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MODELLING TRANSITION FOR THE DESIGN OF MODERN AXIAL TURBOMACHINES

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Abstract. The aim of this paper is to investigate whether or not a correlation-based transition model can be used for the design of multistage turbomachinery components. To this end, two components, a low-pressure turbine and an axial compressor, are computed at design and off-design conditions. The results of the steady computations are compared with experimental data in terms of overall performance and transition occurrence. In all cases, the agreement between the measurements and the computations is good, meaning that the computational setup can be used in a multistage turbomachinery context.

1 INTRODUCTION

The increasing price of fossil fuels requires an augmentation of turbomachine efficiencies. Because of their high economical importance, such improvements are crucial for axial turbomachines used for aircraft propulsion and power generation. To meet this goal, new cutting-edge concepts must be conceived, requiring a deep understanding of the flow physics involved. As pointed out by Denton [2], in turbomachine flows, many physical phenomena can be potentially present and their interactions result in loss generation. Among all physical phenomena, boundary layer transition plays a special role in turbomachines.

Mayle [13] shows that despite the fact that the flow inside a turbomachine is expected to be turbulent, large portions of the boundary layers developing on the surfaces are in fact laminar. Hence, depending on numerous flow parameters, such as the Reynolds number, the streamwise pressure gradient or the free-stream turbulence level, boundary layer transition can appear. Moreover, transition can follow different patterns, or following Mayle's classification, modes. For a turbomachine, three main modes are likely to occur. The first mode appearing in attached boundary layer is denoted as *bypass* transition.

Within a laminar boundary layer subjected to free-stream turbulence of weak intensity, instabilities are generated. It results from flow internal mechanisms and requires a large extend to complete transition. However, when the free-stream perturbations are strong enough, they interact with the boundary layer and short-cut the mechanisms associated with the natural mode. The second transition mode is related to separated shear layers. When a strong enough adverse pressure gradient is present, the laminar boundary layer separates from the wall. In the resulting shear layer, instabilities appear and lead to a rapid transition. The shear layer reattaches and a so-called separation bubble is created. This transition mode is commonly named *separation-induced* transition. In the case of a multistage component, upstream rows shed wakes in the free-stream. Those wakes interact periodically with the boundary layers developing on the downstream blades and finally influence transition. In particularly, the high turbulent intensity contained in the wakes plays a major role by promoting transition. This mode is called *wake-induced* transition and is specific to turbomachinery. Mayle demonstrates also that transition can be present for compressors, turbines as well as in combustion chambers. Therefore, considering the flow inside a turbomachine as being fully turbulent can be misleading in terms of component's performance and flow physics. Consequently, transition must be taken into account for the design of efficient turbomachines.

Because of the complexity of the flow physics involved, numerical simulations play an essential role in turbomachinery design. Hence designers need CFD codes able to predict accurately transition in an industrial context. Many computational techniques are available to predict transition. For instance, the Direct Navier Stokes Simulation (DNS) technique does not involve any flow modelling which guarantees a high quality of the prediction. However, due to the huge computational resources required, this technique can not be used for industrial purpose even for simple configurations. The Large Eddy Simulation (LES) technique requires slightly less computational resources than DNS since it resolves only the largest scales of the considered flow-path. Nevertheless, this is not sufficient to allow a standard use of LES in a design process. Finally, the Reynolds Averaged Navier-Stokes (RANS) technique models the flow completely and relatively low computational effort is needed. Currently, this is the only technique which can be used in an industrial environment.

