Numerical Study on Effect of Tip Clearance Size on Tip Leakage Flow in a Linear Cascade at Off-design Condition

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1. Introduction

Operators of nuclear power reactor periodically check pump performance through in-service testing (IST) of pumps that perform safety functions such as capability to shut down the reactor and maintain it in a safe-shutdown condition or capability to prevent accidents or to mitigate the consequences of accidents. They also monitor and evaluate the degree of pump vulnerability over time. In some cases, due to various causes, the performance of the safety-related pump is dissatisfied with the regulatory requirements in the course of conducting IST. One of the major reasons, tip leakage flow, caused by the pressure difference between the pressure surface and the suction surface of an impeller, may contribute a large part of the total loss occurring in the centrifugal pump, and may affect the stable operation range. In addition, tip leakage flow and tip leakage vortex (TLV) collide with the subsequent blade and consequently may cause vibration, flutter and high stress. TLV with low pressure in the core can cause cavitation, resulting in the reduced pump efficiency and blade tip damage due to erosion. To prevent detrimental effects of these tip leakage flow and TLV, a variety of TLV control techniques for preventing or delaying the roll-up of tip leakage flow, reducing the strength of TLV and correcting the trajectory of TLV at blade tip, have been proposed. Therefore, in order to accurately verify the validity of these control techniques, it is required to use an appropriate numerical model that can quantitatively and accurately identify the strength and trajectory of TLV. On the other hand, two most important parameters controlling the strength of tip leakage flow are tip clearance size and blade loading (local pressure difference between the pressure and suction surfaces). In this study, the effect of tip clearance size on tip leakage flow pattern in a linear cascade at off-design condition was explained by using the commercial computational fluid dynamics (CFD) software, ANSYS CFX R18.1.

2. Analysis Model

2.1 Test Facility

A linear cascade, tested by Kang and Hirsch [1] in Vrije Universiteit Brussel, consists of seven NACA 65-1810 blades. The main blade design parameters are as follows: blade chord length 200.0 mm; aspect ratio 1.0; solidity 1.111; blade stagger angle 10°. Tip clearance sizes are 2 mm and 4 mm, which corresponds to 1% and 2% of blade chord length respectively. Detailed geometry specifications and flow conditions are summarized in Table I.

Table I: Geometry specifications and flow conditions

Blade type	NACA 65-1810
Blade chord	200 mm
Pitch	180 mm
Aspect ratio	1.0
Blade angle (inlet)	32.5°
Blade angle (outlet)	-12.5°
Stagger angle	10.0°
Tip clearance size	2 mm, 4 mm
Flow angle (inlet)	36.5°
Flow angle (outlet)	-1.4°

As shown in Fig. 1, there are 15 transverse measurements planes from 7.5% chord upstream of the leading edge to 25% chord downstream of the blade trailing edge. In each transverse planes 24 stations from the suction to pressure side of the blade and 33 stations behind the blade trailing edge. Fourteen points in each station are detected from near endwall (2 mm away from the endwall) to midspan.

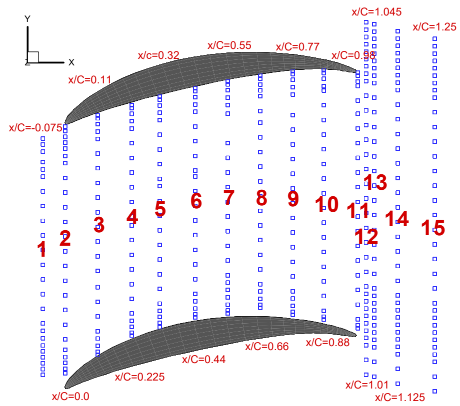


Fig. 1. Transverse measurement positions.

2.2 Test Conditions

For off-design condition, the mass-averaged flow inlet angle, measured at 40% chord upstream, is 36.5° and the outlet angle at 25% chord downstream is -1.4°. The Reynolds number, based on the inlet velocity (23.5m/s) and chord length, is about 3.0×10^5. The free stream turbulence intensity is 3.4%.

3. Numerical Modeling

3.1 Numerical Method

The flow inside a linear cascade was assumed to be steady, incompressible, isothermal and turbulent. Due to the interaction of tip leakage flow with through-flow and endwall boundary layer, very complex turbulent flow fields are formed inside TLV. Under these circumstances, the use of low-order accurate discretization scheme may cause the excessive numerical diffusion and, as a result, adversely affect the accuracy of the solution. Therefore, a high resolution scheme for the convection-terms-of-momentum and -turbulence equations was used. The solution was considered to be 'converged' when the residuals of variables were below 10^{-6} and the variations of the target variables were small.

