

# Numerical Study on the Performance of a New Passive Tip-Leakage Control Method for Axial Turbines

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## 1. Introduction

Losses in axial turbine blade rows are usually divided into profile, secondary and tip-leakage losses. Depending on the blade aspect ratio, tip-leakage losses can contribute up to one third of the total losses. In unshrouded turbine blade rows (Fig. 1), the radial tip gap allows the working fluid to pass from the pressure to the suction side. This tip-leakage flow driven by the blade pressure difference does not contribute to the work output of the turbine stage. A detailed review of the various aspects of axial turbine tip-leakage flow is given in the VKI Lecture Series 1997-01 [6] and more recently in the VKI Lecture Series 2004-02 [1]. Reducing the negative effects of tip-leakage flow is generally referred to as tip desensitization. A new method for tip desensitization is investigated in this report: passive blade tip injection [2, 4].

## 2. Basic Concept and Experimental Results

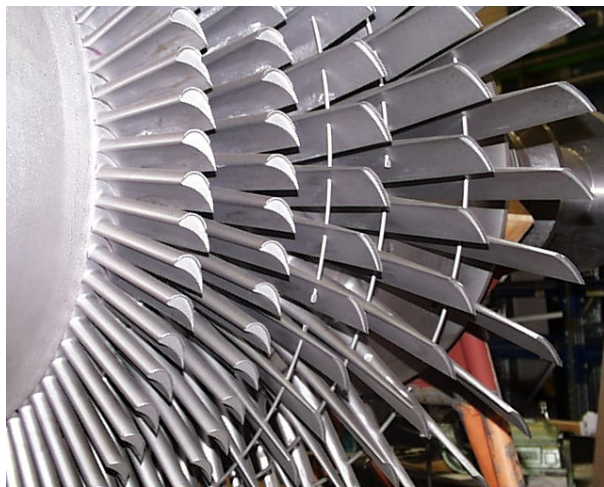


Figure 1: Axial turbine rotor with unshrouded blades

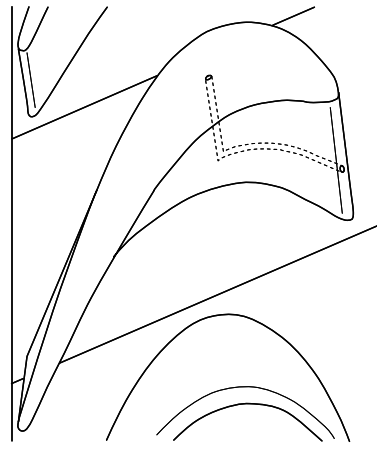


Figure 2: Axial turbine rotor blade with proposed tip injection channel (schematic)

The basic concept of the proposed tip desensitization method is as follows (Fig. 2): The rotor blade leading edge is connected with the blade tip by a channel. The diameter of this channel is small compared with the blade chord length. A small amount of working fluid of the turbine will be extracted at blade leading edge (stagnation point) and supplied to the injection hole at blade tip. The resulting injection jet acts as a partial blockage for the tip-leakage flow from the blade pressure to the suction side. Therefore, the intensity of the tip-leakage flow and vortex and associated losses can be expected to be reduced. The injection jet will be driven by the pressure difference between the stagnation region at blade leading edge and the low

pressure region at blade tip. Therefore, the method can be characterized as a passive method, since no external source is used.

Preliminary experimental results on the performance of the passive tip injection method have been obtained from a linear cascade wind tunnel. Figure 3 shows the geometry of the cascade under investigation. The blade profile corresponds to the tip section of a low-pressure gas turbine rotor blade row with rather weak turning ( $\approx 50^\circ$ ). In the past, this cascade geometry has been used for a number of detailed tip-leakage flow investigations by Sjolander and co-workers [6]. One of the six turbine blades in the cascade is equipped with a tip injection channel of diameter 5 mm (Fig. 3). At the blade leading edge the injection channel is located 30 mm away from the endwall. This spanwise position, just outside the endwall boundary layer guarantees that the full freestream total pressure of the inlet flow is captured. Flow measurements about 0.3 axial chord lengths downstream of the cascade have been performed using a pneumatic five-hole probe. Further details on the investigation and on the experimental results can be found in [3] and [5].

