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Correlation Analysis of Suction Location on the Blade Suction Surface, Corner Separation, and Separation Control Performance

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ABSTRACT

Corner separation is one of the major sources of aerodynamic loss in highly loaded axial-flow compressor cascades, where large amounts of low-momentum fluid accumulate in the three-dimensional corner region between the blade suction surface and the endwall. Boundary-layer suction provides an effective active-flow-control approach for removing low-energy fluid and mitigating separation. However, the aerodynamic effectiveness of suction is strongly dependent on the axial location of the suction slot relative to the onset of corner separation. This study systematically investigates the correlation among suction-slot location, corner-separation onset, and separation-control performance using computational fluid dynamics (CFD) simulations of a high-subsonic, highly loaded compressor cascade. A full-span suction slot with a constant suction-mass-flow ratio of 1% is considered, and seven axial slot positions are evaluated under a range of incidence angles. To establish a transferable design criterion, the axial distance between the leading edge and the onset of three-dimensional corner separation, denoted as (Z_{CS}), is introduced as a characteristic length scale. The suction-slot location is subsequently normalized by its axial distance from the separation onset position. The results show that the total-pressure-loss coefficient initially decreases and then increases as the suction slot is progressively displaced downstream. At the design incidence of (0°), the optimum slot position is located downstream of the natural corner-separation onset, at an axial distance corresponding to approximately (0.33Z_{CS}), resulting in a 10.9% reduction in total-pressure loss. At an incidence of (2°), the optimum normalized distance increases to approximately (0.87Z_{CS}), producing an 8.2% reduction. The results further demonstrate that suction located excessively upstream of the separation onset can intensify reverse flow and increase aerodynamic loss, whereas appropriately positioned downstream suction effectively removes low-momentum fluid and suppresses the development of corner separation. The proposed normalization based on (Z_{CS}) establishes a physically meaningful correlation between suction location and separation topology and provides a standardized framework for the preliminary design of suction-based separation-control systems in highly loaded compressor cascades.

1. Introduction

The continuous demand for higher overall pressure ratios and improved aerodynamic efficiency has driven the development of highly loaded axial-flow compressors. Increasing aerodynamic loading, however, inevitably intensifies the complexity of the internal flow field. One of the most important loss-generating mechanisms is the accumulation of low-momentum fluid within the three-dimensional corner region formed by the blade suction surface and the endwall. Under strong adverse pressure gradients and cross-passage pressure gradients, the endwall boundary layer is transported toward the blade suction surface, resulting in the formation and subsequent development of corner separation.

Corner separation can substantially increase total-pressure loss, blockage, flow turning distortion, and aerodynamic instability. As compressor loading increases, the adverse axial pressure gradient becomes stronger and the accumulation of low-energy fluid becomes more pronounced. Consequently, controlling the formation and growth of three-dimensional corner separation has become an important research topic in the development of high-performance axial compressors.

A variety of passive and active flow-control techniques have been proposed to alleviate separation-related performance deterioration in turbomachinery. Among these approaches, boundary-layer suction has demonstrated considerable potential because it directly removes low-momentum fluid from the near-wall region. The application of boundary-layer suction to axial compressors can be traced back to the middle of the twentieth century. Early investigations demonstrated that suction could effectively remove low-energy boundary-layer fluid and consequently improve the pressure-rise capability and aerodynamic efficiency of compressor components.

Kerrebrock et al. investigated the concept of a suction-based compressor and demonstrated the potential of boundary-layer suction for controlling low-energy fluid accumulation. Subsequently, Gbadebo et al. examined different suction-slot locations and reported significant improvements in total-pressure loss and passage blockage when suction was appropriately positioned relative to the corner-separation region.

Since approximately 2011, extensive investigations conducted by research groups associated with the Technical University of Berlin and the German Aerospace Center have further clarified the influence of boundary-layer suction on compressor-cascade performance. Based on earlier investigations, Chen et al. examined the influence of endwall suction-slot location and demonstrated that the axial extent of a suction slot should be related to the onset of corner separation. Their findings indicated that the separation onset position provides an important physical reference for suction-slot design.

The suction mass-flow ratio is another important parameter governing the effectiveness of boundary-layer suction. Previous studies have shown that increasing the extracted mass flow generally decreases total-pressure loss and increases the static-pressure-rise coefficient until a limiting condition is reached, beyond which further increases in suction provide relatively little aerodynamic benefit. Nevertheless, large suction flow rates require substantial external power and may therefore reduce the overall efficiency of a practical compressor system. For this reason, a suction mass-flow ratio of 1% is adopted in the present investigation as a representative and practically relevant active-flow-control condition.