The aim of this paper is to present and compare state of the art transition prediction models for industrial relevant test cases. In this paper, simulations carried out with DLRs in-house turbomachinery specific CFD solver TRACE are presented. Different RANS turbulence and transition models are available in TRACE. During the last years, the γ-Re_{Θ} transition model of Menter [16] and Langtry [7] has gained popularity and has been implemented in TRACE. It can be coupled with the the k-ω turbulence model of Wilcox [21] or the k-ω SST turbulence model of Menter [15]. Moreover, some correlations required to close the transition model had not been released in its first publication [16]. Therefore, several correlation sets, formulated by different authors, have been implemented and tested in TRACE in combination with the available turbulence models. From such studies, a numerical setup is chosen as explained in this paper. Many publications focus on the transition prediction for turbine or compressor cascades but it seems that little work has been published for multistage configurations. This paper contributes to improve this situation. To do so, two multistage components, a 3-stage low-pressure turbine and a 4.5-stage transonic compressor, are computed with TRACE. The quality of the computations are evaluated with the help of experimental measurements at design and at off-design conditions.

2 NUMERICAL METHODS

For more than 20 years, DLR has developed an in-house CFD software package dedicated to turbomachinery. The CFD code, called TRACE, is a density-based Navier-Stokes solver. The viscous fluxes of the RANS equations are discretized using a central difference scheme while the convective fluxes' discretization use the TVD upwind scheme of Roe. An implicit numerical scheme [17] solves the resulting system of equations. A more complete description of the RANS solver can be found in [6]. Different transition models are implemented in TRACE and in particularly, the γ-Re$_\Theta$ model developed by Menter and Langtry [7]. This model represents the current state of the art for the modelling of transition. Therefore, it is chosen for all computations presented in this paper.

The γ-Re$_\Theta$ model is constituted of two transport equations. Equation 1 considers the evolution of the intermittency γ while equation 2 models the change of Reynolds number based on the momentum thickness $\tilde{Re}_{\Theta t}$. When those equations are solved, the resulting intermittency γ is used to modify the turbulence model, which is, according to Menter and Langtry [16], the SST model of Menter [14].

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_i \gamma)}{\partial x_i} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_i}\right] \tag{1}$$

$$\frac{\partial(\rho \tilde{Re}_{\Theta t})}{\partial t} + \frac{\partial(\rho U_i \tilde{Re}_{\Theta t})}{\partial x_i} = P_{\Theta t} + \frac{\partial}{\partial x_i}\left[\sigma_{\Theta t}\left(\mu + \mu_t\right)\frac{\partial \tilde{Re}_{\Theta t}}{\partial x_i}\right] \tag{2}$$

The source terms of equations 1 and 2 are detailed in the equations 3. They depend on F$_{onset}$, F$_{length}$ and Re$_{\Theta t}$. The parameter F$_{onset}$ controls the start of the transition, F$_{length}$ influences its length and Re$_{\Theta t}$ is the actual value of the Reynolds number based on the momentum thickness, depending on the boundary layer. Those three parameters must be computed in order to close the model and are provided by different experimental correlations. F$_{onset}$ depends also on a correlation for the critical Reynolds number $Re_{\Theta c}$. Unfortunately, in the first model's publication the experimental correlations for F$_{length}$ and Re$_{\Theta c}$ were missing for proprietary reasons.

$$
\begin{aligned}
P_{\gamma} &= f\left(F_{length}, F_{onset}\right) \\
E_{\gamma} &= f\left(F_{length}, F_{onset}\right) \\
P_{\Theta t} &= f\left(Re_{\Theta t}\right)
\end{aligned}
\tag{3}
$$

Different authors published their own correlation sets in order to close the model. In TRACE [11], the model has been implemented with the correlation set of Malan et al [10] and worked together with the k-ω turbulence model of Wilcox [21]. Later, the influence of the different correlation sets and turbulence models has been tested on different low-pressure turbine cascades by Longhitano [9] as well as for compressor cascades by Marciniak et al [12] and Klioutchnikova [4]. These studies show that the turbulence model and the correlation set used have a great impact on transition prediction. In particularly, some combinations can simulate very accurately complex flow phenomena such as long separation bubbles and shock-induced transition. Unfortunately, those combinations simulate other flows rather poorly. By considering all computations, it was found that the use of the k-ω SST turbulence model of Menter [15] leads to optimal results. Concerning the γ-Re$_{\Theta}$ model, the chosen correlations and closure coefficient values are those published by Langtry et al [8], except the Re$_{\Theta}$ correlation. In fact, the correlation published by Menter et al [16] is found to perform better in many considered cases and is therefore used here.

