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Influence of coupled boundary layer suction and bowed blade on flow field and performance of a diffusion cascade

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Abstract Based on the investigation of mid-span local boundary layer suction and positive bowed cascade, a coupled local tailored boundary layer suction and positive bowed blade method is developed to improve the performance of a highly loaded diffusion cascade with less suction slot. The effectiveness of the coupled method under different inlet boundary layers is also investigated. Results show that mid-span local boundary layer suction can effectively remove trailing edge separation, but deteriorate the flow fields near the endwall. The positive bowed cascade is beneficial for reducing open corner separation, but is detrimental to mid-span flow fields. The coupled method can further improve the performance and flow field of the cascade. The mid-span trailing edge separation and open corner separation are eliminated. Compared with linear cascade with suction, the coupled method reduces overall loss of the cascade by 31.4% at most. The mid-span loss of the cascade decreases as the suction coefficient increases, but increases as bow angle increases. The endwall loss increases as the suction coefficient increases. By contrast, the endwall loss decreases significantly as the bow angle increases. The endwall loss of coupled controlled cascade is higher than that of bowed cascade with the same bow angle because of the spanwise inverse "C" shaped static pressure distribution. Under different inlet boundary layer conditions, the coupled method can also improve the cascade effectively.

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1. Introduction

Boundary layer suction, or aspiration, was first introduced by Kerrebrock et al. in 1997 with the purpose of increasing aerodynamic loading and avoiding severe flow separation of axial flow compressors in the meanwhile.[1–3]

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A transonic aspirated compressor stage and an aspirated fan stage are designed and experimentally investigated to validate the application of boundary layer suction in axial flow compressor.[4,5] The transonic aspirated compressor stage has a design tip speed of 457 m/s, and it achieved a maximum pressure ratio of 1.58 and efficiency of 90% under the design conditions. The design tip speed of the fan stage is 229 m/s, and it achieved a total pressure ratio of more than 3.0 at the design rotation speed in the experiment. Gbadebo et al. first investigated the nature of three-dimensional (3D) separations in axial compressors.[6,7] Then, with the application of boundary layer suction, he eliminated the typical compressor stator hub corner 3D separation.[8] Chen et al.[9] performed active control of corner separation in a linear cascade by boundary layer suction, and investigated the influence of the location of the endwall suction slot. Wang, Chen, Song et al.[10–13] also investigated the application of boundary layer suction in compressors. In their investigations on the control of corner separation, the optimum slot is the endwall slot, which is sufficiently long to remove the limiting streamline. However, the suction slot on the blade surface cannot effectively eliminate the corner separation.

In a highly loaded compressor, the suction surface boundary layer suction and endwall suction are combined to eliminate trailing edge separation and corner separation.[5] However, suction slots on the suction surface and endwall lead to the complexity of the suction system. Investigation on the possibility to control the corner separation and trailing edge separation by a single suction slot is rarely seen in published literatures.

In the 1960s, Deich et al. adopted 3D blade to reduce the loss of turbines.[14] In the 1980s, Wang Zhongqi et al. reported that it was the spanwise redistribution of static pressure that reduced the loss of cascade.[15] Breugelmans[16] and Shang et al.[17] investigated the leaned and bowed cascade in a wind tunnel. The results showed that the corner separation was eliminated by bowed blade, but the loss of mid-span increased as low momentum fluid migrated to the region. The increment of mid-span loss may exceed the decrement of endwall loss. Thus, the overall loss of cascade may be more than that of the linear cascade. Bogod[18] investigated five different bowed stators in a multi-stage compressor. In his investigation, positive bowed stators could increase stage efficiency by 1.0–1.5%, whereas negative bowed stators could increase stage efficiency by 2.0–3.0% at most. Positive bowed stator overloads the mid-span and improves the near endwall flow field. Fischer et al.[19] investigated the influence of strongly bowed stator on the performance of a four-stage axial flow compressor. The efficiency and total pressure ratio between design and blocking conditions decreased as the increased surface area increased the friction loss. The efficiency and total pressure ratio between maximum total pressure ratio and stall conditions increased as the corner separation was eliminated.

As the bowed blade can effectively improve the endwall flow field and control the corner separation, bowed cascade is appropriate for coupling with mid-span boundary layer suction to control the trailing edge separation and corner separation. In this study, a highly loaded compressor cascade, which has both corner separation and trailing edge separation, is investigated. First, mid-span local boundary layer suction and bowed blade are adopted in the cascade separately, and four different bow angles are investigated. Then, coupled mid-span local boundary layer suction and bowed blade is adopted to further improve the performance of the cascade. Moreover, the length effect of the suction slot is also investigated. Corner separation and trailing edge separation are effectively controlled by the coupling method with a single suction slot.

2. Diffusion cascade description and experimental procedure

A highly loaded compressor linear cascade is investigated in the study. The details of the cascade are given in Table 1. Design inlet Mach number is 0.6, and design incidence angle is 0.5°. Airfoil of the cascade is shown in Fig. 1. The baseline linear cascade was experimentally investigated in a high subsonic cascade wind tunnel at inlet Mach number of 0.6, incidence angle of 0.5° and 5.0°, and Reynolds number (Re) of 8.02×10^5 under the design conditions based on the chord. Fig. 2 shows the test region of the linear cascade wind tunnel. This study assessed blade surface static pressure coefficient (C_p) of baseline linear cascade. Blade surface static pressure was measured from static pressure holes, located at the mid-span of the suction surface and pressure surface.

3. Computational method and validations

3.1. Computational method

The 3D numerical simulation is performed on a single cascade passage with the assumption of periodicity. The structure grid is created by AUTOGRID in NUMECA FINE/TURBO. The "O-type" mesh is created around the blade to achieve a high quality. The total grid number of the baseline linear cascade is approximately 1,030,000. The mesh on the blade surface and endwall is shown in Fig. 3. The "H-type" mesh is created for the suction slot by IGG of NUMECA FINE/TURBO. The simulation code employed is FINE/TURBO. The Spalart-Allmaras turbulence model is utilized in the simulations. Inlet total pressure, inlet total temperature, inlet flow angle, and outlet static pressure are presented at the boundary according to the experimental data. The investigation is conducted at an incidence angle of 0.5°. In the experiment, the endwall boundary layer is removed by boundary layer suction at one chord upstream the inlet of the cascade, and thus the simulations in most of the study are conducted with clean inlet conditions. With the purpose of validating the effectiveness of coupled method under different inlet endwall boundary layer characteristics, two different inlet endwall boundary layers are defined and investigated in Section 4.5.

Table 1 Main geometric parameters of cascade.

Parameter	Data
Chord (m)	0.063
Inlet blade angle	40.17°
Outlet blade angle	−13.21°
Setting angle	15.40°
Solidity	1.66
Blade height (m)	0.10
Maximum thickness/chord	0.08
Relative position of maximum thickness	0.61

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