearance from 1.25% to 2.00% (of the channel height), a zone of large flow angles from casing till 80% of the channel height appears. For the largest tip clearance, this increased values of the flow angle extends to the hub, even if the loading is slightly lower.

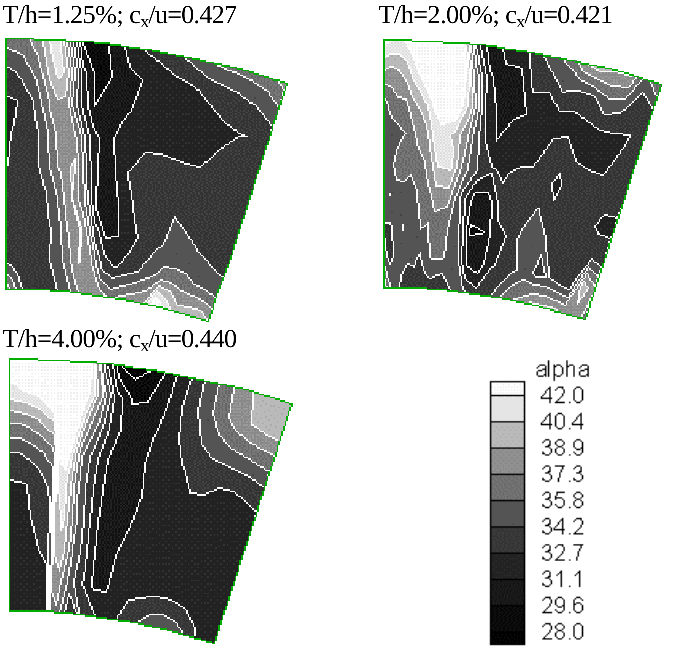

**Fig. 5** Absolute flow angle measured 84.7% axial chord downstream of the stator for the three tip clearances and for the high loaded cases

## THE DETAILED PITOT MEASUREMENTS

Little published results can be found concerning the effect of the tip clearance size in a compressor stage, with detailed measurements of the flow downstream of the following stator row. In fact the gradient are relatively high and very small steps in the pitchwise and spanwise directions are needed to capture the phenomenon. Stauter [ref. 15] made LDV measurements for one rotor tip clearance with 30 points in the pitchwise direction and 20 radial locations from midspan to the tip. Inoue and al. [ref. 8] investigated the flow field for different tip clearances, but the interest was focused on the flow field in the tip region.

### a) Pitot measurements downstream of the rotor

Fig. 6 shows the distribution of the stagnation pressure in section 3 (between rotor and stator) issued from the detailed Pitot probes measurements at design conditions ($c_x$/u=0.48). The presence of the IGV wake is still visible after having past the rotor row. In addition to the IGV wake, a second zone of high loss is visible close to the casing.