Although previous studies have established that suction-slot location significantly affects compressor performance, a systematic quantitative relationship between the suction location and

APPLIED SCIENCE

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the natural onset of three-dimensional corner separation remains insufficiently established. In particular, simply specifying the slot position using the blade axial chord does not adequately account for the variation of separation topology with incidence angle and operating condition.

Therefore, the present study introduces a normalized separation-based coordinate system to establish a direct correlation between suction-slot location and corner-separation onset. The main objectives are:

1. **To quantitatively identify the onset position of three-dimensional corner separation** under different incidence conditions and establish (Z_{CS}) as a characteristic separation length scale.
2. **To determine the relationship between suction-slot location and corner separation**, with particular emphasis on identifying the optimum axial position relative to the separation onset.
3. **To investigate the influence of incidence angle** on the aerodynamic effectiveness of suction at different axial locations.
4. **To establish a normalized design criterion** that can provide preliminary guidance for positioning suction slots in highly loaded axial-compressor cascades.

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2. Compressor Cascade, Suction Configuration, and Methodology

2.1. Compressor Cascade

A high-subsonic axial-compressor cascade is selected as the research object. The blade profile is based on the NACA-65 K48 airfoil, which has previously been investigated experimentally in a high-subsonic cascade wind tunnel at the Institute of Propulsion Technology of the German Aerospace Center.

The experimental cascade facility consists of a rectangular nozzle with a width of approximately 40 mm and a length of approximately 90 mm. The nozzle has a contraction ratio of approximately 1:2.18 and accelerates the incoming flow to a Mach number of approximately 0.7.

The design inlet Mach number of the cascade is approximately 0.67, while the Reynolds number is approximately (5.6\times10^5). The principal geometric and aerodynamic parameters of the cascade are summarized in Table 1.

Table 1. Principal geometric and aerodynamic parameters of the compressor cascade

Parameter	Symbol	Value
Blade profile	—	NACA-65 K48
Design inlet Mach number	Ma_{in}	0.67
Reynolds number	(R_e)	(5.6\times10^5)

Blade pitch	(t)	According to cascade geometry
Leading edge	LE	Reference position
Trailing edge	TE	Reference position
Measurement plane	—	0.4 axial chord downstream of TE
Suction mass-flow ratio	$\dot{m}_s/\dot{m}_{in}$	1%

The principal geometric parameters are illustrated schematically in Figure 1. The blade pitch is denoted **by (t),** LE represents the leading edge, and TE represents the trailing edge. The aerodynamic measurement plane is located at 0.4 axial chord downstream of the blade trailing edge.

Figure 1. Geometric configuration and principal aerodynamic parameters of the compressor cascade.

2.2. Boundary-Layer Suction Configuration

At elevated incidence angles, the endwall boundary layer is transported toward the blade suction surface under the influence of the cross-passage pressure gradient. The resulting accumulation of low-momentum fluid in the suction-surface/endwall corner region can eventually develop into a large-scale three-dimensional separation structure.

A suction slot installed on the blade suction surface can remove part of this low-energy fluid and thereby modify the local momentum distribution and suppress the development of corner separation.

A full-span suction slot is adopted in the present study. A three-dimensional suction chamber is constructed inside the blade to reproduce the non-uniform suction characteristics associated with a realistic suction system. The downstream portion of the suction chamber is extended by approximately 0.5 blade height to minimize the influence of the chamber outlet boundary condition on the flow through the suction slot.

Figure 2 illustrates the three-dimensional configuration of the blade, suction slot, and internal suction chamber.

Figure 2. Three-dimensional computational geometry of the compressor cascade with a full-span suction slot and internal suction chamber.

Figure 3 presents the two-dimensional view of the suction-slot configuration. Because the principal objective is to investigate the influence of the axial slot location, the position of each suction slot is characterized using the axial distance between the slot center and the blade leading edge.

The axial location is represented by Z_{SS}, where the subscript SS denotes suction slot. The suction-slot width is represented by W_{SS}.

Figure 3. Two-dimensional configuration and definition of suction-slot location.