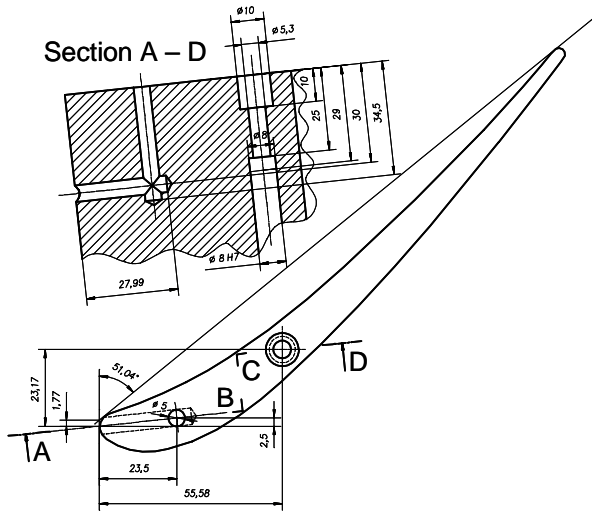


Figure 3: Cascade blade geometry

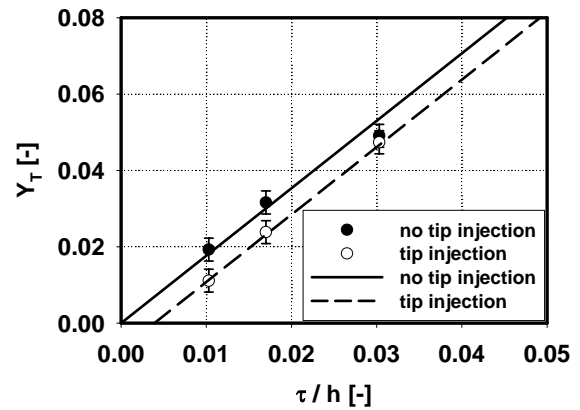


Figure 4: Measured tip-leakage loss coefficient

Figure 4 provides the measured tip-leakage loss coefficient  $Y_T$  versus the nondimensional tip gap width  $\tau/h$ , with  $\tau$  as tip gap width and  $h$  as blade height. The filled symbols represent the cascade without tip injection and the open symbols the cascade with tip injection, respectively. For the case with no tip injection, a regression line indicates the linear relationship between the tip-leakage loss coefficient and the nondimensional tip gap width. This linear relationship is proposed by many semi-empirical tip-leakage models. For the cascade with tip injection, the linear relationship has the same slope but it is shifted to lower values of tip-leakage loss coefficients. This observation is consistent with results from simple flow models presented in [4] and [5].

### 3. Analytical Model

Various tip-leakage models are available in the open literature to predict the influence of the tip-leakage flow on the losses in axial turbine blade rows. All of these models require a so-called discharge coefficient  $C_D$ , which is the ratio of actual tip gap mass flow rate to tip gap mass flow rate at one-dimensional ideal conditions. The analytical model to predict the discharge coefficient is based on the following assumptions (Fig. 5): The tip gap flow at the blade pressure side is accelerated without any losses up to the vena contracta. Velocity components and static pressure are assumed to be uniform across the vena contracta and

across tip gap exit. Mixing of the flow is fully completed at tip gap exit. The flow is assumed to be incompressible and total pressure losses are approximated by the assumption of fully developed pipe flow. Finally, the model assumes that there is no relative motion between blade tip and endwall. In the next step, the mass as well as the momentum balance are applied to the control volume. Under the assumption that no further surface forces are acting on the control volume, the following expression for the discharge coefficient can be derived:

$$C_D = \frac{1}{\sqrt{\left(2 + \frac{\lambda d}{2\tau}\right)(1 + \gamma\theta)^2 + \frac{1}{\sigma^2} - \frac{2}{\sigma} + 2\gamma\theta^2 \cos \delta}}. \quad (1)$$

