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# The role of AVDR in linear cascade testing

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**Abstract:** Linear cascade testing plays an important role in the research and development of turbomachinery and is widely used over the world. The ideal cascade model of a turbomachinery blade row is two dimensional. In actual linear cascade testing, the flow through the test section converges due to the development of the boundary layer and secondary flow along the sidewall surfaces of the test section. Axial velocity density ratio (AVDR) is adopted to account for the deviation of the tested cascade flow from the ideal 2D model. Among numerous published cascade works, the influence of AVDR on cascade performance is seen to be complicated with many affecting factors, such as those related to cascade/ blade geometry and flow conditions. Also, controlling AVDR is limited by the facility capability. Furthermore, real blade to blade flow in turbomachines is usually associated with AVDR greater than unity due to limited span of blades between the hub and shroud such that cascade testing without reducing AVDR could be favored sometimes. All these facets add complexity and diversification to the matter. The current paper reviews previous studies and results on AVDR. Consolidated understanding on the role of AVDR and recommendations on how to deal with it in linear cascade testing are provided.

**Key words:** axial velocity density ratio(AVDR); linear cascade testing; cascade performance; sidewall air removal

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## Nomenclature

|                                                                                                                                                    |                                                                                        |            |                                                         |
|----------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------|---------------------------------------------------------|
| $AR$                                                                                                                                               | aspect ratio= $L/C$                                                                    | $\gamma$   | stagger angle                                           |
| $AVDR = \frac{\int_0^{2\pi ch} \rho_2 \cdot V_2 \cdot \cos \alpha_2 \cdot ds_2}{\int_0^{2\pi ch} \rho_1 \cdot V_1 \cdot \cos \alpha_1 \cdot ds_1}$ |                                                                                        | $\varphi$  | camber angle                                            |
| $C$                                                                                                                                                | blade chord                                                                            | $\rho$     | density                                                 |
| $DF$                                                                                                                                               | diffusion factor= $1 - V_2/V1 + (V_1 \sin \alpha_1 - V_2 \sin \alpha_2)/(2\sigma V_1)$ | $\sigma$   | solidity= $C/S$                                         |
| $I$                                                                                                                                                | incidence angle                                                                        | $\omega$   | loss coefficient= $(p_{t1} - p_{t2})/(p_{t1} - p_{s1})$ |
| $L$                                                                                                                                                | blade span                                                                             | $\Omega$   | AVDR                                                    |
| $Ma$                                                                                                                                               | Mach number                                                                            | Subscripts |                                                         |
| $p_s$                                                                                                                                              | static pressure                                                                        | 1          | inlet plane                                             |
| $p_t$                                                                                                                                              | total pressure                                                                         | 2          | outlet plane                                            |
| $q$                                                                                                                                                | dynamic pressure head                                                                  | tot        | total                                                   |
| $Re$                                                                                                                                               | Reynolds number                                                                        |            |                                                         |
| $S$                                                                                                                                                | pitch                                                                                  |            |                                                         |
| $V$                                                                                                                                                | flow velocity                                                                          |            |                                                         |
| $X$                                                                                                                                                | distance in axial direction                                                            |            |                                                         |
| $\alpha$                                                                                                                                           | flow angle (with respect to axial direction)                                           |            |                                                         |

## Introduction

Linear cascade testing still plays an important role in the research and development of turbomachinery and is widely used over the world. One primary function of linear cascade testing is to verify the cascade performance and validate the blade design. In addition, flow diagnostic experiments on the compressor or turbine cascades

are easier to carry out than those on the annular cascades or compressor/turbine rigs. As such, cascade experiments are favored in the study of turbomachinery flow fundamentals. Significant progress of CFD and computer techniques in recent years have made it practical to simulate various turbomachinery flows, from steady to unsteady, from one dimensional to three dimensional, and from one stage to multistages. However, the power of CFD cannot be fully harnessed without the validation and support by experiments. Even a modern sophisticated CFD tool, which is capable of full flow simulation with employing state-of-the-art turbulence models, has not achieved a self-proving level. Linear cascade testing will continue to be indispensable in modern turbomachinery research.