APPLIED SCIENCE

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https://international-journal-of-applied-sciences.jo

3. Numerical Method

3.1. Computational Domain and Boundary Conditions

The numerical simulations are conducted using the commercial CFD software ANSYS CFX. The computational mesh is generated using the IGG/AutoGrid5 module of NUMECA.

Because the compressor cascade has an approximately symmetric spanwise configuration, only half of the blade span is modeled to reduce the computational cost while maintaining the principal aerodynamic characteristics.

The computational domain, boundary conditions, and mesh topology are shown in Figure 4.

All solid blade and endwall surfaces are treated as no-slip walls. Symmetry conditions are applied to the upper surface of the passage and to the appropriate surfaces of the suction system. A total-pressure boundary condition is imposed at the inlet. The inlet flow angle is varied to reproduce different incidence conditions.

A static-pressure boundary condition corresponding to atmospheric pressure is imposed at the cascade outlet. To ensure adequate mixing of the wake before reaching the outlet boundary, the computational domain is extended to approximately 2.5 axial chord lengths downstream of the blade trailing edge.

The suction-chamber outlet is specified using a static-pressure boundary condition. The suction mass-flow rate is controlled by adjusting the static pressure at the suction-chamber outlet.

Periodic boundaries are implemented using a translational-periodic condition.

Figure 4. Computational domain, boundary conditions, and mesh topology.

To maintain ($y^+<1$), the height of the first near-wall cell is set to approximately 10^{-6} m. A boundary-layer growth ratio of approximately 1.1 is adopted with 33 nodes distributed across the boundary layer. An O-type topology is employed around the blade, while additional grid refinement is introduced near the leading and trailing edges.

The suction chamber is discretized using a butterfly-type topology, and local mesh refinement is applied around the suction slot to accurately capture the strong velocity gradients and pressure variations associated with suction.

3.2. Grid Independence and Numerical Model Validation

The $\text{SST}\ k-\omega$ turbulence model is employed based on previous numerical investigations of the same cascade configuration. Grid-independence analysis is performed to ensure that the numerical results are sufficiently accurate while avoiding unnecessary computational cost.

Eight meshes are generated, containing approximately 0.54, 1.00, 1.63, 2.42, 2.98, 3.45, 3.91, and 4.43 million nodes, respectively. The number of nodes is increased systematically in three spatial directions while maintaining the near-wall mesh distribution.

The International Journal of Applied Sciences.
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https://international-journal-of-applied-sciences.jo

The mass-averaged total-pressure-loss coefficient ζ and outlet Mach number are extracted at the measurement plane located 0.4 axial chord lengths downstream of the trailing edge.

Figure 5. Grid-independence analysis based on total-pressure-loss coefficient and outlet Mach number.

As the mesh density increases, the total-pressure-loss coefficient gradually decreases while the predicted Mach number increases. When the mesh contains more than approximately 3.45 million nodes, both parameters become nearly insensitive to further mesh refinement.

Accordingly, the mesh containing approximately 3.45 million nodes is selected for all subsequent simulations.

The total-pressure-loss coefficient is defined as

$$\zeta(x, y, z) = \frac{P_{t,in} - P_t(x, y, z)}{P_{t,in} - P_{in}}, \quad (1)$$

where **(P_t)** denotes total pressure, **(P)** denotes static pressure, and the subscript **(in)** represents the inlet condition.

3.3. Validation Against Experimental Data

To evaluate the reliability of the numerical method, the calculated results are compared with available experimental measurements.

Figure 6 compares the numerical and experimental distributions of total-pressure-loss coefficient and outlet flow angle along the normalized blade span.

Figure 6. Comparison between numerical predictions and experimental measurements.

The calculated total-pressure-loss distribution agrees well with the experimental data. A small underprediction is observed near the endwall region, which may be attributed to measurement uncertainty associated with the highly non-uniform three-dimensional flow.

The calculated outlet flow angle also reproduces the experimental variation along the blade span satisfactorily, although a slight overall overprediction is observed.

The generally good agreement between the numerical and experimental results confirms that the present CFD methodology is sufficiently reliable for investigating the influence of suction-slot location on corner separation and cascade performance.

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4. Suction-Slot Location and Separation-Control Performance

4.1. Definition of Suction-Slot Locations

The International Journal of Applied Sciences.
Vol. 2, No. 1, 2025, pp. 120-138
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https://international-journal-of-applied-sciences.jo

Boundary-layer suction on the blade suction surface provides an effective mechanism for removing low-energy fluid from the near-wall region. However, the location at which this fluid is removed is crucial to the overall effectiveness of the control strategy.