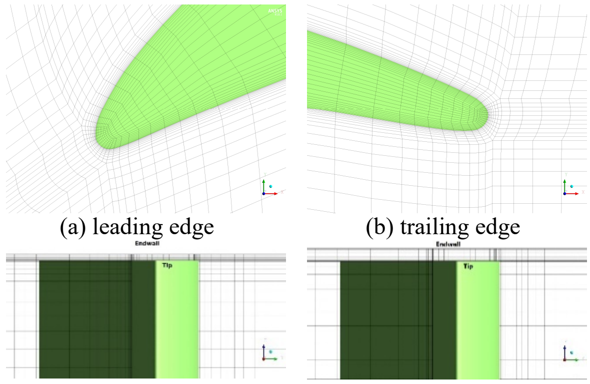
3.2 Turbulence Model

An anisotropic feature of turbulence inside TLV invalidates the use of an isotropic turbulence model based on the Boussinesq assumption and instead encourages the use of an anisotropic turbulence model, such as the Reynolds Stress Model (RSM). RSM may show superior predictive performance compared to eddy-viscosity model (EVM) in the following types of flow: flows with strong streamline curvature, secondary flow, swirl flow. RSM also solves the problem of excessive turbulent kinetic energy prediction in regions of large strain rate, which is a consequence of the treatment of the production terms in two-equation models [2]. In this study, SSG (Speziale, Sarkar and Gatski) model [3] was chosen. According to CFX Solver Modeling Guide, this turbulence model is more accurate than other ε-series RSM implemented in ANSYS CFX.

3.3 Grid System

Although the tip clearance is small compared to the blade dimension, tip leakage flow can influence up to approximately 10%~30% of the span from blade tip and therefore, it is important to adequately resolve the tip leakage flow.

Despite a series of reports on the successful use of the simple non-gridding model [4] or pinched type model [5] for the prediction of tip leakage flow in a reliable level, the embedded H-type grid has been known to provide a more accurate estimation of the strength of TLV and locus of its center than the formers [6]. In addition, Van Zante et al. [4] and Gupta et al. [7] showed that accurate analysis of shear layer through fine grid arrangement at blade tip and end walls was required to accurately predict tip leakage flow. In this study, based on the above-mentioned previous research results, hexahedral grid system of an embedded type generated by ICEM-CFD, a grid generation program, was used for calculating the tip leakage flow. (see Fig. 2) The total number of grids used in the calculation was 547,240, and 15 grids with dense distribution near the wall were used for tip clearance region. To properly predict the flow near the wall, the first grid located on the adjacent wall was placed at approximately $y^+ \sim 1$.



(a) leading edge (b) trailing edge
(c) mid-chord (t=2 mm) (d) mid-chord (t=4 mm)

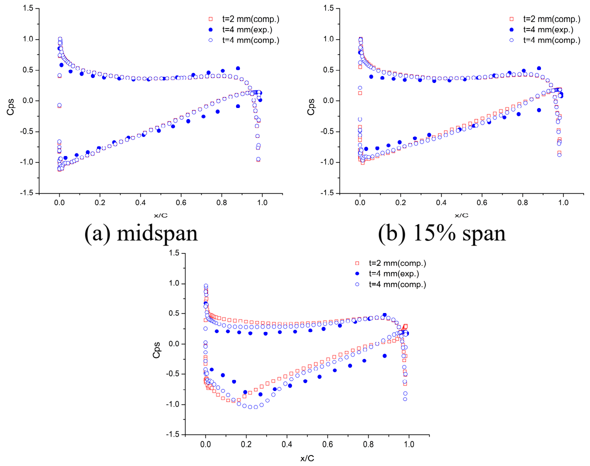
Fig. 2. Grid system.

3.4 Boundary Conditions

Inlet condition was specified from the measured velocity components. Turbulent kinetic energy, k, and turbulent dissipation rate, ε, were calculated from the magnitude of inlet velocity, turbulence intensity and the characteristic length scale. The length scale was set to be 2.0 mm (1% of blade chord length). The Reynolds stresses at the inlet were derived from the assumption of an isotropic turbulence by using the pre-calculated k and ε. The 'average pressure over the whole outlet' option; with a relative pressure of 0 Pa, was used as an outlet-boundary condition. No-slip condition was applied at the solid wall. For all flow variables, the same values were imposed on the periodic boundary. To model the flow in the near-wall region, the scalable wall function method was applied.