In Eq. (1),  $\lambda$  is the pipe friction coefficient. For a hydraulically smooth surface,

$$\lambda = \frac{0.266}{Re_T^{0.25}} \quad (2)$$

can be used in the range  $1160 \leq Re_T \leq 50000$ .  $Re_T$  is the gap Reynolds number, defined with the mean velocity in the gap and the gap width  $\tau$ , and  $d$  is the tip gap length. The contraction coefficient of a potential flow through a sharp edged orifice is  $\sigma = \pi / (\pi + 2) = 0.611$ . The geometry of the tip injection hole is described by the orientation angle  $\delta$  and the area ratio  $\gamma$ . Finally, the injection velocity ratio is defined as

$$\theta = \frac{w_5}{\sigma w_3}, \quad (3)$$

with  $w_3$  as the velocity at the vena contracta and  $w_5$  the injection jet velocity.

## 4. Numerical Simulation

### ***Numerical Method and Finite-Element Mesh***

The numerical investigation is based on the governing equations for steady, three-dimensional, incompressible, turbulent flow. To take into account the turbulent behaviour of the flow, the standard  $k/\varepsilon$ -model with wall functions is used. The set of governing equations is solved numerically using the finite-element based CFD code FIDAP8.7.4. The solver and the pre- and postprocessing modules of FIDAP are available at the Cluster for Fluid Dynamics and Finite-Element Applications at the Computer Center (ZID) of Vienna University of Technology. Figure 6 shows the computational domain which is bounded by the inlet planes, two parallel symmetry planes, the endwall, the blade pressure side, the blade tip and the gap exit plane. The length of the inlet domain is set to 20 gap widths. Preliminary computations have shown that this inlet domain size is acceptable for the application of the chosen far field inlet boundary conditions. Figure 7 shows a typical finite-element mesh with about 200000 cells. As can be seen, the mesh density is higher in the vicinity of the walls to resolve the velocity gradients and to meet the  $y^+$ -requirements of the chosen turbulence model.