3 MULTISTAGE TRANSONIC COMPRESSOR Rig250

Rig250 is a 4.5-stage downscaled axial compressor representative of a stationary gas turbine investigated at DLR Institute of Propulsion Technology. The compressor has been driven with different rotational speeds, but concerning transition, the most interesting phenomena appear when the compressor operates at 60 % of its design rotational speed. Therefore, such conditions are presented here to evaluate the transition model. The geometry of Rig 250 is shown in Figure 1. The inlet guide vane (IGV), stator 1 (S1) and stator 2 (S2) are adjustable blades, which allow an adaptation for off-design conditions, while stators 3 and 4 are cantilevered with clearance gaps at hub. Since the compressor is working at only 60 % of the design rotational speed, IGV, S1 and S2 are re-staggered at 50, 25 and 12.5 degrees respectively.

Different types of experimental data are available to asses the quality of the computations. Pressure taps, symbolized by the black dots in Figure 1, are present on the suction sides of IGV and S1 and measurement probes, represented by the red diamonds, provide total pressure and total temperature on the leading edges of IGV and S1. Moreover, Waitz et al. [19] report additional measurements with hot films placed on the suction side of S1 to determine the position of transition. The domain considered for the computations is limited by the red dotted lines.

The computations use a structured three-dimensional grid with basic O-C-H topologies generated with DLR's grid generator G3DHexa [20]. It consists of 88 blocks representing

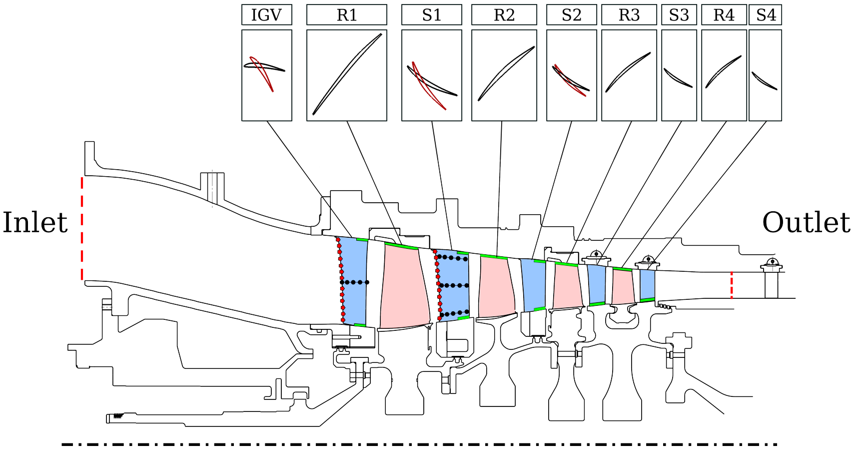

Figure 1: Rig250 - Setup and blade setting (60 percent RPM in red)