The cascade model of a turbomachinery blade row is two dimensional by its definition<sup>[1]</sup>. Apparently, the ideal cascade model cannot be achieved in practice due to the fact that the width of the test section in a cascade wind tunnel is finite. In actual linear cascade testing, the flow through the test section converges due to the development of the boundary layer and secondary flow along the endwall (or called sidewall) surfaces of the test section, as illustrated in Fig. 1. Therefore, the cascade flow in the test section becomes three dimensional in essence. To quantify the flow contraction, a parameter called "axial velocity density ratio" ( $AVDR$ ) is adopted (see the Nomenclature for its definition). All variables in the calculation of  $AVDR$  are measured in the midspan plane of the tested cascade and the integration is for one or two pitches. In order to obtain 2D cascade flow, i. e., reduce the flow contraction, endwalls with openings are used and air is bled or sucked away from the test section (see Fig. 1). As such,  $AVDR$  can be controlled by adjusting the amount of air removed from the endwalls.

It is seen that  $AVDR$ , as a sum-up flow parameter in the cascade midspan, reflects the deviation of the tested flow from the ideal 2D cascade model. Although  $AVDR$  is not adequate for

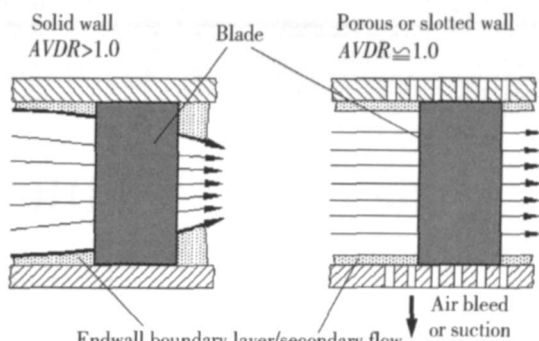


Fig. 1 Flow contraction and  $AVDR$  control in cascade testing

a rigorous judgment of two dimensionality of the flow (a flow across the test section can be manipulated with  $AVDR$  being unity while it is still three dimensional), it serves as a practical measure to approximate the offset of the tested flow from the ideal 2-D model.

Among numerous cascade testing works published in the open literature,  $AVDR$  was not always reported. Those papers that published the effects of  $AVDR$  seemed to be not always concurrent (probably due to the complexity of the matter).

Another fact is that the control of  $AVDR$  in cascade testing is limited by the facility capability hence it cannot be always guaranteed. Moreover, the blade-to-blade flow in turbomachines is usually associated with  $AVDR$  greater than unity due to limited span of blades between the hub and shroud. From this perspective, cascade testing with  $AVDR$  greater than unity (no need to reduce it) can be acceptable.

Given the diversification of the subject in discussion, this paper is intended to review previous  $AVDR$  studies and results to consolidate understanding. The paper ends with recommendations on how to deal with the  $AVDR$  issue in linear cascade testing. Discussion is primarily directed to compressor cascades. Limited turbine cascade results are also discussed to make the current review a more generic effort.

## 1 Earlier studies

The important role of  $AVDR$  in 2D linear cascade testing was ascertained earlier in the

1960s. The experimental investigation conducted in a low-speed cascade wind tunnel by Pollard and Gostelow<sup>[2]</sup> was a pioneering effort dedicated to studying the effect of *AVDR* on compressor cascade flow and the improvement by sidewall air removal. They found that the cascade flow with solid sidewalls was significantly twisted by the sidewall secondary flow for a low aspect ratio ( $AR=2$ ), but for high aspect ratios ( $AR\gg3.0$ ), a large part of the span was unaffected by the secondary flow although the blockage effect of the nearwall region was still appreciable ( $AVDR>1.1$ ). A low aspect ratio would give good two-dimensional results if porous sidewalls were used to remove the sidewall boundary layer. Nevertheless, even with sidewall suction in use, an area of low energy air was present near junction of the wall and the blade suction surface. Their attempts to remove it failed. The complexity of the cascade flow under real cascade wind tunnel conditions (three dimensional in essence) and the limitation in reducing the 3D effects by sidewall air removal can be viewed from this early work.

