Volumetric entropy generation rate associated with tip clearance flow in linear cascade

Long Bingxiang1, Chen Qin1, Ren Zebin1, Liao Daxiong1

1. Facility Design and Instrumentation Institute of Chinese Aerodynamic Research and Development Centre, No. 6, South Section, Second Ring Road, Mianyang City, Sichuan Province, P.R. China.

bingxiang2011@126.com

Abstract: The tip clearance flow structure and its corresponding entropy generation rate of a linear cascade with 1.85mm radial tip clearance operating under three different incidence angle are investigated. The incidence angle influences the tip leakage vortex position as well as the size of the tip leakage vortex. Larger incidence angle results in larger tip leakage vortex and pushes the tip leakage vortex further away from the suction side. The entropy generation rate related to the tip clearance flow structure is calculated and it is confirmed that tip clearance flow is the main major source of aerodynamic loss in linear cascade. Larger incidence angle leading to higher entropy generation rate. Results also show that it’s not the core region of tip leakage vortex but the edge vortex and shear layer of the tip clearance flow which has the highest entropy generation rate. When operating under an incidence angle of 4°, there exist an extra high entropy generation rate region in main flow. It is found that the compression and expansion of fluid due to the existence of tip clearance vortex was the main reason for this extra high entropy generation.

1. Introduction

The radial clearance between stator-vane to end-wall and between rotor-blade to end-wall is indispensable for turbomachine operation and adjusting. The clearance flow, including tip clearance flow and hub clearance flow, due to the existence of radial clearance, however, has been a major source for loss, blockage, instability and noise, and is detrimental to the aerodynamic, aero-acoustic and structural performance of turbomachine. Since clearance flow has significant influences on turbomachinery performance, it attracts numerous researchers’ attention.

A number of numerical and experimental investigations have been carried out across the world for the purpose of getting deep insight into the detailed structure of the clearance flow. The investigation of Kang and Hirsch shows that horseshoe vortex and multiple vortex exist in tip region and the existence of tip clearance vortex results in passage vortex close to end wall and suction side, Kang and Hirsch also find that the vorticity of tip clearance vortex increase right after it formed in the leading edge region and then decrease gradually[1][2]. Kang and Hirsch also indentified tip separation vortex and pointed out that leakage flow mixing has a significant influence on the internal loss of compressor cascade[3]. Zhong studied the unsteadiness of tip clearance flow using DDES method and found that smaller tip gap results in weaker anisotropy[4]. The investigation of Kunz shows that Navier-Stokes procedures with k-epsilon turbulence model has satisfactory performance in capturing important physical phenomena of tip clearance flow[5]. Tian and Li found that the intensity and influence area of
tip leakage vortex increase with increasing tip leakage clearance[6]. The investigation of Muthanna and Devenport reveals that the dynamics of tip clearance vortex are dominated by streamwise mean-velocity deficit the vortex produces[7]. Alexej studied the tip clearance flow of axial-flow fan using LES method and found that tip clearance flow results in lower turbulence kinetic energy[8]. Some passive methods has been utilized to control the tip clearance flow. Mehdī pointed out that porous treatment can reduce the intensity of tip vortex as well as the shear layer rollup and boundary layer separation[9]. The investigation of Chen demonstrated that circumferential groove can suck low energy tip clearance flow and thus has a significant importance in extending stall margin of centrifugal compressor[10]. Wang studied the effects of blade tip profile and found that optimized blade tip profile can reduce tip leakage flow velocity, weakens the strength of mixing, and therefore results in loss reduction[11].

The loss induced by clearance flow is a dominant part of turbomachinery total loss. Clarifying the loss mechanism associated with the complex tip clearance flow structure is beneficial for developing design method to improve the turbomachinery efficiency as high as possible. According to the theory of the second law analysis, the volumetric entropy generation rate is capable to present the local loss intensity and thus providing researchers the possibility of clarifying the loss mechanism[12]. Up to date, three main approaches has been proposed for volumetric entropy generation rate calculation. By adding a turbulent conductivity and turbulent viscosity to the molecular conductivity and viscosity, Moore and Moore proposed the first method to close the volumetric entropy equation[13]. The Moore model has been utilized for studying end-wall sealing flows[14] and tip cavity flows[15] in turbines based on RANS method. Kramer-Bevan[15] proposed a new model for volumetric entropy equation closing and has been used by Kock[17] and Takakura[18] to investigate the entropy generation rate in the tip region of a high-pressure turbine using RANS simulation results. Adeyinka[16] extended past Reynolds averaging techniques for the momentum and scalar transport equations to the second law for turbulent and has been used by Orhan[20] to study loss mechanism of an axial turbine cascade. The applicability of the model proposed by Kramer Bevan in loss mechanism study has been validated and is used in this paper.