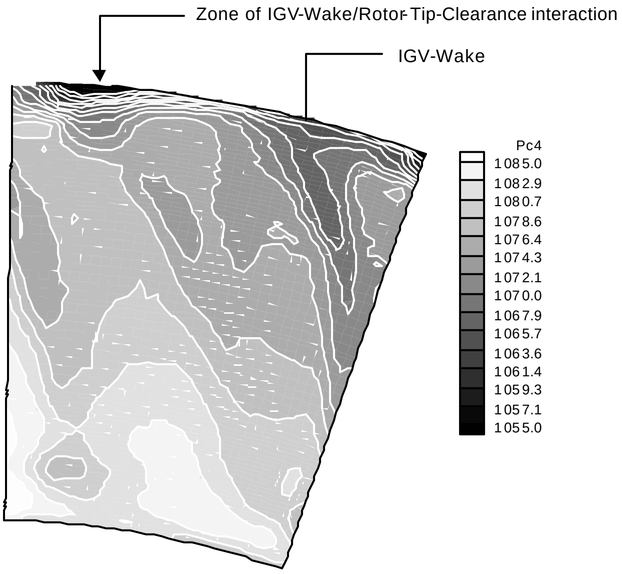

**Fig. 6** Reduced stagnation pressure distribution downstream of the rotor; t/h=1.25%

Hoynacki [ref. 6] made measurements in a section downstream of a rotor, with presence of an upstream-IGV. The rotor tip vortex position, relative to the rotor wake position, and its extend was time dependant. The author indicates also that when the IGV wake arrives on the rotor tip vortex, this tip vortex will be split. The vortex turning in counter clockwise will be weakened. Indeed, the second zone of loss shown in Fig. 6 corresponds to the described IGV-wake/rotor-tip-clearance interaction. Thus in the absolute frame of reference, the flow field behind a rotor is not only non-axisymmetric because of the IGV wake, but also because of the rotor tip clearance. Hence, the flow arriving on the stator inlet will depend on the upstream IGV pitchwise position.

### b) Pitot measurements downstream of the stator

The Pitot measurements downstream of the stator were performed for the three rotor tip clearances (t/H=1.25%, 2.00% and 4.00%). Fig. 7 shows the distribution of the reduced stagnation pressure 84.7% axial chord (23 mm) downstream of the stator. The increase of the tip clearance has not only an effect on the losses in the tip region but on the overall channel height. This effect is in this case pronounced due to the small aspect ratio of the blade rows. For this reason it is important to investigate the flow field over the entire channel height. On the pressure side of the wake appears a "bubble" of high loss at about 70% of the channel height (Fig. 9). The location of this loss zone is independent of the size of the tip clearance. Joslyn and Dring [ref. 9] reported that under certain circumstance a tip corner stall can appear, which is caused by the increased incidence due to the rotor tip clearance flow. Moreover the zone of interaction between the IGV-wake and the rotor tip clearance flow crosses the stator leading edge close to the tip. This low energy flow is likely to be trapped by the tip corner vortex. This creates an additional supply in low energy fluid. The tip clearance causes a decrease of the stagnation pressure over the whole span. Fig. 7 shows that the loss in stagnation pressure due to increased tip clearance is especially high at the tip as expected.

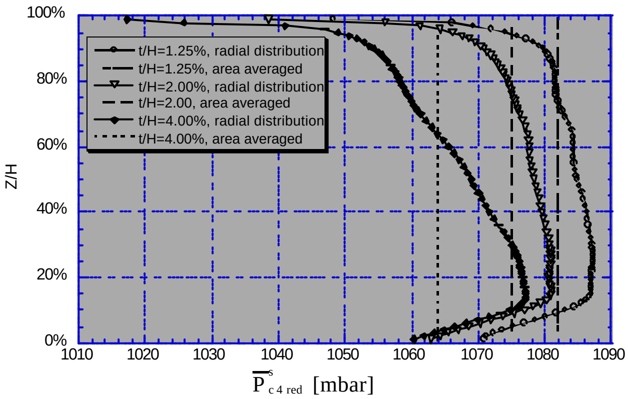

**Fig. 7** Radial distribution of the pitchwise-area-averaged reduced stagnation pressure for $c_x/u=0.48$ and for the three tip clearances.

The hub region of the flow downstream of the

## EFFECT OF THE INDEXING

It has to be pointed out that the effect of the clocking on the tip clearance flow was measured in a study concerning the effect of the axial spacing on the characteristics of the same compressor [ref. 13]. Changing the axial spacing by shifting the stator up or downstream will change the position of the IGV wake at stator inlet. The circumferential position of IGV wake at stator inlet has an influence on the characteristics of the compressor stage and on the flow itself. Fig. 6 shows that the flow downstream of the rotor is only inhomogeneous because of the upstream IGV wake, but also because of the interaction of the rotor tip clearance with this IGV wake. Moreover, the strongest pressure gradients downstream of the rotor can be found in the zone of losses created by this interaction.