4. Results and Discussion

Fig. 3 shows the distributions of static pressure on the blade surface at three spanwise positions, i.e., 1.5% and 15% span from the endwall, and midspan. The predicted static pressure at midspan showed a similar distribution patterns regardless of tip clearance size. On the other hand, the distribution of static pressure on the blade surface at 1.5% of span, which was close to the blade tip, tended to increase the blade loading acting on the suction surface as the tip clearance increased. As the tip clearance increased from 2 mm to 4 mm, the position of the peak pressure on the suction surface shifted from about 14% to about 25% of the chord length downstream from the leading edge. This local peak pressure on the suction surface represents the existence of TLV. For t=4 mm, except for the suction surface at 1.5% of span, the static pressure distribution showed good overall agreement with the measurement data. One of reason for the difference between the experimental data and calculations may be the limitation of SSG turbulence model. For t=2 mm, because there was no available measured blade static pressure in the open literature, direct comparison between experiment and computation was impossible.

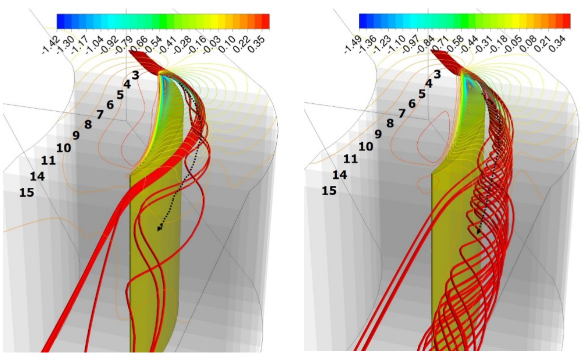


(a) midspan (b) 15% span

(c) 1.5% span

Fig. 3. Static pressure distribution on blade surface in the different spanwise positions.

Fig. 4 shows the distribution of the endwall static pressure and the particle traces released at 0.1% span from the blade tip to the endwall. The particle had a strong helical motion after being ejected from the suction side, and the locus of TLV center (expressed by dot line in Fig.4) coincided with the endwall pressure trough. The TLV moved away from the suction side as the flow proceeded downstream. The predicted distribution of the endwall static pressure and the particle traces showed different pattern depending on tip clearance size. For example, for t=4 mm, the endwall pressure trough had even steeper gradient and roll-up of tip leakage flow was much stronger than t=2 mm.



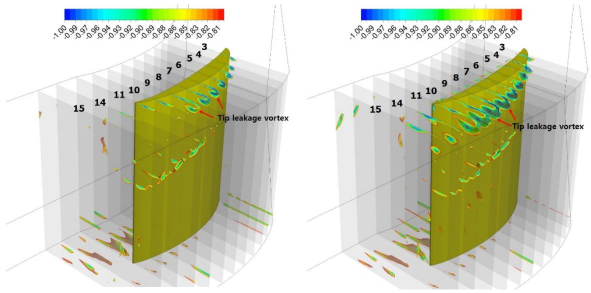
(a) t=2 mm (b) t=4 mm

Fig. 4. Static pressure coefficient on the endwall and particle traces released at 0.1% span from the blade tip to the endwall.

Fig. 5 shows the distribution of the normalized helicity defined as

$$\mathrm{H}_n = \frac{\vec{\omega}\cdot\vec{V}}{|\vec{\omega}||\vec{V}|} \qquad (1)$$

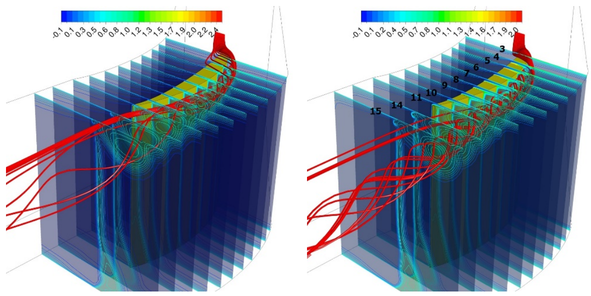
where $\vec{\omega}$ is the vorticity vector and $\vec{V}$ is the velocity vector. The magnitude of the normalized helicity closes to unity in the core of TLV, and its sign indicates the direction of TLV relative to the streamwise velocity component [8]. For t=2 mm, after forming the structure of TLV near the plane 3 (11% chord downstream from the leading edge), the normalized helicity at TLV core kept the unity in the forward half of the blade passage, but its magnitude began to decrease in the after part of the blade due to the vorticity diffusion. On the other hand, for t=4 mm, the position where TLV started to form was almost same as t=2 mm, but TLV still maintained its structure in the downstream (plane 14 and15).