To systematically investigate the influence of axial position, seven suction-slot locations are considered, as shown in Figure 7.

The axial coordinate is normalized by the blade axial chord, with the leading-edge reference position corresponding to zero and the trailing-edge reference position corresponding to unity.

The seven suction slots are positioned at normalized axial locations ranging from 0.2 to 0.8, with an interval of 0.1. They are designated SS1–SS7:

$$Z_{SS1} = 0.2C,$$
$$Z_{SS2} = 0.3C,$$
$$Z_{SS3} = 0.4C,$$
$$Z_{SS4} = 0.5C,$$
$$Z_{SS5} = 0.6C,$$
$$Z_{SS6} = 0.7C,$$
$$Z_{SS7} = 0.8C.$$

Figure 7. Distribution of the seven suction-slot locations along the blade suction surface.

4.2. Modified Total-Pressure-Loss Coefficient

When boundary-layer suction is introduced, part of the incoming flow exits through the suction chamber rather than through the cascade passage. Therefore, the contribution of the extracted mass flow must be included when evaluating the overall aerodynamic loss.

A modified total-pressure-loss coefficient is therefore defined as

$$\zeta_{suc} = \frac{(1-\dot{m}_s)(P_{t,in}-P_{t,out})+\dot{m}_s(P_{t,in}-P_{t,ple})}{P_{t,in}-P_{in}}, \tag{2}$$

where $P_{t,ple}$ is the total pressure at the suction-plenum outlet and $\dot{m}_s$ is the suction mass-flow ratio defined as

The International Journal of Applied Sciences.
Vol. 1, No. 2, 2025, pp. 120-138
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https://international-journal-of-applied-sciences.jo

$$\dot{m}_s = \frac{\dot{m}_{ple}}{\dot{m}_{in}}.$$

Here, $\dot{m}_{ple}$ represents the mass flow discharged from the suction chamber and $\dot{m}_{in}$ denotes the inlet mass flow.

In the following analysis, ζ refers to the original cascade without suction, whereas ζ_{suc} refers to the cascade equipped with the suction slot.

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5. Quantitative Correlation Between Suction Location and Corner-Separation Onset

5.1. Normalized Separation-Based Coordinate

To establish a physically meaningful correlation between suction location and corner separation, the axial distance between the blade leading edge and the onset of three-dimensional corner separation is defined as $\mathbf{Z}_{CS}$.

The normalized suction-slot position is expressed as

$$Z^*_{SS,i} = \frac{Z_{SS} - Z_{CS}}{Z_{CS}}, \qquad (3)$$

where $\mathbf{Z}_{CS}$ is the axial distance between the leading edge and the onset of three-dimensional corner separation under the corresponding operating condition.

A negative value of $Z^*_{SS,i}$ indicates that the suction slot is located upstream of the separation onset, whereas a positive value indicates that the suction slot is located downstream of the separation onset.

At the design condition of 0° incidence, the natural corner-separation onset is located approximately at

$$Z_{CS} = 0.45C.$$

This normalized formulation allows the suction-slot position to be evaluated relative to the actual flow-separation topology rather than solely according to an absolute blade-chord coordinate.

Figure 8. Definition of the corner-separation onset position and normalized suction-slot coordinate.

5.2. Effect of Suction Location at the Design Incidence

The International Journal of Applied Sciences.
Vol. 2, No. 1, 2025, pp. 120-138
ISSN 3104-8935
https://international-journal-of-applied-sciences.jo

Figure 9 presents the variation of total-pressure-loss coefficient with suction-slot location at the design incidence of 0°.

The prototype cascade without suction is represented by the reference value, while the suction-equipped configurations are evaluated at the outlet measurement plane using the mass-averaged total-pressure-loss coefficient.

The results demonstrate a clear non-monotonic relationship between suction location and aerodynamic performance. As the suction slot moves downstream from SS1 toward SS7, the total-pressure-loss coefficient first decreases and subsequently increases.

For SS1–SS3, the suction slots are positioned upstream of the natural corner-separation onset. In these cases, the total-pressure-loss coefficient is higher than that of the baseline cascade, indicating that premature suction can adversely affect the flow field.

When the suction slot is moved downstream of the separation onset, corresponding to SS4–SS7, the total-pressure-loss coefficient decreases. An optimum is observed at SS5.

Figure 9. Influence of suction-slot axial location on total-pressure loss at (0°) incidence.