Direct and quantitative study of clearance flow in actual turbomachines is challenge due to some safety issues and some technique limitation. Linear cascade with gap can reproduce flow structures quite similar to the tip clearance flow in actual turbomachines and providing researchers an efficient and effective way of studying clearance flow phenomenon. In this paper, a numerical research using RANS is carried out to study the tip clearance flow structure and the loss mechanism associated with tip clearance flow under three different incidence angle (α). The paper is organized as follows: After the validation of the RANS method, the numerical model is introduced and the numerical results are presented. The tip clearance flow structure and the loss production associated with these flow structures under three different incidence angle is then analyzed in detail to understand the tip clearance flow structure, the corresponding loss-generating mechanism and the influence of incidence angle on clearance flow structure and the corresponding loss mechanism.

2. Model and Numerical Method

2.1. The studied cascade

the linear compressor cascade of LMFA at Ecole Centrale Lyon is selected for the purpose of evaluating the accuracy of numerical methods as there are many detailed and accurate experiments of this cascade were carried out in previous researches. The geometric parameters of the cascade are shown in Table 1. The inlet velocity is 40m/s so that the flow in the cascade can be treated as incompressible. The incident angle is set to 4 degrees, so that the corner separation exist. More detailed information can be found in Reference. In order to study the effects of incidence angle on clearance flow structure and entropy generation rate, a 1.85mm tip clearance gap is added to the LMFA cascade and three different operating condition, which corresponding to an incidence angle of -4°, 0° and 4°, were set in this study.
Table 1 Geometric parameters of the cascade

| Parameter                        | Value  |
|----------------------------------|--------|
| Chord (mm)                       | 150    |
| Camber angle (Degree)            | 23.22  |
| Stagger Angle (Degree)           | 42.7   |
| Pitch spacing (mm)               | 134    |
| Solidity                         | 1.12   |
| Blade span (mm)                  | 370    |
| Aspect ratio                     | 2.47   |
| Design upstream flow angle (Degree) | 54.31 |
| Incident angle (Degree)          | 4      |
| Design downstream flow angle (Degree) | 31.09 |

2.2. Numerical setup
The HOH mesh topology is employed for meshing the studied cascade. To guarantee the accuracy of the numerical simulation, the Y-plus of the first layer near-wall of computational mesh is less than 1. The length of the inlet and outlet region are 1.5 times of the chord length (1.5C) and 2C in order to make these two boundaries less reflective. Half of blade span is used to carry out this research for the purpose of reducing the computational consumption. The mesh dependence was studied and the grid number chosen for this study is about 3.0 million. Mesh information is show in Figure 1.

Ansys Fluent 15.0 is used as the computational platform. Realizable k-epsilon turbulent model with enhanced near-wall treatment is employed in this study. Velocity inlet and Outflow boundary condition is set up for inlet and outlet respectively. The inlet velocity distribution is taken from experiments. Other boundary conditions were give in normal ways for internal flow simulation.

2.3. Numerical validation.
Static pressure coefficient is a common parameter to quantify the blade load distribution and Total pressure loss coefficient is a parameter corresponding to loss generation in turbomachine and they are defined as eqn.(1) and eqn.(2) respectively.

\[ C_P = \frac{p - p_{\infty}}{p_{\infty} - p_{e}} \]  \hspace{1cm} (1)

\[ \omega^* = \frac{\int_C C_{ps}(y,z) \rho(y,z) u(y,z) dy}{\int_C \rho(y,z) u(y,z) dy} \]  \hspace{1cm} (2)
Figure 2 depicts the static pressure coefficient on the blade of the experiment and RANS results at the 50%, 21.6% and 5.4% and it also presents the total pressure loss coefficient taken from experiment and CFD results at the plane 0.363 times of the axial chord length away from the trailing edge of the cascade. From Figure 2, it is clear that RANS can predict the separation vortex and the total pressure loss corresponding to the separation vortex with satisfactory accuracy.

3. Results and Analysis

3.1. Clearance flow structure

It is clear from Figure 3 that tip leakage vortex originates from the suction side and being pushed away from the suction side to the pressure side of the neighbouring blade as well as lifted away from the
casing wall. Figure 3 also presents that the tip leakage vortex size expanded as the tip leakage vortex being convected downstream. The generation and development process of tip leakage vortex revealed is consistent with other previous researches.

Figure 3 also reveals the variation of tip leakage vortex structure with the change of incidence angle. The origin of the tip leakage vortex moves downstream along the blade suction side with decreasing incidence angle. The origin of the tip leakage vortex located around 3%, 10% and 30% chord length for incidence angle of 4°, 0° and -4°. Increasing incidence angle pushes the tip leakage vortex further faraway from the suction side. From Figure 3, it is also clear that larger incidence angle results in larger tip leakage vortex.