(a) t=2 mm (b) t=4 mm

Fig. 5. Normalized helicity distribution.

Fig. 6 shows the distributions of total pressure loss and particle traces released at 0.1% span from the blade tip to the endwall. At the corner between the suction surface and the endwall, isolines with high total pressure loss were quasi-circular and were well consistent with TLV. Though the magnitude of the predicted total pressure loss differed locally, high total pressure loss region showed a similar distribution regardless of tip clearance size.



(a) t=2 mm (b) t=4 mm

Fig. 6. Distributions of total pressure loss and particle traces released at 0.1% span from the blade tip to the endwall.

Fig. 7 shows the secondary velocity vector and turbulence intensity distribution at the measured transverse planes, x/C=0.77 (plane 9) and 0.98 (plane 11). Turbulence intensity (TI) can be defined as

$$TI = \sqrt{\frac{\left(\overline{u'u'}+\overline{v'v'}+\overline{w'w'}\right)}{3V_1}} \times 100 \qquad (2)$$

where $\overline{u_i'u_j'}$ is Reynolds stress tensor and V_1 is inlet velocity. The velocity vector shows that TLV develops in a nearly circular shape at the corner between the suction surface and the end wall. As the tip clearance increased from 2 mm to 4 mm, the center of TLV (denoted by square) was located farther away from the endwall. The turbulence intensities were highly predicted in the region where tip leakage flow exited the tip clearance in the form of a jet. As the tip clearance size increased from 2 mm to 4 mm, the area with high turbulent intensity expanded into the flow passage along the end wall.

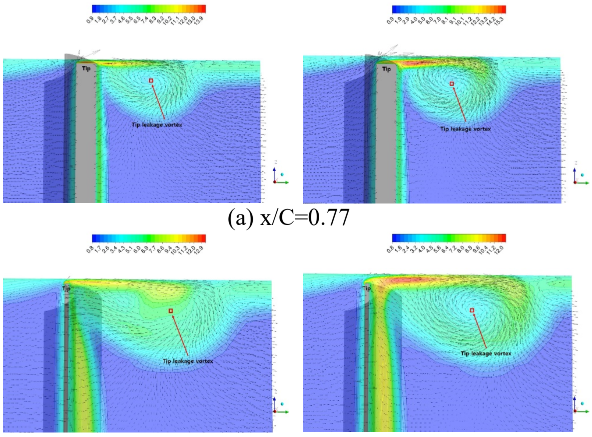


Fig. 7. Secondary velocity vector and turbulence intensity distribution for t=2 mm (left) and t=4 mm (right).

Fig. 8 shows the variation of TLV center location in the streamwise direction. In Fig. 8, L_y is the pitchwise coordinate of TLV from blade suction surface and s is pitch. Inside blade passage, location of TLV center was similar regardless of tip clearance size. On the other hand, TLV center located farther away from blade suction surface with increasing tip clearance size. As the TLV moved downstream of the blade trailing edge, the pitchwise coordinate of TLV center changed less because there was no jet-type tip leakage flow any more in this region. For t=4 mm, the predicted TLV center located farther away from blade suction surface compared to the measured data.

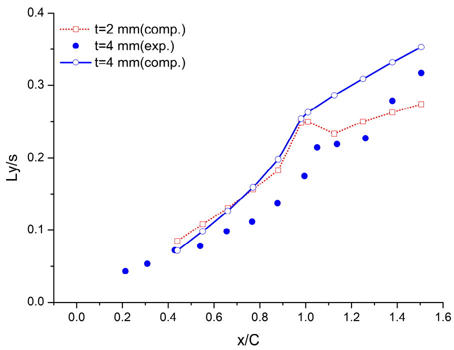


Fig. 8. Variation of TLV center location in the streamwise direction.

5. Conclusions

In this study, the influence of tip clearance size on tip leakage flow pattern in a linear cascade under off-design conditions was investigated by using commercial CFD software, ANSYS CFX R18.1. The main conclusions are as follows.

(1) The distribution of static pressure on the blade surface at 1.5% of span, which was close to the blade tip, tended to increase the blade loading acting on the suction surface as the tip clearance increased.

(2) As the tip clearance increased from 2 mm to 4 mm, the endwall pressure trough had even steeper gradient and roll-up of tip leakage flow was much stronger than t=2 mm.

(3) For t=4 mm, the position where TLV started to form was almost same as t=2 mm, but TLV still maintained its structure in the downstream.

(4) As the tip clearance increased from 2 mm to 4 mm, the center of TLV (denoted by square) was located farther away from the endwall, and the region with high turbulent intensity expanded into the flow passage along the end wall.

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