At 0° incidence, SS5 is located at (0.6C), while the natural separation onset occurs at (0.45C). Therefore,

$$Z_{SS5} - Z_{CS} = 0.15C,$$

and

$$\frac{Z_{SS5} - Z_{CS}}{Z_{CS}} = \frac{0.15}{0.45} \approx 0.33.$$

Thus, the optimum suction position occurs approximately (0.33 **ZCS**) downstream of the natural corner-separation onset.

At this position, the total-pressure-loss coefficient is reduced by approximately **10.9%** relative to the baseline cascade.

These results demonstrate that the effectiveness of suction cannot be described solely by the absolute axial position of the slot. Instead, the slot should be positioned according to the location of the natural separation onset.

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6. Flow-Field Mechanism of Separation Control

To clarify the physical mechanism responsible for the observed optimum, the three-dimensional flow fields of the baseline cascade, SS1, and SS5 configurations are compared at 0° incidence in Figure 10.

APPLIED SCIENCE

The International Journal of Applied Sciences.
Vol. 1, No. 2, 2025, pp. 120-138
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https://international-journal-of-applied-sciences.jo

The suction slot is indicated in red, while limiting streamlines are displayed on the blade surface. A three-dimensional iso-surface corresponding to an axial velocity of

$$v_z = -0.0001 \text{ m/s}$$

is used to identify regions of reverse flow. The enclosed region therefore represents the three-dimensional separation zone.

The total-pressure-loss distribution is also extracted at the plane located 0.4 axial chord lengths downstream of the trailing edge.

Figure 10. Three-dimensional flow-field comparison among the baseline, SS1, and SS5 configurations at 0° incidence.

For the baseline cascade, the three-dimensional separation begins approximately (0.45C) downstream of the leading edge.

When SS1 is positioned at (0.2C), significantly upstream of the natural separation onset, the separation region unexpectedly becomes larger. The increase is particularly evident in the spanwise direction, and the downstream total-pressure-loss region also becomes more intense.

By contrast, when the suction slot is positioned at SS5, corresponding to (0.6C), the three-dimensional corner-separation region is substantially reduced. The reduction is particularly pronounced in the spanwise extent of the separated region. The downstream total-pressure-loss distribution also shows a significant reduction in both loss intensity and high-loss area.

The flow mechanism can therefore be interpreted as follows.

When suction is positioned excessively upstream of the natural separation onset, the slot extracts fluid before the primary separation structure has fully developed. This can induce an upstream-directed flow response and draw relatively energetic downstream fluid toward the suction location, thereby promoting reverse flow and enlarging the separation region.

When suction is positioned moderately downstream of the separation onset, however, it directly removes the low-momentum fluid accumulated within the already developing separation region. The resulting increase in near-wall momentum suppresses the upstream and downstream growth of the separated zone and reduces the associated total-pressure loss.

This observation provides a physical explanation for the existence of an optimum normalized suction position.

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7. Influence of Incidence Angle

7.1. Separation Onset at 2° Incidence

To determine whether the proposed separation-based normalization remains applicable under different operating conditions, the influence of suction-slot location is subsequently investigated at an incidence angle of 2°

The International Journal of Applied Sciences.
Vol. 2, No. 1, 2025, pp. 120-138
ISSN 3104-8935
https://international-journal-of-applied-sciences.jo

As the incidence angle increases, the aerodynamic loading and adverse pressure-gradient environment change, causing the onset of corner separation to move upstream.

At 2° incidence, the three-dimensional corner-separation onset is located approximately

$$Z_{CS} = 0.32C.$$

Figure 11. Three-dimensional corner-separation onset at 2°incidence.

7.2. Suction-Location Effect at 2° Incidence

Figure 12 presents the total-pressure-loss coefficient obtained for the seven suction-slot locations at 2° incidence.

The same general trend observed at (0°) incidence is maintained: total-pressure loss initially decreases as the suction slot moves downstream and subsequently increases.

However, the transition occurs at a different slot position because the natural separation onset has moved upstream.

In particular, SS3 is located downstream of the separation onset at 2°incidence and therefore begins to provide a net aerodynamic benefit. This result provides further evidence that suction effectiveness is governed by the relative position between the suction slot and the natural corner-separation onset.

Using the normalized coordinate defined by Eq. (3), the optimum suction position corresponds to an axial distance of approximately

$$0.87Z_{CS}$$

downstream of the separation onset.