Figure 4 demonstrates the strength of tip leakage vortex at 50% chord length. From Figure 4, it is obvious that the strength of the tip leakage vortex increases with the increase of the incidence angle. The streamwise component of tip leakage vortex vorticity is negative, which means tip leakage vortex rotate clockwise. Figure 4 also reveals that tip leakage vortex size and its distance to suction side increase with incidence angle increase. Increasing incidence angle results in large static pressure difference between blade suction side and blade pressure side as well as rapid flow acceleration on the suction side, which is the fundamental reason for tip leakage flow structure and vortex strength variation with incidence angle.

3.2. Entropy Generation Rate
3.2.1. Total pressure loss coefficient. Figure 5 presents the variation of total pressure loss coefficient with incidence angle. Data is extracted from a plane which is 0.363 times of axial chord length away from the blade trailing edge. Total pressure loss coefficient is calculated according to Eq. (2). From Figure 5, it is clear that the loss magnitude associated with the tip clearance flow increase with incidence angle. It can also be seen from Figure 5 that the region which is influenced by tip clearance flow expanded as incidence angle increases. For operating conditions with an incidence angle of -4°, 0° and 4°, the origin of influence gradually increase from about 0.025m to around 0.035m. In the incidence angle range from -4° to 4°, the influence of incidence angle on the profile loss is relatively small.

3.2.2. Entropy Generation Rate. According to Kramer-Bevan’ model, volumetric entropy generation rate ($S^\prime\prime\prime$) is defined as

$$S^\prime\prime\prime = \frac{2\mu \tau_{ij}}{\overline{T}} + \frac{\phi}{\overline{T}} + \left(1 + \alpha \frac{\lambda}{\alpha} \right) \frac{\partial \overline{T}}{\partial x_i} \frac{\partial \overline{T}}{\partial x_j} \frac{\partial \overline{T}}{\partial x_i} \frac{\partial \overline{T}}{\partial x_j}. \tag{3}$$

Where, $\overline{T}$ is the temperature, $\rho$ is the density, $2\mu \tau_{ij}$ is the viscous stress tensor, $\varepsilon$ is the turbulence dissipation rate, $\alpha$, and $\alpha$ represents the turbulent thermal diffusivity and thermal diffusivity respectively. $\lambda$ is the heat transfer coefficient. For incompressible flow, $\overline{T}$ is assumed as a constant. In this way, $\left(1 + \alpha \frac{\lambda}{\alpha} \right) \frac{\partial \overline{T}}{\partial x_i} \frac{\partial \overline{T}}{\partial x_j} \frac{\partial \overline{T}}{\partial x_i} \frac{\partial \overline{T}}{\partial x_j} = 0$. Then, Eq. (3) can be simplified as:

$$S^\prime\prime\prime = \frac{2\mu \tau_{ij}}{\overline{T}} + \frac{\phi}{\overline{T}}. \tag{4}$$

Figure 6 and Figure 7 clearly demonstrate the volumetric entropy generation rate associated with tip clearance flow around the leading edge and trailing edge region. Around the leading edge, when incidence angle is -4°, the aerodynamic loss source is confined in the tip clearance region and it is obvious that the highest entropy generation rate occurs around the suction side, which means when cascade operating under incidence angle of -4°, around the leading edge region, part of main flow fluid moves from the suction side to the pressure side, which results in edge vortex exist around the suction side. Increasing incidence angle, entropy generation rate associated with edge vortex located near the pressure side increases and the loss source extend to the main flow close to the suction side. Figure 6 also reveals that, around the leading edge, the magnitude of entropy generation rate of boundary layer is relatively small compared to that of the tip clearance flow.

Figure 7 clearly demonstrates that, around the trailing edge, tip clearance flow is still the main loss source. For tip clearance flow, the highest entropy generation rate associated the edge vortex around the pressure side and shear layer generated by the tip clearance flow and the main flow. The entropy
generation rate in the vortex core region, however, is relatively small compared to that of edge vortex and shear layer. From Figure 7, it is obvious that on the pressure side, there exist a region with high entropy generation.

![Figure 7: Entropy generation rate around trailing edge](image1)

Figure 8 presents the streamlines go through this high entropy generation region. It is clear from Figure 8 that, due to the existence of tip clearance vortex from the neighbouring blade, the streamline undergo quick compression and expansion. The compression and expansion of the fluid is the reason for such an high entropy generation rate region.

![Figure 8: Streamlines pass through high entropy generation rate region](image2)

### 4. Conclusions

Incidence angle plays an important role in deciding the origin, the size and the position of tip leakage vortex. The tip leakage vortex origin moves downstream with the increase of incidence angle, the vortex size increase with the increase of the incidence angle. Increasing incidence angle moves the tip leakage vortex further faraway from the blade suction side.