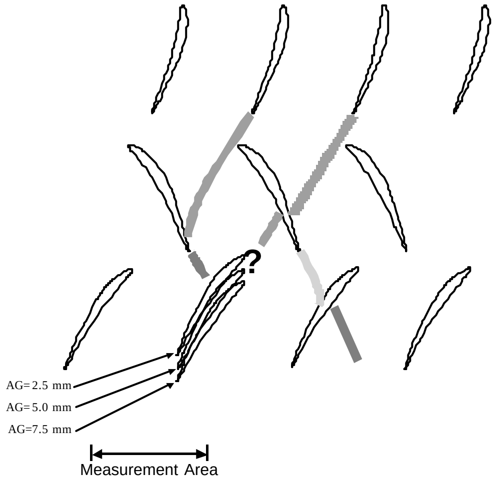

**Fig. 8** Impact of IGV on the stator row

Fig. 10 shows that the variation of the axial spacing between rotor and stator (and hence the indexing between IGV and stator) has an influence of the flow in the tip region downstream of the stator. It can be seen that a zone of stagnation pressure loss move to the right as the axial spacing is increased. This zone is the issued from the loss material from the interaction between the IGV wake and the rotor tip clearance. As the location of this zone in the absolute frame of reference depends of the position of the IGV, it will play a major role in the indexing between the IGV and the stator. It was shown in ref. 13 that for high loaded cases the presence of this zone of loss close to the suction side of the stator tip region caused an earlier separation of the flow.

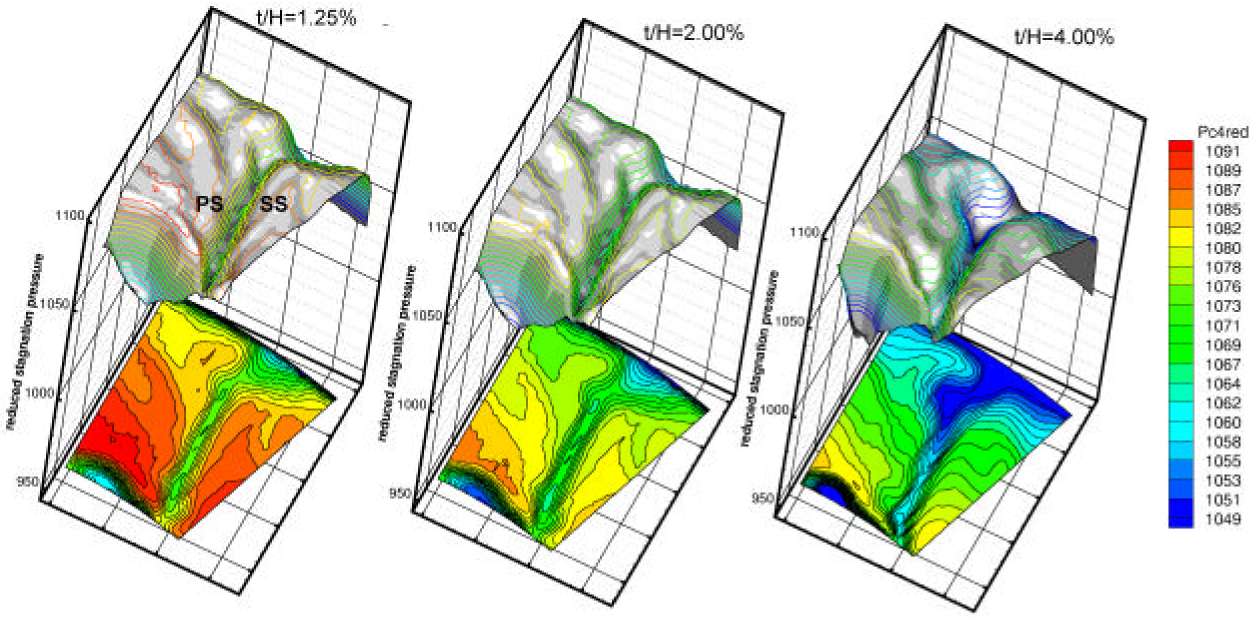

**Fig. 9** Reduced stagnation pressure distribution 84.7% axial chord downstream of the stator, for the three investigated tip clearances at design conditions (2.25 kg/s)