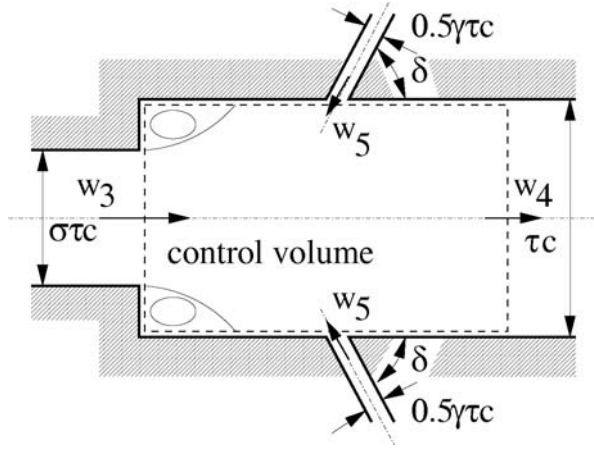


Figure 5: Control volume for analytical model

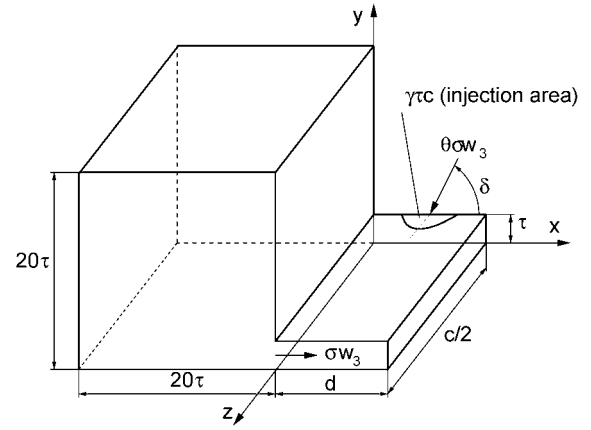


Figure 6: Computational domain

### Boundary Conditions

Boundary conditions have to be applied to the inlet planes, to the exit plane, to the solid walls and to both symmetry planes. At the inlet planes, a velocity distribution according to a sink flow is applied. The origin of this sink flow is located at the endwall at the gap inlet and its strength results from the chosen gap Reynolds number  $Re_T = 10000$ . At the stationary endwall, at the blade pressure side and at the blade tip, a no-slip boundary condition is applied. The circular tip injection hole is located at one half of the gap length. It is modelled by a constant velocity inlet boundary condition, taking into account the area ratio  $\gamma$  of the injection hole as well as its orientation angle  $\delta$ . Assuming isotropic turbulence, the turbulent kinetic energy boundary condition is calculated from the mean velocity at the inlet and an estimated turbulence intensity  $Tu = 5\%$ . The same turbulence intensity is used for the turbulent kinetic energy boundary condition at the tip injection hole. The turbulent dissipation rate is calculated according to

$$\varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{l_t}, \quad (4)$$

using a turbulence length scale  $l_t = 0.4 \tau$  at the inlet and  $l_t = 0.1 \tau$  at the injection hole, respectively. At both symmetry planes, the velocity components in  $z$ -direction are set to zero. At the gap exit plane, the so-called traction free condition is set. This boundary condition represents more or less a prescribed constant static pressure distribution. Furthermore, the normal gradients of the turbulence parameters are set to zero at the gap exit plane.

### Convergence Criteria and Calculation Time

The simulations are performed using the segregated iterative solver of FIDAP8.7.4. The convergence criteria is set to  $VELCONV = 10^{-4}$ . The required calculation time depends on the area ratio  $\gamma$  and the jet orientation angle  $\delta$  and is in the range from about 10 to 24 hours.

## 5. Results

Figure 8 shows the discharge coefficient  $C_D$  versus the injection velocity ratio  $\theta$  for fixed geometry, gap Reynolds number and area ratio. The injection velocity ratio  $\theta = 0$  represents

the tip gap flow without any tip injection. For this case, the result from the analytical model  $C_D = 0.82$  is higher than the numerical value  $C_D = 0.78$ . For increasing injection velocity ratio  $\theta$ , the discharge coefficient  $C_D$  decreases. This means that the flow entering the tip gap is blocked partially by the tip injection. If the analytical results for  $\delta = 90^\circ$  and  $\delta = 45^\circ$  are compared, it can be seen that this blockage effect is more pronounced when the injection hole is orientated against the tip gap flow. This effect is also reflected by the numerical results. However, the discharge coefficients obtained from the numerical investigation are lower than the corresponding analytical values.

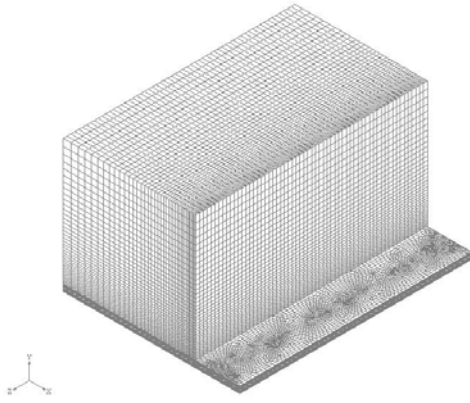


Figure 7: Typical finite-element mesh

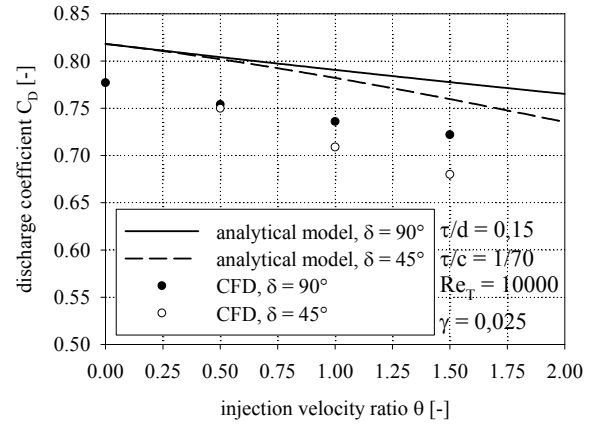


Figure 8: Discharge coefficient versus injection velocity ratio

Since the proposed tip injection method assumes that the injection mass flow rate is driven by the difference between the stagnation pressure at the blade leading edge and the pressure at the blade tip, an injection velocity ratio  $\theta = 1$  can be set. As a result, the area ratio  $\gamma$  can be interpreted as the relative injection mass flow rate