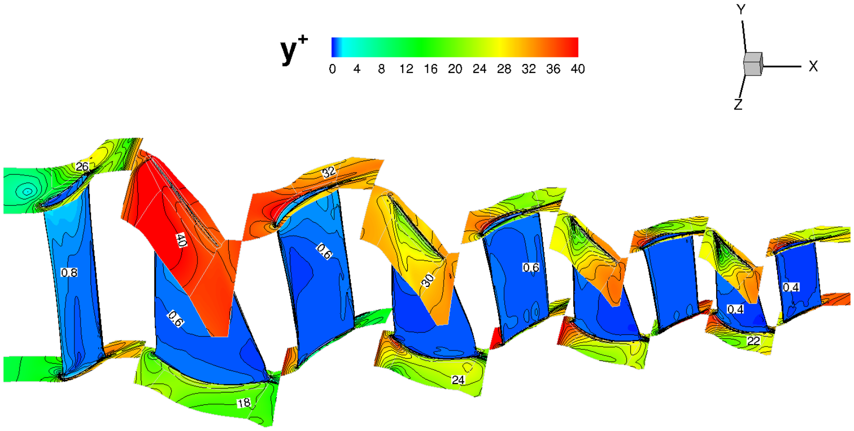

Figure 2: Rig250 - Global distribution of y^+ for OP 6

approximately 16 million nodal points. In radial direction, the overall resolution uses 121 points with 21 points placed into the clearance gaps. As shown in Figure 2, the mesh is conceived to allow low Reynolds wall treatment on the blades ($y^+ < 1.0$). Near hub and shroud walls a coarser spanwise spacing is used which gives y^+ values close to 20.0. This is because the flow on those surface is assumed to be fully turbulent and therefore turbulent wall functions can be used.

Steady computations are presented in the following by using the computational setup described in the section numerical methods, except that the reattachment modification is additionally activated [1]. The complete compressor speedline is computed and the resulting compressor map is compared with experiments in Figure 3. Considering that the computations are at extremely off-design conditions, the results are very good. The chocking mass flow rate differs by only 0.5 kg/s between the experiments and the compu-

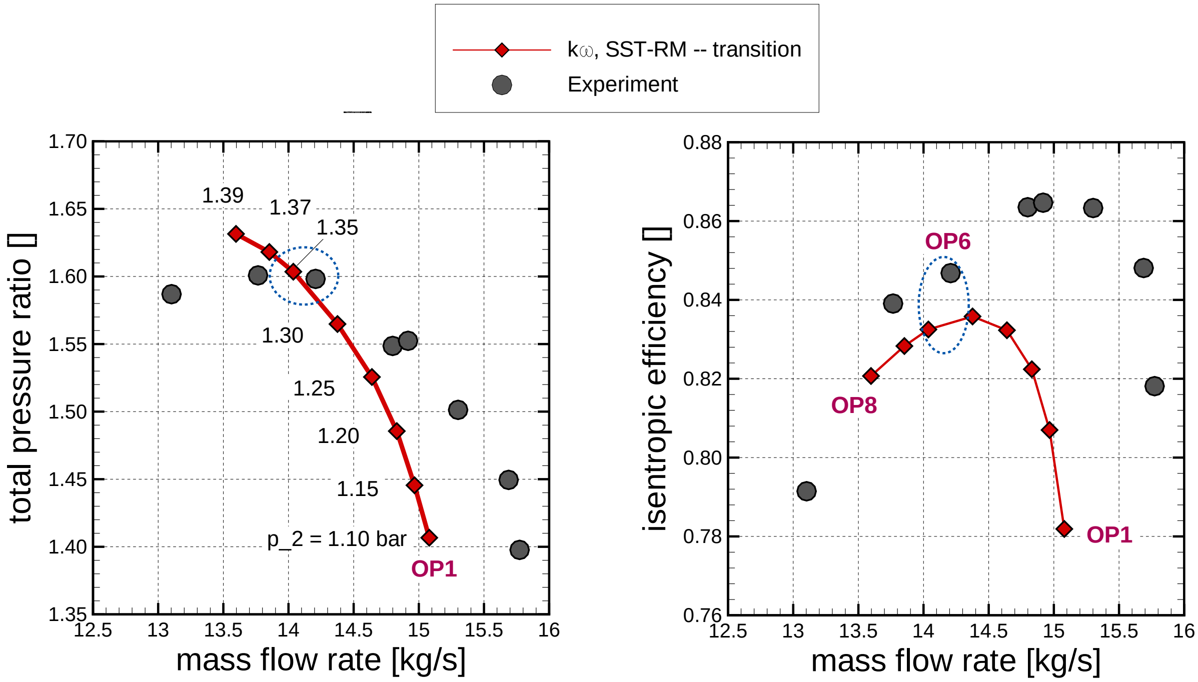

Figure 3: Rig250 - Performance maps for 60 percent design RPM

tations and in the simulation stall appears somewhat earlier. Moreover, the trend of the efficiency curve is met by the simulations and the peak efficiency is only underestimated by 0.025.