At this position, the total-pressure-loss coefficient decreases by approximately **8.2%** relative to the baseline cascade.

Figure 12. Influence of suction-slot location on total-pressure loss at 2° incidence.

The comparison between the 0° and 2° incidence conditions demonstrates an important feature of the proposed criterion: the optimum absolute axial position changes with operating condition, but the position can be interpreted consistently by referencing it to the natural separation location.

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8. Overall Performance of the Optimum Suction Configuration

To further evaluate the robustness of SS5, Figure 13 compares the aerodynamic performance of the baseline cascade and the SS5 configuration over incidence angles ranging from 0° to (6°).

Figure 13. Influence of incidence angle on total-pressure loss with the SS5 suction configuration.

At low and moderate incidence angles, SS5 provides a substantial reduction in total-pressure loss.

The largest improvement occurs at the design condition of 0°, where the loss coefficient decreases by approximately 10.9%.

For incidence angles below 4°, the reduction in total-pressure loss remains within approximately 8.2–10.9%, indicating that the suction configuration effectively controls the low-energy fluid associated with corner separation.

As the incidence angle increases beyond 4°, however, the aerodynamic benefit gradually disappears. A small increase in total-pressure loss is eventually observed.

This deterioration can be attributed to the increasingly severe and extensive separation structure generated at high incidence. Under such conditions, a fixed suction mass-flow ratio of 1% is insufficient to remove the increasing volume of low-momentum fluid accumulated in the corner region.

Therefore, the effectiveness of a fixed suction system depends not only on slot location but also on the severity and spatial extent of the underlying separation structure.

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9. Three-Dimensional Flow-Field Analysis

To further investigate the mechanism by which SS5 modifies the flow field, Figure 14 compares the baseline and SS5 configurations at incidence angles of 0°, 2°, and (4°

The reverse-flow region is identified using the three-dimensional iso-surface, while the corner-separation region is highlighted by a dashed boundary. The downstream total-pressure-loss distribution is obtained at the plane located 0.4 axial chord lengths downstream of the trailing edge.

Figure 14. Comparison of three-dimensional separation structures and total-pressure-loss distributions for the baseline and SS5 configurations at different incidence angles.

For the baseline cascade, increasing the incidence angle from 0° to 4° causes the three-dimensional corner-separation region to expand in both the spanwise and chordwise directions.

As a result, the separation onset progressively moves toward the blade leading edge.

When SS5 is introduced, the separation region is substantially reduced at 0° and 2°incidence. In particular, the separation region upstream of the suction slot is almost completely eliminated.

The downstream total-pressure-loss core is also weakened, and the loss distribution near the mid-span region is reduced.

At 4° incidence, however, the suction-induced improvement becomes less pronounced. Although the high-loss core becomes somewhat weaker, the spatial extent of the loss region remains relatively large.

This observation indicates that the fixed 1% suction-mass-flow ratio is adequate for controlling the separation structure at low and moderate incidence but becomes insufficient as the separation region grows substantially at high incidence.

The International Journal of Applied Sciences.
Vol. 2, No. 1, 2025, pp. 120-138
ISSN 3104-8935
https://international-journal-of-applied-sciences.jo

10. Discussion: Physical Interpretation of the Suction–Separation Correlation

The results obtained in this study reveal that the relationship between suction location and separation control is not linear.

Three characteristic regimes can be identified.

Regime I: Suction upstream of separation onset

When

$$Z_{SS} < Z_{CS},$$

the suction slot is located upstream of the natural corner-separation onset. Under this condition, suction can disturb the developing boundary layer before the dominant low-momentum region has formed. Excessive upstream suction may induce reverse-flow structures and increase the total-pressure loss.

Regime II: Suction moderately downstream of separation onset

When

$$Z_{SS} > Z_{CS},$$

and the separation-to-slot distance is appropriately selected, suction directly removes the low-momentum fluid accumulated within the corner-separation structure.

This regime produces the greatest reduction in separation size and total-pressure loss.

Regime III: Suction excessively downstream

When the slot is moved too far downstream, a significant portion of the separated flow develops upstream of the suction location. Consequently, the suction slot can no longer effectively prevent the development of the upstream separation structure.

The total-pressure-loss coefficient therefore increases again.

These three regimes explain the observed **decrease–minimum–increase** trend of total-pressure loss with downstream movement of the suction slot.

