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Comparison of aerodynamic characteristics between a novel highly loaded injected blade with curvature induced pressure-recovery concept and one with conventional design

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Abstract This paper introduces a novel design method of highly loaded compressor blades with air injection. CFD methods were firstly validated with existing data and then used to develop and investigate the new method based on a compressor cascade. A compressor blade is designed with a curvature induced pressure-recovery concept. A rapid drop of the local curvature on the blade suction surface results in a sudden increase in the local pressure, which is referred to as a curvature induced 'Shock'. An injection slot downstream from the 'Shock' is used to prevent 'Shock' induced separation, thus reducing the loss. As a result, the compressor blade achieves high loading with acceptable loss. First, the design concept based on a 2D compressor blade profile is introduced. Then, a 3D cascade model is investigated with uniform air injection along the span. The effects of the incidence are also investigated on emphasis in the current study. The mid-span flow field of the 3D injected cascade shows excellent agreement with the 2D designed flow field. For the highly loaded cascade without injection, the flow separates immediately downstream from the 'Shock'; the initial location of separation shows little change in a large incidence range. Thus air injection with the same injection configuration effectively removes the flow separation downstream from the curvature induced 'Shock' and reduces the size of the separation zone at different incidences. Near the endwall, the flow within the incoming passage vortex mixes with the injected flow. As a result, the size of the passage vortex reduces significantly downstream from the injection slot. After air injec-

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tion, the loss coefficient along spanwise reduces significantly and the flow turning angle increases.

1. Introduction

The development of future aero-engines requires a higher thrust-weight ratio and higher efficiency. It challenges one of the main components of an aero-engine, axial compressor, by increasing the stage loading[1], which requests an increase of the compressor blade loading and normally results higher losses.[2] The stage loading of a conventional blade design is limited by the separated flows in the compressor.[3–6] For example, Dickens and Day[2] showed that significant separations occur in the stator of a highly loaded compressor design.

Controlling these separations and the loss is the key to improve aerodynamic performance, e.g., the turning angle and efficiency, of highly loaded compressors.[7–23] Flow control methods are used to mitigate the negative effects due to the flow separation of highly loaded compressors, e.g., air injection or blowing is used on the blade suction side surface to control local flow separations.[15–23] In the experimental studies by Culley et al.[15] and Kirtley et al.[16], streamwise blowing air was applied on the suction surface of a compressor cascade. The blowing air reenergized the laminar boundary layers, which suppressed the flow separation, thus reducing the losses of blade rows. They believed that air blowing delays separation by reenergizing the inner boundary layer with high-momentum fluid transported from freestream. Sarimurat and Dang[17] investigated steady blowing on a low-speed compressor cascade by an analytical model. The influences of the momentum, the velocity magnitude, and the angle of the blowing flow on the performance of the boundary layer were investigated. Feng et al.[18] experimentally studied the effects of air injection near the suction surface corner on the flow separation and losses of a highly loaded compressor cascade. The results show that air injection improves the flow field at the suction surface/endwall corner. The energy loss coefficient reduces by 5.5% at most. Nerger et al.[19] conducted active flow control by means of endwall and suction surface blowing on a controlled diffusion cascade. The suction surface blowing reduces the boundary layer separation effectively. In the investigation work of Vorreiter et al.[20], circulation control was conducted by an active blowing method on a linear compressor cascade to inhibit boundary layer separation. Then the result of the cascade was transferred to a four-stage high-speed compressor. Circulation control or active blowing was applied in the first stator. For their numerical investigation results, the performances of the cascade and the compressor show impressive benefits by air blowing. Guendogdu et al.[21] further investigated air injection flow control on a high-speed compressor. Their intent was to reduce the number of stator vanes. The results show that the solidity of the stator can be decreased by 25% by active injection flow control with a blowing rate of 0.5% of the main mass flow. Furthermore, impulsive suction surface injection[22,23] has also been investigated.

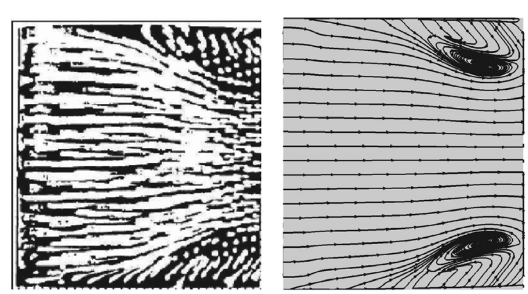
Most studies have developed flow injection methods to control the blade surface separation based on an existing compressor blade. However, the distributions of the flow within the blade passage are significantly different for cases with or without blade surface injections. It's necessary to design the injected airfoil in conjunction with flow control.

In this paper, an exploration of the design of a highly loaded injected compressor blade is reported. The investigation aims at the design of a highly loaded compressor blade in conjunction with local air injection. The blade is designed by a curvature induced pressure-recovery concept, which will be discussed in the following. The airfoil is divided into three sections: a highly loaded section from the leading edge to about 74% axial chord; a curvature induced 'Shock' section near 74% axial chord; and a flow controlled section from 74% to the trailing edge. The low adverse pressure gradient level on the suction surface of the highly loaded section prevents the flow from separating in a rather large incidence range. Thus the injection slot downstream from the 'Shock' is effective in a large incidence range to remove the 'Shock' induced separation. As a result, the compressor blade achieves high loading with an acceptable loss. 3D flow field simulations are performed in the investigation, which further validates the novel design method.

2. Numerical method and validations

The analysis code employed is ANSYS FLUENT, a fully three-dimensional Reynolds-Averaged Navier–Stokes (RANS) solver. The code uses a finite volume method. Calculations were carried out using a second order accurate in space and turbulence numeric based on a density-based solver. The transition shear stress turbulence (SST) model is adopted for accounting for the transportation of the turbulence shear stress and modelling highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients. 'O' type mesh around the blade surface and 'H' type mesh in other domains are created for the calculations.

In order to validate the numerical method on capturing the near wall flow field and the corner separation, the experimental results from an NACA 64A-905 compressor cascade are adopted to compare with the numerical results. Fig. 1[24] shows the comparison of the surface flow field of the compressor cascade. It shows that the limiting streamlines of the numerical



(a) Experiment (b) Calculation

Fig. 1 Suction surface flow field of NACA 64A-905 cascade.[24]