The comparison of the isentropic profile Mach number for S1 at two spanwise positions is shown in Figure 4 to assess the quality of the prediction. The operating point considered, namely OP6, is computed with a back pressure of 1.35 bar (circled in Figure 3). The agreement between experiments and simulations is quite good. Indeed, for both spanwise positions, the isentropic Mach number distribution shows that the negative incidence of the experiments is well simulated in the computation. Therefore, an appropriate comparison of transition over S1 can be carried out.

For the same operating point, the wall shear stress distribution along the suction side of S1 at midspan is extracted and displayed in Figure 5, left. With the help of this plot, the start and the end of transition can be defined. This process is repeated for all the simulations carried out. It is then possible to compare the simulated start and end of transition with the experiments of Waitz et al [19] in Figure 5, right. Waitz et al use the maximum value of the RMS signal from the hot film to define a transition location, while the simulations allow to determine a transition range. The simulations predict that the location and extend of transition is independent of the total pressure ratio. This result is in accordance with the experiments. However, the measurements show that transition

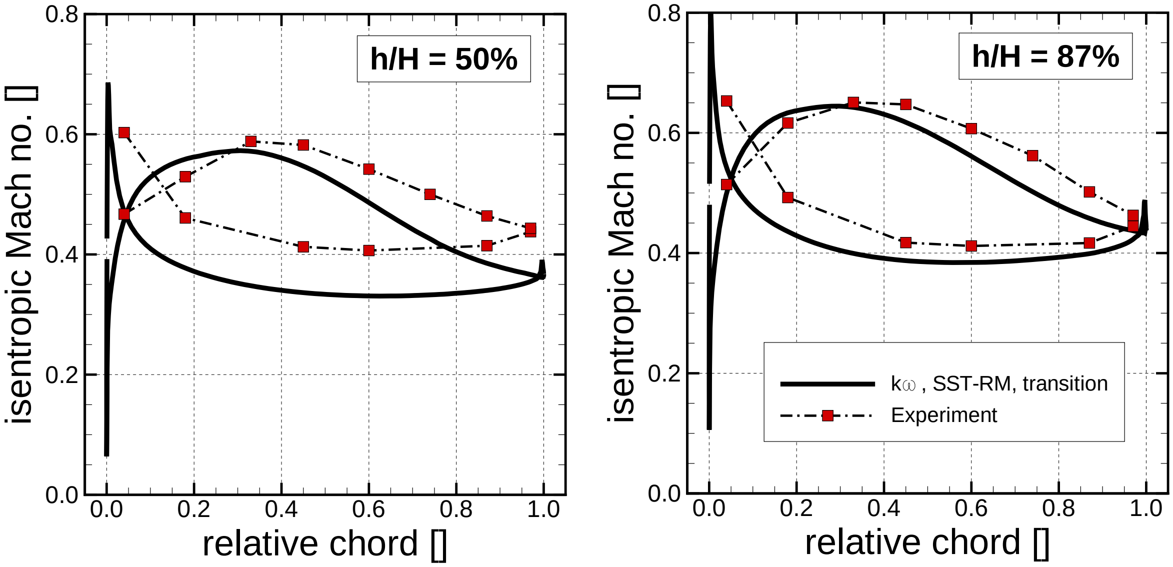

Figure 4: Rig250 - Isentropic Mach number distribution for OP6 (Stator 1)

appears on a more downstream position than in the computations but the difference is quite small. In addition, the definition of transition's occurrence in the experiment is by nature close to the end of transition.

4 MULTISTAGE LOW-PRESSURE TURBINE

To illustrate the importance of transition for aircraft engines, a 3-stage low pressure turbine is presented. The turbine is a design from MTU Aero Engines [3] representative of low pressure turbines used in jet engines for regional aircrafts. Kožulović [5] uses this test case to demonstrate the capability of his transition model. The turbine's geometry is displayed in Figure 6.