The results also demonstrate that the separation onset **(Z_{CS})** is a more physically meaningful reference length than the absolute blade-chord coordinate.

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11. Proposed Design Criterion

Based on the present numerical results, the suction-slot design can be expressed using the normalized distance

$$\Lambda = \frac{Z_{SS} - Z_{CS}}{Z_{CS}}.$$

APPLIED SCIENCE

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The current simulations indicate that the optimum value of (\Lambda) is operating-condition dependent.

At (0°) incidence,

$$\Lambda_{\text{opt}} \approx 0.33,$$

whereas at (2°incidence,

$$\Lambda_{\text{opt}} \approx 0.87.$$

Therefore, the present results do not suggest that a single universal value of Λ can be applied to all compressor operating conditions. Instead, the results establish a **separation-based design framework** in which the natural separation onset is first identified and the suction slot is subsequently positioned downstream of this location.

For preliminary design, the following procedure is proposed:

1. Determine the three-dimensional corner-separation onset at the target operating condition.
2. Measure the axial distance (Z_{CS}}) between the leading edge and the separation onset.
3. Normalize the candidate suction-slot position using (Z_{CS}).
4. Position the suction slot downstream of the separation onset rather than upstream of it.
5. Optimize the normalized distance according to the expected incidence range and suction-mass-flow ratio.
6. Verify the final design using three-dimensional CFD and, where possible, experimental measurements.

This procedure provides a more transferable design methodology than defining the suction location solely as a fixed percentage of the blade chord.

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12. Conclusions

A numerical investigation has been conducted to clarify the correlation among blade suction-surface suction location, three-dimensional corner separation, and separation-control performance in a high-subsonic compressor cascade. A full-span suction slot with a 1% suction-mass-flow ratio was investigated at multiple axial positions and incidence angles. The main conclusions are as follows:

1. **Suction-slot location has a strong influence on cascade aerodynamic performance.** At both (0°and (2°) incidence, the total-pressure-loss coefficient decreases initially and then increases as the suction slot is moved downstream. This demonstrates the existence of an optimum suction position.

APPLIED SCIENCE
The International Journal of Applied Sciences.
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2. **The natural corner-separation onset provides an effective physical reference for suction-slot design.** At (0°incidence, the separation onset occurs approximately at (0.45C), while at (2°incidence it moves upstream to approximately (0.32C).

3. **At the design condition, the optimum suction position is downstream of the natural separation onset.** For (0°incidence, the optimum configuration is SS5 at (0.6C), corresponding to a normalized distance of approximately (0.33Z_{CS}) downstream of the separation onset. This configuration reduces total-pressure loss by approximately **10.9%**.

4. **The optimum normalized distance changes with incidence angle.** At (2°) incidence, the optimum position corresponds to approximately (0.87Z_{CS}) downstream of the natural separation onset and reduces total-pressure loss by approximately **8.2%**.

5. **Excessively upstream suction can be detrimental.** When the suction slot is located substantially upstream of the natural separation onset, it can promote reverse flow and enlarge the three-dimensional corner-separation region, thereby increasing total-pressure loss.

6. **Appropriately positioned downstream suction effectively suppresses corner separation.** The suction removes accumulated low-momentum fluid, reduces the spanwise and chordwise extent of the separation structure, and decreases the high-loss region downstream of the cascade.

7. **The effectiveness of fixed-rate suction depends strongly on incidence angle.** The SS5 configuration provides substantial aerodynamic improvement between (0°) and (4°incidence, with loss reductions of approximately 8.2–10.9%. At incidence angles above (4°however, the 1% suction-mass-flow ratio becomes insufficient to control the increasingly extensive low-momentum region.

8. **A normalized separation-based coordinate provides a useful framework for suction-slot design.** Rather than specifying suction location solely as a percentage of blade chord, the proposed parameter

$$\Lambda = \frac{Z_{SS} - Z_{CS}}{Z_{CS}}$$

directly relates the suction location to the underlying separation topology.

Overall, the study demonstrates that **the effectiveness of suction-based separation control is fundamentally governed by the spatial relationship between the suction slot and the natural onset of three-dimensional corner separation**. The proposed **(Z_{CS})**-based normalization can therefore serve as a practical preliminary design framework for suction slots in highly loaded axial-compressor cascades. Further validation using additional blade geometries, Reynolds numbers, suction mass-flow ratios, and operating conditions is required to establish a broader universal correlation and improve the generality of the proposed design criterion.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

None.

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