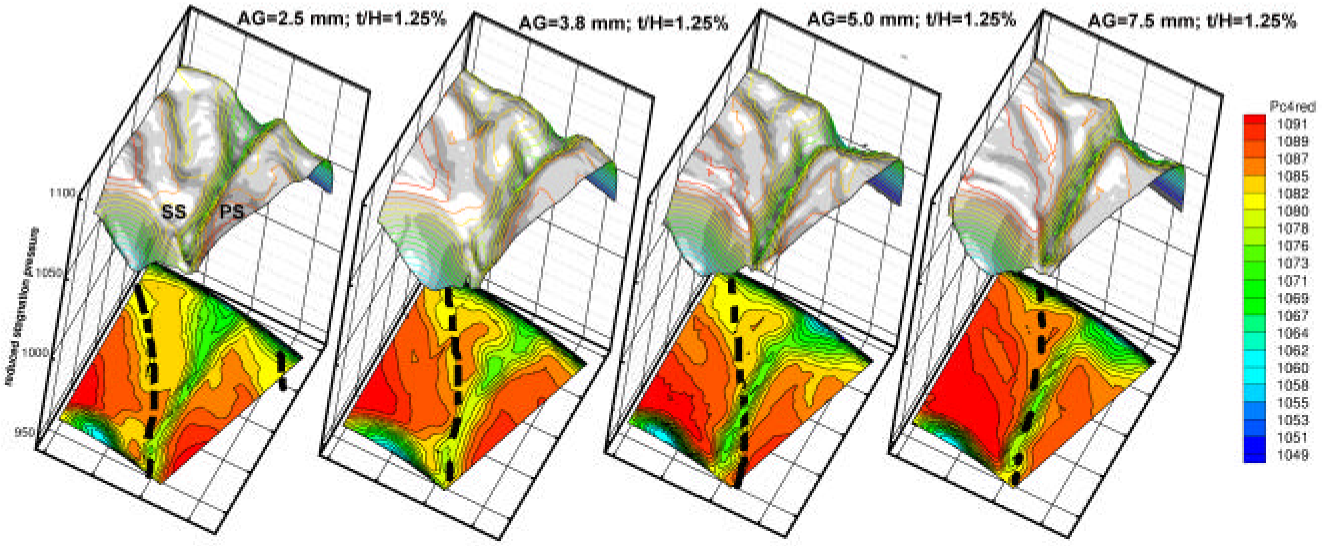

**Fig. 10** Reduced stagnation pressure distribution 84.7% axial chord downstream of the stator, for the four investigated axial spacings (AG) in ref. 13. (design conditions)

In order to investigate the effect of the clocking, Pitot measurements were performed for five indexed positions between the IGV and the stator for a tip clearance of t/h=1.25%. To increase the effects of the secondary flows, the mass flow was set to 2.00 kg/s, which corresponds to a flow coefficient of 0.43. The clocking positions and the area averaged reduced stagnation pressure are listed in Table 2. All the previous measurements were performed with the defined zero clocking. The clocking was performed by turning the stator. The position of the blades for the different clocking and the measurement location are drawn in Fig. 11.

| Clocking | –0.45° | 5.45° | 7.45° | 9.45° | 11.45° |
|---|---|---|---|---|---|
| Test Nr | 903 | 901 | 905 | 906 | 902 |
| $P_{c4red}$ | 1104.89 | 1104.89 | 1102.81 | 1103.48 | 1103.28 |

**Table 2** Test cases for the measurements

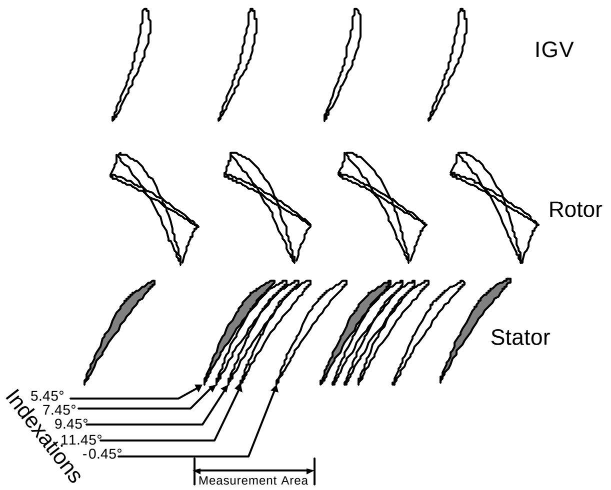

**Fig. 11** Blade positions for the different clocking cases

The reduced stagnation pressure measured 84.7% axial chord downstream of the stator trailing edge is plotted in Fig. 12 for the 5 clocking positions.

