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Inlet conditions effect on tip leakage vortex breakdown in unshrouded axial turbines

Jie Gao [a, *], Qun Zheng [a], Tianbang Xu [b], Ping Dong [a]

[a] College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China
[b] Harbin Marine Boiler & Turbine Research Institute, Harbin 150078, China

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ABSTRACT

The TLV (tip leakage vortex) breakdown occurs under some conditions in modern turbines, which leads to extra vortex breakdown losses, but the mechanisms of vortex breakdown and its influencing factors remain unclear. This paper computationally investigates the effects of inlet conditions on the TLV dynamics in an unshrouded turbine. The TLV dynamics analysis is first shown, and then the effects of inlet CBL (casing boundary layer) parameters and flow incidence on the TLV breakdown and loss are investigated respectively. Based on these, a comparison of effects of different inlet conditions on tip leakage mixing loss is examined. Results indicate that the increased CBL thickness and turbulence intensity increases the adverse-pressure gradient in the rear part of the blade tip in varying degrees, but has a minor effect on TLV breakdown location. An increased incidence leads both to the reduction of the initial streamwise velocity on the vortex core and the adverse-pressure gradient in the rear part of the blade tip. Overall, as the incidence increases, the TLV breakdown location moves first upstream and then downstream. All these mean that the TLV initial state is another influencing factor on its breakdown.

1. Introduction

Turbomachinery has seen widespread use in the industry (Wu et al. [1], Gomes et al. [2] and so on); however, turbine blade tips have been, and continue to be one of major causes for the loss of efficiency as well as the loss of work in turbomachinery (Bunker [3]). Extensive works have been published on the tip leakage flows in turbines (Bunker [3], Sjolander [4], Mohamed and Shaaban [5] and so on), and several different flow-control methods were further investigated to minimize the tip leakage loss (Lee and Chae [6], Zhou et al. [7], and Gao et al. [8]). It should be noted that, these control methods mainly take the more straightforward approach of simply reducing the total tip leakage flow. However, modern sealing arrangements or methods have reached their efficiency limits, and thus further improvement can be achieved mainly by controlling the leakage flow itself (Barmpalias et al. [9]). Therefore, it is necessary to well understand the tip leakage mixing mechanisms and then to influence them.

Although Yaras and Sjolander [10] found that the losses within the tip gap comprised only 10%~15% of the tip leakage loss, with most of the leakage loss tied to the mixing of the leakage flow with the main flow, little information about the tip leakage mixing mechanisms is available in the literature. Furthermore, there has been very little work in examining the leakage flow for additional loss sources. Until now, the loss within the gap and the tip leakage mixing loss have been the only leakage loss mechanisms identified in the literature.

Vortex breakdown is a practically important phenomenon which can be observed in many flow situations. Recently, the TLV (tip leakage vortex) breakdown phenomenon has been observed in unshrouded axial turbines. Sell et al. [11] numerically and experimentally investigated the flow field generated by the presence of tip clearance in an annular turbine cascade. The wall flow visualization and the tip static-pressure distribution show that, the flow in the TE (trailing edge) region is producing a stagnating domain away from the walls at the largest tip clearance (5% chord). They think that the possible explanation for this behavior is the interaction of the tip leakage with the adverse-pressure gradient over the rear part of the blade, which induces a vortex breakdown type flow. Huang et al. [12] carried out a numerical simulation of the tip leakage flow to define the loss generation mechanisms associated with tip leakage in unshrouded turbines. Through both control volume arguments and axisymmetric computations, it is shown

* Corresponding author. Tel.: +86 13895710245.
E-mail address: gaojie_d@hrbeu.edu.cn (J. Gao).

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that as a swirling leakage flow passes through a pressure rise, i.e. in the rear part of the blade SS (suction side), the mixed-out loss can either reduce or increase. For axial turbines, the latter typically occurs if the deceleration is large enough to initiate vortex breakdown, and it demonstrates that this is the case in modern turbines.

As is well known, the TLV breakdown leads to the extra vortex breakdown loss, which belongs to a part of tip leakage mixing losses, and the TLV breakdown loss may behave differently from the conventional view of the flow exiting a turbine tip clearance (Gao et al. [13]). It is therefore necessary to well understand the TLV breakdown mechanisms and then to identify the influencing factors on the vortex breakdown.

More recently, the focus of blade tip studies has been gradually moved towards investigating the tip leakage flow in more engine-realistic conditions. Therefore, one of the questions often raised is whether the inlet conditions, such as inlet CBL (casing boundary layer) thickness, turbulence level and flow incidence could affect the TLV breakdown characteristics and associated loss, or whether there are any other factors that influence the TLV breakdown.

Few studies have examined the effect of inlet flow conditions on the tip leakage flows. For the effects of inlet CBL parameters, the numerical study of Coull et al. [14] found that the inclusion of a realistic CBL alters the relative aerodynamic performance of different winglet tip designs. The experimental and numerical study of Zhang et al. [15] indicated that the level of inflow turbulence alters the balance between the TPV (tip passage vortex) associated secondary flow and the over tip leakage flow. Consequently, the enhanced inertia of near wall fluid at a higher inflow turbulence weakens the cross-passage flow. As such, the weaker TPV leads the TLV to move further into the middle passage, with the less spanwise coverage on the suction surface. However, the investigation of Coull et al. [16] indicates that only minor changes to the leakage flow are induced by introducing a more realistic inlet condition.

On the effects of off-design incidence on tip leakage flows, the linear turbine cascade data of Yamamoto [17] reported that, for three tip clearance heights, at incidences of 0° and 7.2°, both passage and tip leakage vortices have been observed, which are rotating in opposite directions and are interacting. At incidences of −8.3° and lower, the TPV could not be observed. However, the TLV still appears and its strength is independent of the incidence. Willinger and Haselbacher [18] extended the knowledge of off-design incidence effects on the tip leakage flow to a typical low-pressure turbine tip section. Based on the experimental results, they put forward a tip leakage loss model which can take into account off-design incidences. The model is applied to the present turbine cascade as well as to the turbine cascade of Yamamoto. Buske et al. [19] numerically studied the influences of flow incidence and gap height on tip leakage losses in turbine cascades and rotors. It was found that positive incidences, i.e. increased blade loadings, decrease the tip leakage loss magnitude and emphasize the additional passage loss, giving in total a rise of the global tip leakage loss coefficient. The high loss region is shifted in counter-rotating direction. Furthermore, negative incidences result in opposite effects.

As described above, the inlet conditions have a strong effect on tip leakage flow fields, which inevitably has some impacts on TLV breakdown. However, to the authors' knowledge, no research papers have been published to describe the effects of inlet conditions on TLV breakdown characteristics and associated loss.

The objectives of this paper are to examine how the inlet conditions would affect TLV breakdown characteristics and associated loss, and then to consider new influencing factors on the TLV breakdown. Therefore, the TLV dynamics analysis is first shown, and then the effects of inlet CBL parameters and flow incidence on TLV breakdown and loss are systematically investigated respectively. Based on these, a comparison of effects of different inlet conditions on tip leakage mixing loss is examined. Numerical methods (similar methods have been successfully used for the studies both on a small scale horizontal axis wind turbine in Ref. [20] and on a highly loaded turbine rotor in Ref. [21]) have been employed to make a comprehensive understanding of inlet conditions effects on the TLV dynamics in unshrouded axial turbines.

2. Computational method and validation

In this investigation, results are presented for a wide range of inlet CBL profiles, five inlet turbulence intensity levels from 1% to 10%, and five incidences from −20° to +15°. The design clearance is 1.5 percent of blade span. It is noted that the blade geometry chosen for this investigation is taken from GE-E^3 first stage turbine rotor as shown in Fig. 1, which represents a modern turbine blade geometry. The rotor blades are twisted, and have a constant axial chord length of 28.7 mm and an aspect ratio (span to chord) of 1.39. The main blade geometry parameters are shown in Table 1, and detailed blade geometry can be found in the NASA report (Timko [22]).

The numerical investigation presented in this paper was performed by using ANSYS CFX 11.0 (AEA [23]), a commercially available general finite volume based Navier–Stokes solver. The governing equations were solved using a finite volume technique with a second-order upwind discretization scheme. The overall accuracy is of the second order. A standard k-ω two-equation model developed by Wilcox [24] is chosen in present investigation for turbulence closure, and no wall functions are used here, that is because the previous research work about turbine tip leakage flows has shown that the standard k-ω turbulence model gives a well match with the experimental data (Yang and Feng [25] and Ameri et al. [26]).

The commercial structured grid generation package Autogrid5 (preprocessor to NUMECA) was used in this investigation. Fig. 1 shows the representative computational grid of the rotor blade. The channel is discretized into H-type grids, while the regions around the blade surface and the tip gap are discretized into O-type grids to ensure high grid quality. Furthermore, the grid is clustered near the LE (leading edge) and TE, and near the tip region, and there are 23 nodes in the boundary layer to provide grid-independent results, and there are 33 grid layers distributed from the blade tip to the casing wall. There are over 100 points from the LE toward the

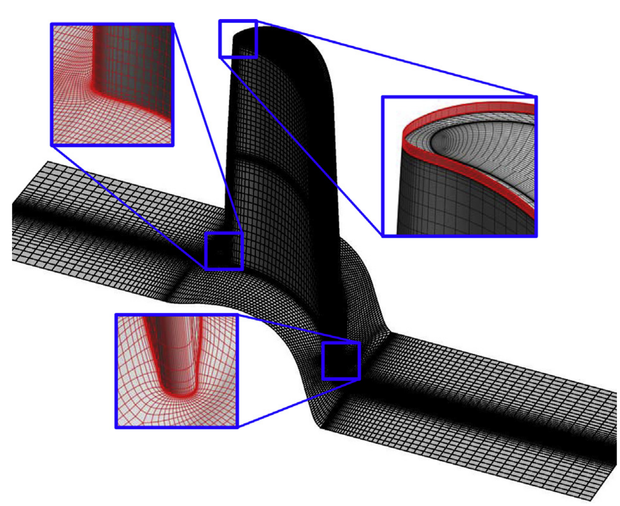

Fig. 1. Three-dimensional computational grid and details of leading edge, trailing edge and tip grids.