The computational grid consists of 3.7 million cells with a low Reynolds resolution on the blade surfaces, i.e. $y^+ < 1.0$. For the hub and casing surfaces, the flow can be considered to be fully turbulent which is a reasonable assumption for realistic three-dimensional turbomachinery flows. Therefore, in order to reduce the number of points in the computational domain, wall functions are used. Consequently, over those surfaces, $y^+ \approx 20.0$. In this way a good compromise between grid density and simulation quality is achieved. The turbine rotor blades are shrouded, so no tip clearances must be taken into account.

In the literature (see for instance Mayle [13]), it is well-known that the Reynolds number is a flow parameter which strongly influences transition. For jet engines, the value of the Reynolds number varies with the flight altitude. Indeed, when the flight altitude increases, the air density decreases causing a reduction of the Reynolds number.

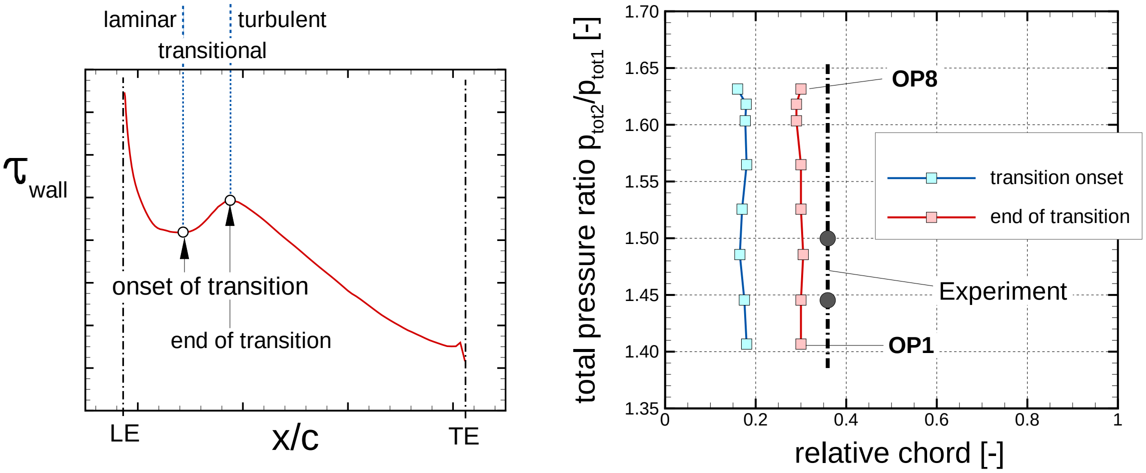

Figure 5: Rig250 - left principal scheme, - right transition position

The low Reynolds number values tend to favor transition and can greatly influence the performance of the machine. This is why experiments are conducted to evaluate the performance of the low-pressure turbine with a varying Reynolds number.

The experimental and predicted efficiencies for different Reynolds numbers, or lapse rate, are compared in Figure 6. The measured efficiency decreases when the Reynolds number is lowered to reach values close to the airplane's cruise conditions (Re$= 240,000$). The simulations reproduce this trend quite well but the magnitude of the efficiency is slightly over-predicted by about 1%. This discrepancy can be attributed to the fact that cavities are neglected in the simulations. Using the knowledge accumulated from similar situations, it is well-known that the inclusion of cavities during the simulations cause an efficiency decrease of approximately 0.5 to 1%. It can be concluded that the γ-Re$_\Theta$ transition model can predict quite accurately the turbine's global efficiency at design and off-design conditions. However, a complete evaluation of the simulation quality requires an investigation of the flow physics.