Fig. 13 represents the pitchwise distribution of the reduced stagnation pressures at respectively 20%, 50% and 80% channel height plotted over two pitches. The plots were adjusted in order to have the stator blades fixed at a certain position and hence the stator wakes superposed on the plots. In the hub region (z/h=20%) and for an indexing of –0.45 degree, losses in stagnation pressure are noticed at the pressure side of the wake. This is caused by the presence of the IGV wake close to the stator wake, or by the fact that the IGV wake crosses the stator leading edge. For an indexing of 5.45 degree, the IGV wake has moved and is present on the suction side of the stator wake. Then the position of the IGV wake moves to the right (on the graph) with the clocking. In the midspan region, the circumferential motion of the IGV wake is characterized by a loss in stagnation pressure that moves to the left on the graph as the indexing is increased.

For the indexing of –0.45 degree, the stator wake appears to be less deep, but outside of the wake the stagnation pressure remains low, at the pressure side. For this case, the IGV wake impacts the pressure side of the stator in the midspan region and the overall stagnation pressure level is slightly higher than the other indexing as can be seen in Fig. 14.

In the tip region (z/h=80%), the stator wake does not seem to be strongly affected by the presence of the IGV wake. At design conditions it was seen in the measurements for the different axial spacings that a zone of loss issued from the interaction between the IGV wake and the rotor tip clearance vortex had an influence on the flow structure in the stator. For higher loaded conditions the flow downstream of the stator is not much affected by the circumferential variation of the low energy zones downstream of the rotor. One reason could be the higher velocities through the tip clearance due to stronger pressure gradients between suction side and pressure side of the rotor blade. These large velocities can be responsible of the wipe out of the regions of low energy.

Fig. 14 shows the radial distribution of the pitchwise area-averaged stagnation pressure issued from the detailed Pitot measurements for the five indexings. For the indexing of –0.45 degree, the reduced stagnation pressure is rather high, up to 50% channel height. As seen before, this is due to the fact that the IGV wake flows onto the pressure side of the stator in this spanwise location. This improves the performances of the compressor as also observed by Dorney [ref. 3]. For the indexing of 5.45 degrees, the IGV wake flows onto the leading edge of the stator and crosses the blade at about z/h=30%. This creates losses in stagnation pressure compared to the clocking of –0.45. For the indexings of 7.45 and 9.45 degrees, Fig. 13 showed the interaction between the IGV wake and the stator hub clearance. This effect leads to a lower stagnation pressure profile in the hub region. 11.45 degree clocking was the worst configuration because the IGV wake is present in the suction side at the tip of the stator and also in the stator hub corner vortex region. The stagnation pressure is the lowest in almost the whole channel height.

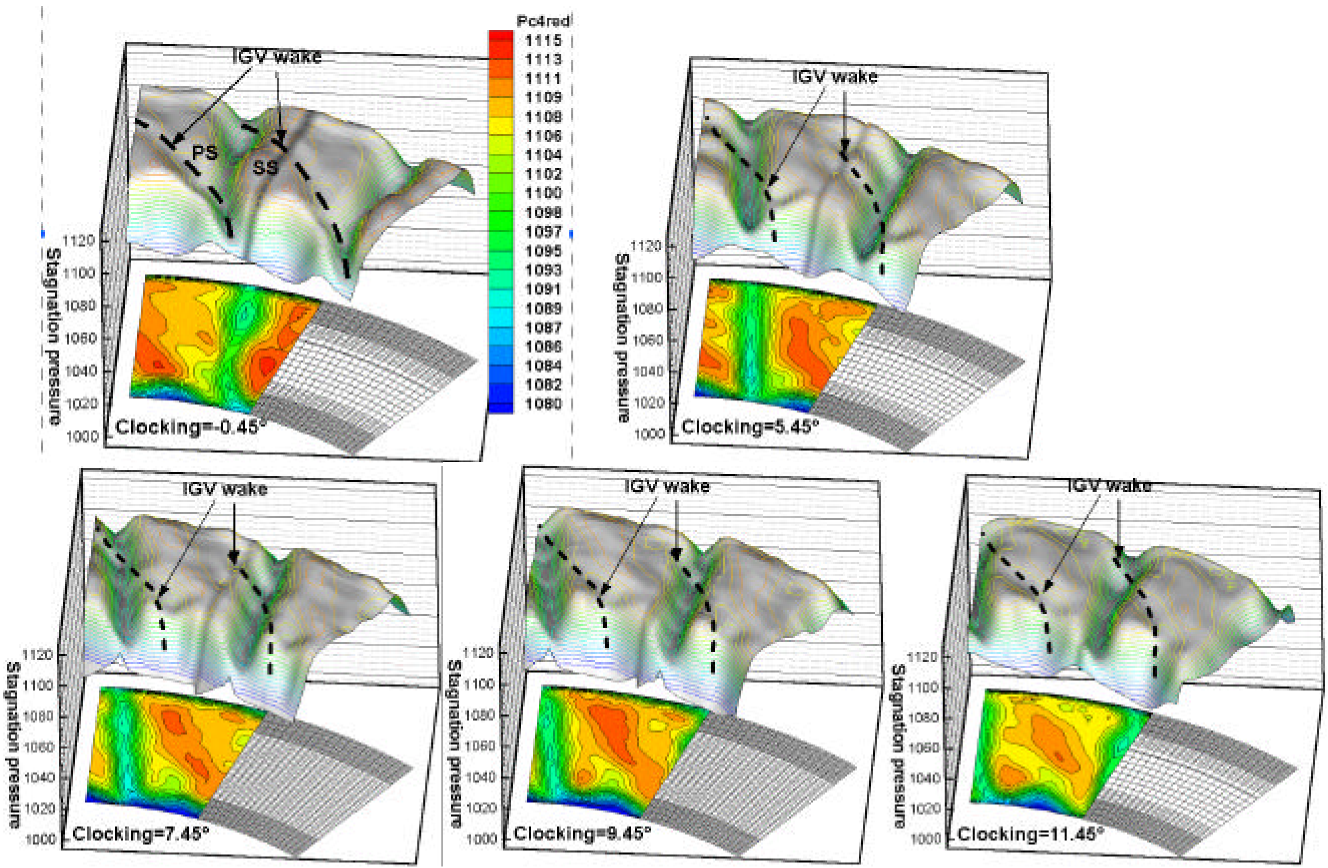

**Fig. 12** Reduced stagnation pressure distribution 84.7% axial chord downstream of the stator, for the five investigated axial indexed positions at 2.0 kg/s