$$\gamma = \frac{\Delta \dot{m}}{\dot{m}_{T0}}. \quad (5)$$

This is the ratio of the injection mass flow rate  $\Delta \dot{m}$  to the tip gap mass flow rate  $\dot{m}_{T0}$  without any tip injection. Figure 9 shows that the discharge coefficient  $C_D$  decreases with increasing area ratio  $\gamma$ . This effect is reflected by the analytical model as well as by the numerical results. Similar to Fig. 8, the blockage effect is more pronounced if the injection jet is oriented against the tip gap flow. For  $\lambda = 0$  and  $\theta = 1$ , Eq. (1) can be transformed using a Taylor series expansion for small area ratios  $\gamma$ . The result is the ratio of the discharge coefficient  $C_D$  with tip injection to the discharge coefficient  $C_{D0}$  without any tip injection:

$$\frac{C_D}{C_{D0}} = 1 - (2 + \cos \delta) C_{D0}^2 \gamma. \quad (6)$$

The result of Eq. (6) is plotted in Fig. 10 together with the corresponding numerical results. As can be seen, the influence of the area ratio  $\gamma$  and the injection jet orientation angle  $\delta$  on the discharge coefficient ratio can be approximated by the analytical model.

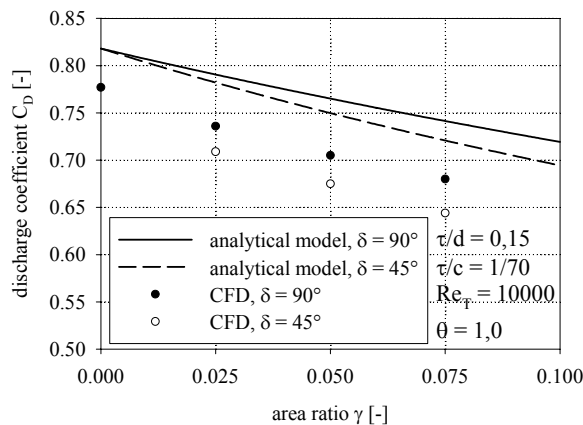


Figure 9: Discharge coefficient versus area ratio

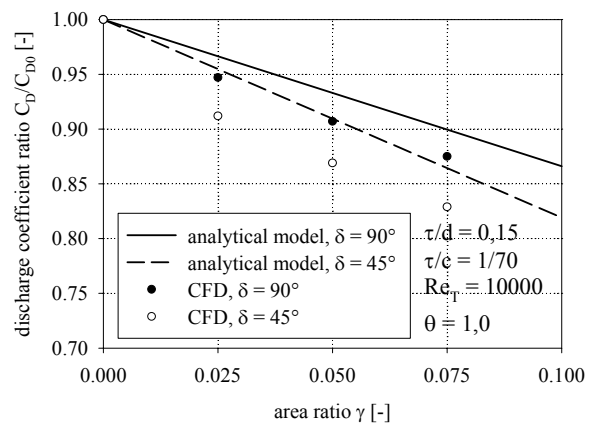


Figure 10: Discharge coefficient ratio versus area ratio

## 6. Summary and Outlook

A new method for the reduction of tip-leakage losses in axial turbine blade rows is presented: passive blade tip injection. Preliminary linear cascade wind tunnel results show that the passive injection method shifts the linear relationship between tip-leakage loss coefficient and tip gap width to lower loss values. This means that the relative performance of the passive tip injection method increases if the tip gap width decreases. An analytical model is presented which is able to predict the effect of the passive injection on the tip-leakage losses. The analytical results are compared with numerical results using the discharge coefficient concept.

For future investigations, it is the objective to compute the three-dimensional flow field in the axial turbine cascade with passive tip injection. Furthermore, the linear cascade wind tunnel experiments will be extended by turbulence measurements using hot-wire anemometry.

## Literature

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