Figure 7 details the flow situation for vane 4 at Re$= 240,000$. First, a comparison between experimental and computed scaled midspan pressure distributions is presented on the right part of Figure 7. On the suction side, experiments put in evidence the presence of a separation bubble close to 90 % relative axial chord. This is well reproduced by the transition model. On the left part of Figure 7, an *averaged* value of the intermittency γ and the contour of zero shear stress (in black) over the whole suction side of vane 4 are shown. In order to respect the proprietary nature of the design, the geometry is arbitrary scaled. The intermittency γ used by the model is a *local* variable computed for each cell of the domain. Its value must be zero on the blade surface. In order to observe the action of the model, an averaged value over the boundary layer is computed for each surface element of the blade. This operation requires the determination of the boundary layer edge over the whole blade. Unfortunately, in some cases the boundary layer edge used

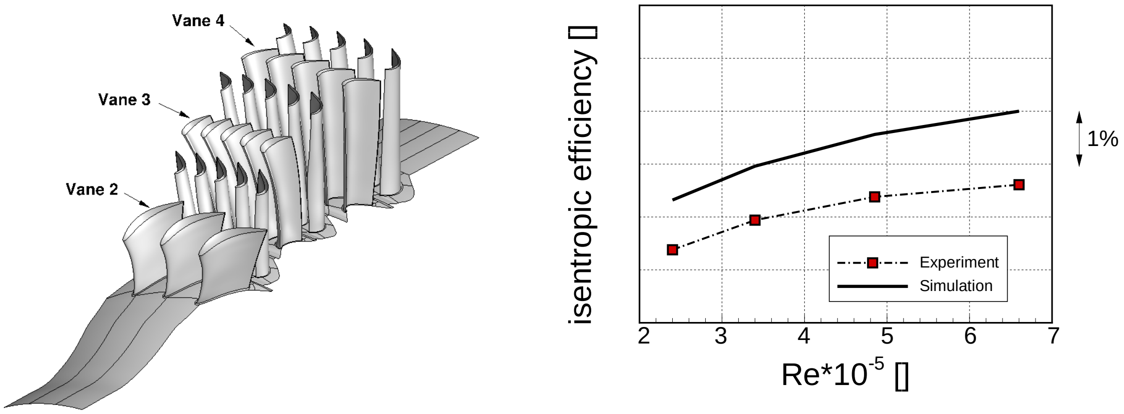

Figure 6: Three stages low-pressure turbine - geometry setup and lapse rate

for the averaging it not the same as the one use by the γ-Re_Θ model. Consequently, the intermittency's value for a laminar (resp. turbulent) boundary layer is not exactly zero (resp. one) but slightly superior (resp. inferior). Concerning the flow field on Figure 7 left, the intermittency variation - from ≈ 0.3 to ≈ 0.8 - indicates that transition takes place over the vane. Over almost the whole blade span, transition takes place following the separation-induced mode as confirmed by the zero wall shear stress contour. This is in accordance with the presence of a separation bubble measured at midspan shown in Figure 7, right.

At the same Reynolds number, the pressure distributions at mid-span for vanes 2 and 3 are shown in Figure 8. For both blades, the presence of a separation bubble is suggested by the experiments on the suction side. Here again, the transition model allows to simulate the pressure plateau corresponding to the separation bubble quite satisfactorily. Hence, the physics of transition is very well simulated for all blades in the computations.

5 CONCLUSION

The aim of this paper is to demonstrate that transition in multistage turbomachinery can be well simulated by a correlation-based model. This goal is reached with the computations of two challenging and representative test cases, namely a low-pressure turbine and a transonic compressor. In accordance to current industrial practice, steady computations using the mixing plane assumption have been carried out. For turbine as well as for compressor, the results are in good agreement with the experiments. Especially, the influence of the wake, crucial in turbomachinery, is therefore handled correctly. It is shown that the global efficiency of the components at design and off-design conditions are well simulated. Moreover, the prediction of the transitional flow features is also good.