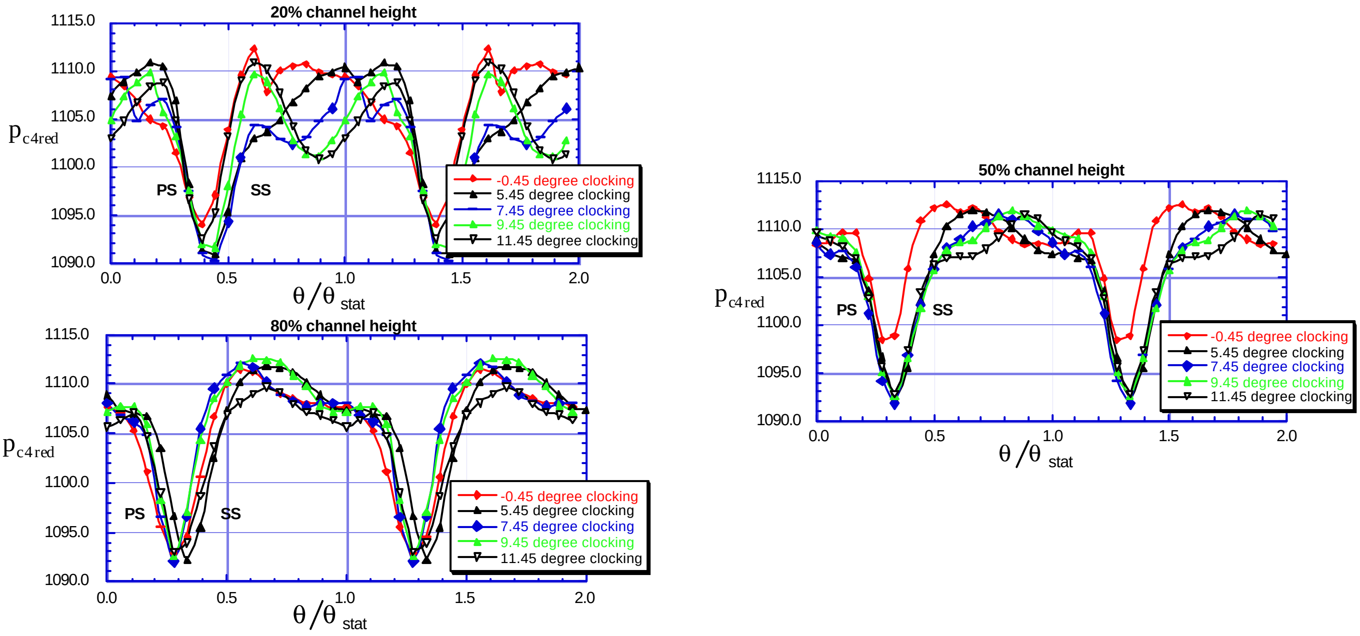

**Fig. 13** Pitchwise distribution of the reduced stagnation pressure at z/h=20%, 50% and 80%, 23 mm downstream of the stator, for the different indexations (ξ/h=12.5% and t/h=1.25%)

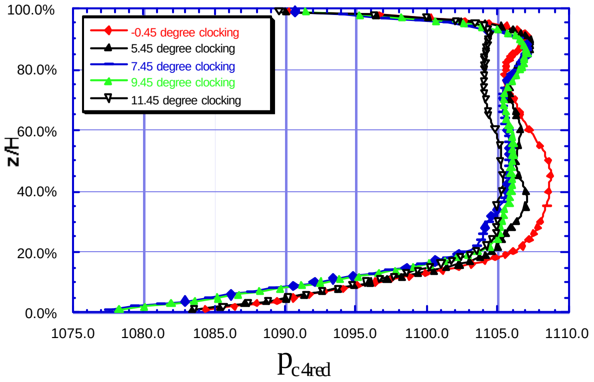

**Fig. 14** Spanwise distribution of the pitchwise averaged reduced stagnation pressure (23 mm downstream of the stator trailing edge) for the different indexations ξ/h=12.5% and t/h=1.25%)

## CONCLUSIONS

As mentioned before, the main objective for turbomachinery manufacturer is to predict as well as possible the performances of their machines. Concerning the tip clearance different models such as the one from Lakshminarayana [ref. 10] exist in the literature.

Fig. 15 shows the effect of the size of the tip clearance on the efficiency of the compressor stage for the measurements, for the analytical model published by Lakshminarayana and for CFD calculations.

These analytical models do not take into account the effect of the circumferential positions of the secondary flows as seen in Fig. 6. Numerical model usually use interfaces between the blade rows where the circumferential distribution will be lost [ref. 7].

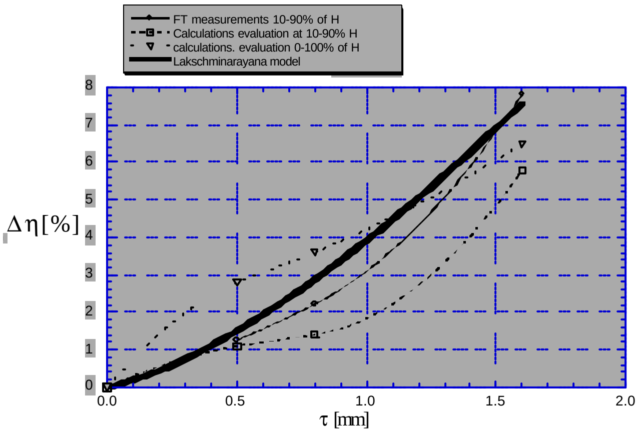

Fig. 15 effect of the size of the tip clearance; traverse measurements, Lakshminarayana prediction model and CFD calculations.

From this study, the following conclusions can be made:

- The circumferential distribution of the flow downstream of a row is not only due to the wakes but also to their interaction with the tip clearances.
- Under certain flow conditions, the zone of low kinetic energy generated by the interaction between a wake and the tip clearance of the following blade row can play a major role in the indexing. In this study the flow field was very influenced by the indexing in the tip region for design flow conditions. When the loading was increased, the influence of the indexing diminished in the tip region, probably due to stronger flows through the tip of the rotor blade.

## REFERENCES

ref. 1 W.S. Barankiewicz, M.D. Hathaway, *Effects of Stator indexing on performance in a Low Speed Multistage Axial Compressor*, 97-GT-496.

ref. 2 N.A. Cumpsty, compressor Aerodynamics (Book). Longman Scientific & Technical,1989.

ref. 3 Dorney D.J., Sharma O.P., Gundy-Burlet K.L., 1998, Physics of Airfoil Clocking in a High speed Axial Compressor, 98-GT-82

ref. 4 R.P. Dring, *Blockage in Axial Compressors*, Jul-84, Journal of Engineering for Gas Turbine and Power, Vol. 106.

ref. 5 Emunds, R., Jennions, I. K., Bohn, D., Gier, J., 1999 "The Computation of Adjacent Blade-Row Effects in 1.5 Stage Axial Flow Turbine"Journal of Turbomachinery, Vol. 121, January 1999, pp. 1-10

ref. 6 A. Hoynacki, Stuffeninteraktion, Vorhaben Nr. 601, Forschungsvereinigung Verbrennungsmaschinen e.V.

ref. 7 K. Hubrich, Final Report of CFD Computation on the 1.5 Stages Compressor, internal Report LTT-99-01, March 1999.

ref. 8 M. Inoue, M. Kuroumaru, *Structure of Tip Clearance Flow in an Isolated Axial Compressor Rotor*, Jul-89, Journal of Turbomachinery, Vol. 111.

ref. 9 H.D. Joslyn, R.P. Dring, *Axial Compressor Stator Aerodynamics*, Apr-85, Journal of Engineering for Gas Turbine and Power, Vol. 107

ref. 10 B. Lakshminarayana, *Methods of Predicting the Tip Clearance Effects in Axial Flow Turbomachinery*, Sept-70, Journal of Basic Engineering

ref. 11 B. Lakshminarayana, M. Pougare, R. Davino, *Three-Dimensional Flow Field in the Tip Region of a Compressor Rotor Passage-Part1: Mean Velocity Profiles and Annulus Wall Boundary Layer*, Oct 82, Journal of Engineering for Gas Turbine and Power, p. 760-781, Vol. 104

ref. 12 B. Lakshminarayana, Fluid Dynamics and Heat Transfer of Turbomachinery, Wiley Interscience Publication,1996

ref. 13 M. Y. Layachi, A. Bölcs, Effect of the Axial Spacing between Rotor and Stator with regard to the Indexation between Stators in an Axial compressor

ref. 14 I.N. Moyle, Analysis of Efficiency Sensitivity Associated with Tip Clearance in Axial Flow Compressors, 88-GT-216.

ref. 15 R.C. Stauter, Measurement of the three-Dimensional Tip Region Flowfield in an axial Compressor, 92-GT-211

ref. 16 A.R. Wadia, T.C. Booth, *Rotor-Tip Leakage: Part II-Design Optimization Through viscous Analysis and Experiment*, Jan 82, Journal of Engineering for Power, p. 162-169, Vol. 104