Experimental Thermal and Fluid Science 90 (2018) 220–230

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experiment study of aerodynamic performance for the suction-side and pressure-side winglet-cavity tips in a turbine blade cascade

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ARTICLE INFO

Keywords:
Winglet-cavity tip
Tip leakage flow
Aerodynamic performance
Turbine cascade

ABSTRACT

The influences of suction-side and pressure-side winglet-cavity tips on the flow field and aerodynamic performance of a turbine blade with tip clearance have been investigated in a low-speed cascade wind tunnel. The flow field of the cascade outlet is measured by a calibrated five-hole probe. The oil flow visualizations and static pressure of the endwall provide insight into the endwall flow structure of these blade tips. Compared with the results of flat tips at the ratio of tip clearance to blade height of $\tau/H = 1.0\%$, the results show that the pressure-side winglet-cavity tip reduces the region and loss of tip leakage flow and enhances the passage vortex. Moreover, the suction-side winglet-cavity tip weakens the tip leakage vortex and passage vortex simultaneously with an 11.4% reduction of total pressure losses and a more uniform flow angle than the flat tip. Thus, the suction-side winglet-cavity tip provides better aerodynamic performance. The pressure-side winglet-cavity tip, with a smaller distance between the tip leakage separation line and the suction side in the flow passage, tends to obtain a smaller tip leakage loss, as shown in the endwall oil flow visualization. The reduction of the range of the buffer zone indicates that the interaction between the tip leakage flow and passage flow decreases and the loss of passage vortex increases. A portion of the fluid in the passage enters the cavity from the front of the suction side. These factors weaken the loss of the passage vortex. Although the suction-side winglet-cavity tip shows a larger distance between the tip leakage separation line and the suction side, the reduction of range along the blade height decreases the loss of tip leakage flow. The effects of tip clearance on the aerodynamic performance indicate that the ratio of change in losses to tip clearance for the pressure side winglet-cavity tip is almost equal to the results for the flat tip owing to the change in the losses of tip leakage vortex and passage vortex with various tip clearances. With a 23.4% reduction in the ratio of change in losses to tip clearance, the influences of tip clearance on the outlet flow field of the suction side winglet-cavity tip are smaller than with other blade tip geometries. Overall, the winglet-cavity tip can be used to reduce the loss of tip leakage flow, while the suction side winglet-cavity tip achieves a better aerodynamic performance among the tested winglet cavity tips.

1. Introduction

In a shroudless axial turbine blade, the pressure difference between the pressure side and the suction side drives the gas passing through the radial clearance between the rotating blade tips and station casing. Then the tip leakage flow forms, leading to a deterioration of performance. According to the test results on several different experimental turbines reported by Booth [1], the losses due to the tip clearance can be as high as one third of the turbine stage losses. With the actions of centrifugal stress, thermal expansion, and corrosion, the tip clearance between the blade tip and casing would be varied. Bunker [2] states that stage efficiency is very sensitive to increased relative blade tip clearance, with sensitivities from 1:1 to 2:1 for various blade tips. The investigations of the tip leakage flow mechanism provide guidance for the blade tip design to control the tip leakage flow.

The tip leakage flow and development of aerodynamic loss of the flat tip have been investigated by many researchers. The investigations of tip leakage flow indicate that there exists a separation bubble near the pressure side in the flat tip and the tip leakage flow separates and reattaches at the leading of the flat tip [3–6]. The endwall flow shows the separation lines of tip leakage flow and passage flow [6,7]. The contraction at the entrance of the tip gap reduces the static pressure of the endwall and flat tip sharply and makes the tip leakage flow accelerate considerably [4,7,8]. Investigations of tip leakage loss show that the total tip clearance consists of the internal gap loss, secondary/endwall loss, and mixing loss of the tip leakage flow and main flow [9]. In addition, the interaction of the tip leakage vortex and passage vortex at various tip clearances has a significant effect on the aerodynamic

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http://dx.doi.org/10.1016/j.expthermflusci.2017.09.020
Received 17 February 2017; Received in revised form 4 September 2017; Accepted 22 September 2017
Available online 22 September 2017

Nomenclature

b	axial chord
C	blade chord
C_p	static pressure coefficient
C_{pt}	local total pressure loss coefficient
$\overline{C}_{pt}$	pitch average total pressure loss
$C_{Pt,t}$	passage total pressure loss
F	given aerodynamic parameter
h	normalized blade span
H	blade height
H_1	shape factor
i	number of point along spanwise
j	number of point along pitch
Re_2	exit Reynolds number
$Re_{\delta^{**}}$	inlet momentum thickness Reynolds number
p	pitch
$\overline{p}$	normalized pitch
P_s	static pressure
P_t	total pressure at measured point
$P_{1,t}$	inlet total pressure
$P_{2,s}$	outlet static pressure
$\overline{U}$	normalized velocity at inlet
x	variable related to the aerodynamic perfromce
α_{1P}	inlet angle
α_{2P}	outlet angle
$\overline{\alpha}$	pitch average outlet flow angle
β_b	stagger angle
δ^*	displacement thicknesses of inlet boundary layer
δ^{**}	momentum thicknesses of inlet boundary layer
δ_F	uncertainty of F
τ	tip clearance height
BZ	buffer zone
Case 1	flat tip
Case 2	cavity tip
Case 3	pressure-side winglet-cavity tip
Case 4	suction-side winglet-cavity tip
LFZ	leakage flow zone
LSL	leakage-flow separation line
RL	reattachment line
PSL	passage-flow separation line
PS	pressure side
PFZ	passage flow zone
SS	suction side

performance of the turbine cascade [10,11]. Thus, adopting reasonable blade tip treatments to reduce tip leakage loss has a great influence on the tip leakage flow.

Squealer tips and winglet tips are two kinds of strategies to reduce tip leakage losses. The squealer acts as a labyrinth seal to increase flow resistance and thus reduces leakage flow. Researches on full-length squealer rims show that the cavity squealer tip is able to reduce the tip leakage mass flow rate and the tip leakage loss [12–15]. Besides, various kinds of partial squealers, such as pressure-side and suction-side squealers, present different flow characteristics and mechanism in controlling the tip leakage flow [16–19]. The effect of cavity tips on tip leakage flow has been proven by investigations of squealer tips.

Patel [20] firstly reported the effects of a winglet tip in an axial turbine with a double winglet tip which has both pressure-side and suction-side winglets. The test results showed a stage efficiency enhancement of 1.2% over the base flat tip at a tip clearance of $\tau/H = 3.0\%$. Harvey and Ramsden et al. [21] proposed a new winglet tip that could be used to improve the turbine efficiency and reduce the rate of change in efficiency, and the test results confirmed that the winglet tip performed as well as a shroud with two fins, with a 45% reduction in the loss slope to the flat tip [22]. However, many types of research on winglet tips show that flat winglet tips may have less effect on the tip leakage flow than cavity tips [23–26]. Combined with squealer tips, winglet tips are able to obtain a further improvement in aerodynamic performance [23,26,27]. All of these researches confirm that winglet tips and winglet cavity tips can be used to improve the aerodynamic performance of an axial turbine.

As stated above, various squealer tips have a greater difference in the tip leakage flow. Similarly, different winglet tips have a large influence on the flow characteristic of the cascade with tip clearance. Dey and Camci [28] measured the downstream flow field with several winglet tips in a single-stage axial flow turbine facility and found that the suction-side winglet tips showed no improvement in efficiency while the pressure-side winglet tips weakened the tip leakage flow and effectively increased the total pressure at the outlet. Papa et al. [29] studied pressure-side winglet tips and obtained a smaller heat transfer coefficient in the cavity wall than the cavity tip. Ledezma et al. [30] investigated winglet tips and squealer tips using experiments and numerical methods in an annular cascade. The pressure-side winglet reduced the tip leakage flow, but the suction-side squealer tip showed the greatest improvement among the modified tips. Wei et al. [31] tested the pressure-side winglet tips and suction-side winglet tips of a turbine cascade in a low-speed wind tunnel and showed that these two kinds of winglet tips can be used to reduce the tip leakage loss. By comparing various winglet tips of the turbine blade, Zhou et al. [32] found that the suction side effectively reduces the driving pressure difference near the leading edge and then tends to reduce the tip leakage loss. The results of numerical calculations indicated that the suction-side winglet tip increases the turbine stage efficiency by 0.9% at a tip gap size of 1% of the span compared to a cavity tip [33]. Thus, further investigation of the impact mechanism of pressure-side and suction-side winglet-cavity tips on the tip leakage flow could provide a reference to the tip design for improving the aerodynamic performance of axial turbines.

In this study, the influence of pressure-side and suction-side winglet-cavity tips on the aerodynamic performance of a turbine cascade has been studied in a low-speed wind tunnel. These two kinds of winglet-cavity tips were described in Zhou et al. [34]. The flow characteristics and aerodynamic performance of a turbine cascade with a flat tip, cavity tip, or winglet-cavity tip are compared and analyzed at a tip clearance of $\tau/H = 1.0\%$. Combined with the oil flow visualization and

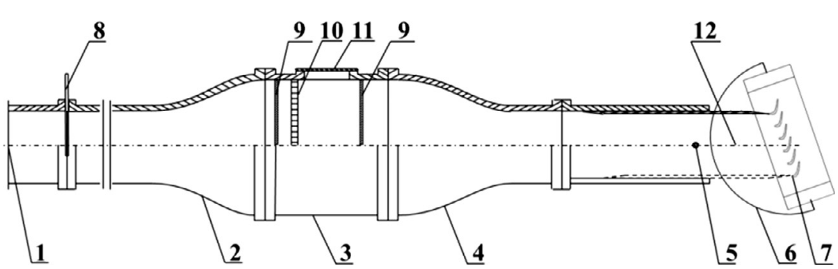

Fig. 1. Diagram of wind tunnel. (1: inlet of wind tunnel; 2: divergent section; 3: pressure stabilizing chamber; 4: convergent section; 5: Pitot tube; 6: adjustable half-disk; 7: test section; 8: adjustable inlet valve; 9: filter net; 10: honeycomb plate; 11: observation window; 12: inlet of cascade).