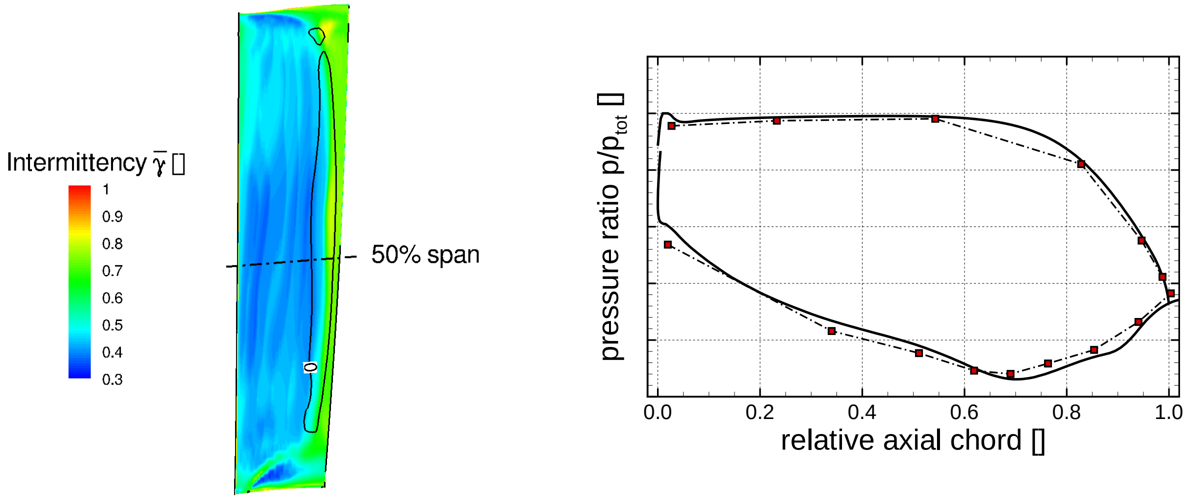

Figure 7: Three stages low-pressure turbine - Flow detail and blade pressure distribution at mid-span for vane 4 at Re=240,000

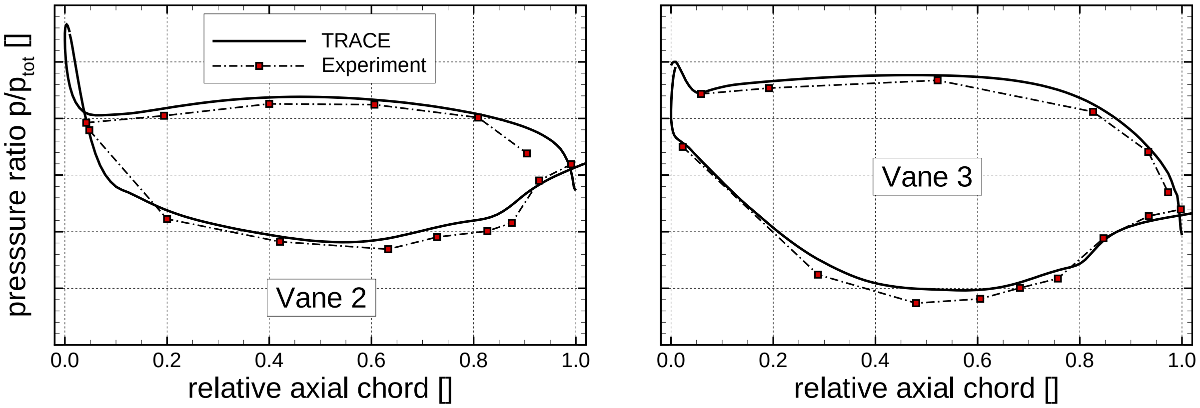

Figure 8: Three stages low-pressure turbine - Blade pressure distribution at midspan for Re=240,000

At industrial scales, it means that TRACE can be used with confidence when transition is expected. The authors hope that this possibility will help turbomachine designers to propose new concepts able to face future challenges.

Further research aimed to improve the transition prediction, in particularly the simulation of long separation bubbles and shock-induced separations, will be followed by using DLR's in-house automated optimization software Auto-Opti [18].

6 ACKNOWLEDGEMENT

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