Tip clearance flow is the main major source of aerodynamic loss in linear cascade. Entropy generation rate associated with tip clearance flow increases with the increase incidence angle. Edge vortex and shear layer corresponding to the tip clearance flow has the highest entropy generation rate. The entropy generation rate associated with the tip leakage vortex, however, is relatively small when compared with the entropy generation rate of edge vortex and shear layer.
When operating under an incidence angle of 4°, there exist another high entropy generation rate region in main flow near trailing edge. It is found that the compression and expansion of fluid due to the existence of tip clearance vortex was the main reason for this extra high entropy generation.

References
[1] Kang, S., Hirsch, C., & Fields, Pressure. (1992). Experimental study on the three-dimensional flow within a compressor cascade with tip clearance: part I—velocity and pressure fields. Journal of Turbomachinery,115(3), 1927-1951.
[2] Kang, S., Hirsch. C. (1992). Experimental Study on the Three-Dimensional Flow Within a Compressor Cascade With Tip Clearance: Part II—The Tip Leakage Vortex.
[3] Kang, S., Hirsch, C. (1994). Tip leakage flow in linear compressor cascade.Journal of Turbomachinery,116(4), 657.
[4] Zhong, L. Y., Liu, Y. W., & Lu, L. P. (2019). Unsteady behavior of tip leakage vortex in an axial compressor with different rotor tip-gap sizes using DDES.Chinese Journal of Turbomachinery,601(002), 1-9.
[5] Kunz, R. F., Lakshminarayana, B., & Basson, A. H. (1993). Investigation of tip clearance phenomena in an axial compressor cascade using Euler and Navier-Stokes procedures.Journal of Turbomachinery,115(3), 453.
[6] Tian, C. R., & Li, B. K. (2018). Large-eddy simulation study on effect of blade tip clearance on performance of the axial flow fan.Chinese Journal of Turbomachinery.
[7] Muthanna, C., & Devenport, W. J. (2004). Wake of a compressor cascade with tip gap, part 1: mean flow and turbulence structure.Aiaa Journal,42(11), p.2320-2331.
[8] Alexej Pogorelov, Matthias Meinke, & Wolfgang Schroder. (2018). Large Eddy Simulation of the Tip Leakage flow in a Axial-fan.Chinese Journal of Turbomachinery,600(001), 1-15.
[9] Mehdi, R., Khorrami, Fei, Li, & Meelan. (2002). Novel approach for reducing rotor tip-clearance-induced noise in turbofan engines.Aiaa Journal.
[10] Chen, X. F, & Qin G. L. (2018). Numerical Simulation of Flow in Centrifugal Compressor with a Single Circumferential Groove. Chinese Journal of Turbomachinery.
[11] Wang, X., Li, W., Zhang, X. H., Zhu, Y. L., Zuo, Z. T., & Chen, H. S. (2019). Tip profile optimization in a low aspect ratio caes radial expander based on orthogonal design.Chinese Journal of Turbomachinery.
[12] C S Tan. (2007). Internal flow - concepts and applications.cambridge university press.
[13] Moore J, & Moore J. G. (1983). Entropy Generation Rates in Air-Cooled Gas Turbine Nozzles: Part-1-A Turbulent Boundary Layer. ASME paper 83-GT-70.
[14] Zlatinov, M. B., Tan, C. S., Montgomery, M., Islam, T., & Seco-Soley, M. (2011). Turbine Hub and Shroud Sealing Flow Loss Mechanisms.Asme Turbo Expo: Turbine Technical Conference & Exposition.
[15] Timothy R. Palmer, Choon S. Tan, Humerto Zuniga, David Little, Matthew Montgomery, & Anthony Malandra. (2016). Quantifying loss mechanisms in turbine tip shroud cavity flows.
[16] Kramer-Bevan J. S. (1992). A Tool for Analysing Fluid Flow Losses. PHD Thesis.
[17] Kock, F., & Herwig, H. (2005). Entropy production calculation for turbulent shear flows and their implementation in cfd codes.International Journal of Heat and Fluid Flow,26(4), p.672-680.
[18] Takakura, Tamuto. (2017). Entropy generation in the tip region of a high-pressure turbine. PHD Thesis.
[19] Adeyinka, O. B., & Naterer, G. F. (2004). Modeling of entropy production in turbulent flows.Journal of Fluids Engineering,126(6), 503-507.
[20] Orhan. O. E. (2014). Investigation of the Effect of Turbulence on Entropy Generation in Turbomachinery. PHD Thesis.
[21] Zambonini, G., Ottavy, X., & Kriegseis, J. (2016). Corner Separation Dynamics in a Linear Compressor Cascade.ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition.