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Experimental study of the impact of hole-type suction on the flow characteristics in a high-load compressor cascade with a clearance

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ABSTRACT

In a low-speed linear cascade wind tunnel, effects of boundary layer suction on the flow characteristic in a highly-loaded compressor cascade with a stator clearance are studied experimentally, and two types of clearance including "long clearance" and "short clearance" are considered separately. In particular, hole-type suctions with different locations and distributions on the endwall are applied to control clearance flow and loss. The nature of flow separation is described by analyzing the properties of the limiting streamlines, based on the ink-trace flow visualizations on the cascade surface and lower endwall. The configuration of suction holes was associated with the kinetic energy of a clearance flow and the interaction of tip clearance flow with the endwall boundary layer and the suction surface boundary layer. The separation line and reattachment line form the base of a separation structure for corners with clearance. The results show that the clearance flow can be greatly improved and the losses reduced to some extent when boundary layer suction is adopted appropriately. The maximum amplitude of the loss reduction in different schemes with clearance is 32%.

1. Introduction

The clearance between the blades and endwall will induce a clearance flow in the endwall region, thereby increasing the flow loss within the flow passage and leading to the deterioration of stage performance. The clearance flow has a greater impact on flow loss and blockage in the flow passage [1,2], especially in the case of a large incidence angle and a high load [3]. The presence of tip clearance between rotor blades and casing also has a limitation on compressor performance [4]. The mixing of the passage vortex, the boundary layer on the suction surface and the clearance flow is more complex [5], with flow loss increasing by more than 30%. In the design condition or at a low load, the clearance flow is generally improved by an optimization in geometric modeling design of the clearance and the endwall [6–8], but the effect is not satisfactory when this design is applied to a cascade with a larger three-dimensional flow separation and a higher load [9]. The different sizes, positions and geometric shapes of a clearance may have different influences on the flow. Thus, in every specific case, an appropriate flow control method needs to be adopted.As an active flow control technology, boundary layer suction has been widely used in internal and external flows to suppress the generation and development of flow separations. With the rising requirement for a higher loading capacity of a single compressor stage in the modern aero-engine, researchers have attempted to make use of the boundary layer suction to suppress the three-dimensional flow separations within the flow passage to increase the load and reduce the impact of the performance degradation owed to the increase in load. The effective use of boundary layer suction in compressors is validated by a large amount of previous research. Kerrebrock et al. [10–13] verified that separation could be postponed and the flow turning enhanced after the low-energy fluid in the boundary layer was removed. The flux capability of the cascade also improved significantly. Thus, the boundary layer suction caused an improvement in the efficiency of the compressor. Boundary layer suction was also adopted in a highly loaded compressor airfoil by Merchant [14]. The suction was located at the start of boundary layer separation in order to obtain a higher single-stage pressure ratio. Furthermore, they observed that the inspiration capacity as well as the suction position had great significance for a compressor adopted by the boundary layer suction. Gbadebo et al. [15] used boundary layer suction to control three-dimensional flow separations and explored the mechanism of boundary layer suction for suppressing three-dimensional separations. Moreover, they concluded that when boundary layer suction was applied, the suction slot's positions and the other suction parameters (the slot length, incidence degree, etc.) had a greater influence on some flow characteristics, such as the limiting streamlines in the corner, the saddle point and so on. In addition, through investigation of a high-load compressor cascade, Carter et al. [16] pointed out that inappropriate suction design often caused a negative effect on the flow field. Therefore, further

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Nomenclature

b	pitch length
D	diffusion factor
h	blade height
i	incidence angle
L	chord length
P	local pressure
H	radial clearance height
Re	Reynolds number ($=\rho VL/\mu$)
RL	reattachment line
SL	separation line
LE	leading edge
TE	trailing edge
V	freestream velocity
ρ	air density
β	metal angle between the midline and the tangential line
μ	air dynamic viscosity coefficient
θ	camber angle
ω	total pressure loss coefficient
ζ	stagger angle

Subscripts

0	cascade inlet
1	cascade outlet
t	total parameters

consideration needs to be given to the design of suction schemes to achieve better control effects when boundary layer suction is adopted in a compressor with clearance.

In numerous related studies, the slot suction is a common type and more detailed studies were carried out on the mechanism of the slot suction controlling flow separations to improve the load [15–19]. Slot-type suction, however, may cause a reduction in the strength of the blade and endwall. Strength may be improved effectively, however, if hole-type suction is adopted. Also, the configuration of hole-type suction is more flexible than that of slot-type suction. In the literature [20–21], some pitch-wise suction holes were adopted in hubs and shrouds to improve the performance of fans with a single row of holes or double rows of holes. Nevertheless, the mechanism of hole-type suction on the impact of three-dimensional flow separations was not subjected to detailed analysis or intensive discussion. The basic design criteria related to suction holes were also not mentioned. Through different layouts of suction holes in the endwall, this paper considers linear cascades of a high-load compressor with clearances in order to study the influence of hole-type suction on the performance of cascades, to explore a mechanism for suppressing three-dimensional flow separations effectively and to attempt to clarify some of the basic layout methods of suction holes.

This paper is a new attempt to apply boundary layer suction to suppress the adverse effects of clearance flow. By comparing and analyzing the impact of hole-type suction on aerodynamic parameters and the flow field, respectively, in the case of the two clearance types, it seeks to make use of an appropriate boundary layer suction design to improve the flow to enhance performance effectively and explore the mechanism of boundary layer suction suppressing three-dimensional flow separations caused by the clearance flow.

2. Experimental device and test method

Performed in a low-speed cascade wind tunnel (as shown in Fig. 1) at Engine Aerodynamic Research Center, Harbin Institute of Technology, this experiment adopts a Mach number of 0.2 and inlet turbulence intensity of 3%. The blade profile is highly loaded, with a camber angle of 60° to obtain a large diffusion factor (the diffuser factor is larger than 0.55). The prototype experimental linear cascades are composed of seven straight blades with a camber angle of 60°. The other detailed geometrical and aerodynamic parameters of the cascades are listed in Table 1. Fig. 2 illustrates the distribution of a cascade inlet pressure ratio.

As shown in Fig. 3, the height of the clearance in each of experimental cascades is 2 mm, 2% of the blade's metal chord. Scheme A is a "long clearance" without suction and Scheme B is a "short clearance" (a length of about 1/3 of the long gap) without suction. Moreover, there is no clearance in partial regions near the leading edge and the trailing edge. The diameter of holes is 2.5 mm in all schemes with boundary layer suction and all holes are perpendicular to the endwall. As can be seen in Fig. 4, the different layouts of holes are specified. Schemes A1 and A2 are two different suction configurations under the condition of clearance Scheme A, and Schemes B1 and B2 are two different suction configurations under the condition of clearance Scheme B. The number of suction holes for Scheme B2 is 14, and one of the other schemes has eight. The suction power is supplied by a device largely based on a vacuum pump, detailed in the literature [11]. In addition, the suction flow rate of all holes is less than 0.5% of the inlet flow rate.

The outlet flow field of the cascades was measured downstream at a distance of about 140% axial chord from the leading edge. The L-type five-hole probe used in the experiment had an accuracy of ±0.5° at the cascade outlet for the angle of pitch and the deflection

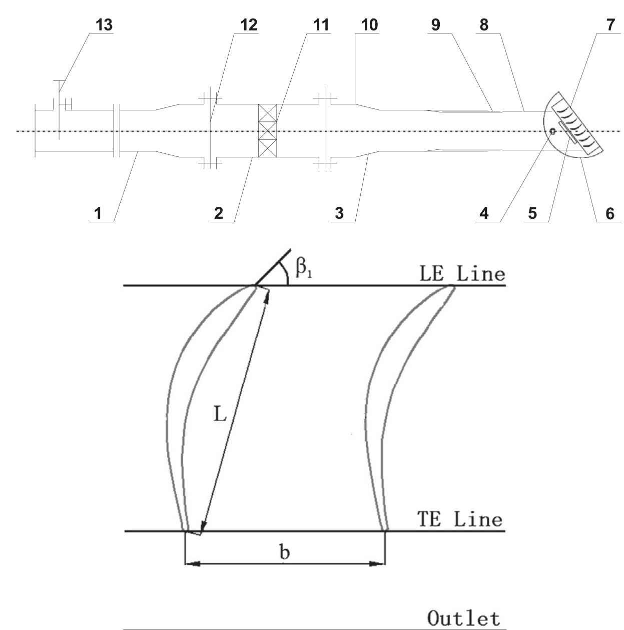

Fig. 1. Schematic diagram of a low-speed wind tunnel and cascade: (1) inlet of wind tunnel; (2) pressure stabilizing chamber; (3) convergent section; (4) pitot tube; (5) position mechanism; (6) adjustable half-disk; (7) test section; (8) inlet of cascade; (9) movable side plate; (10) observation window; (11) honeycomb plate; (12) filter net; (13) adjustable intake valve.