Later, in a review of the earlier cascade testing work, Gostelow<sup>[1]</sup> clarified that it was the influence of *AVDR* that caused the discrepancy between American and British test results, indicating that *AVDR* was an indispensable factor to be considered when comparing cascade test data obtained from different tunnel facilities.

In 1970s and early 1980s, the effect of *AVDR* in cascade testing drew more attention. A few focused studies on compressor cascades were conducted (Fottner<sup>[3]</sup>, Stark<sup>[4]</sup>, Heilmann<sup>[5]</sup>, Starken et al.<sup>[6]</sup>, Stark and Hoheisel<sup>[7]</sup>). Most of the results from these studies indicated a common trend about the influence of *AVDR* on cascade performance, i. e., total pressure losses decreased and blade surface Mach number increased with increasing *AVDR*, see Fig. 2, Fig. 3, and Fig. 4 for examples. This trend can be referred to as “the Normal *AVDR* Influence”. It is not difficult to understand it as the flow speeds up in the mid-span when increasing *AVDR*, re-

sulting in less diffusion, which in turn, would lead to lower losses.

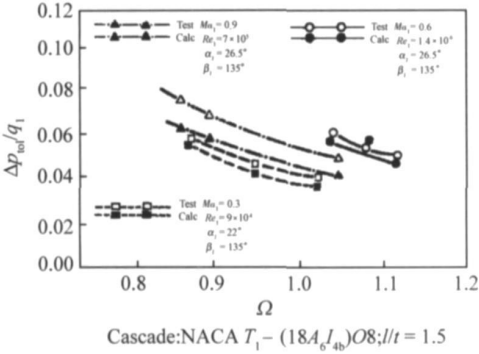


Fig. 2 Normal *AVDR* influence: losses<sup>[5]</sup>

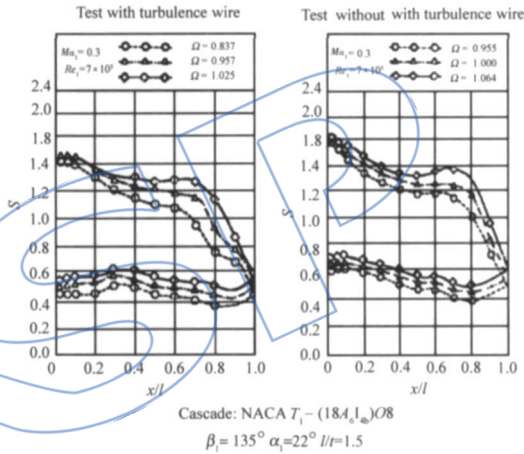


Fig. 3 Normal *AVDR* influence: blade surface Mach number, example 1<sup>[5]</sup>

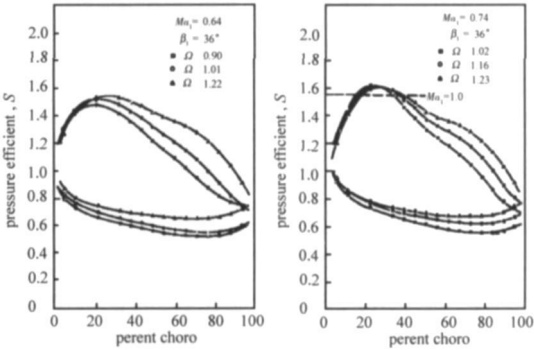


Fig. 4 Normal *AVDR* influence: blade surface Mach number, example 2<sup>[6]</sup>

Some of the results from these early studies also showed that neither did the existing *AVDR* influence fall into the scenario of the Normal *AVDR* Influence nor could it be satisfactorily resolved by endwall air removal. Heilmann<sup>[5]</sup> investigated the influence of *AVDR* on the per-

formance of compressor cascades for different boundary layers and found that the change in cascade performance with  $AVDR$  substantially depended on the blade boundary layer behavior, i. e., the  $AVDR$  influence was coupled with the flow characteristics due to the cascade. In testing a high turning compressor DCA cascade, Starken et al.<sup>[6]</sup> obtained three different loss variation trends with  $AVDR$ , given different flow speeds, flow angles, and  $AVDR$  ranges. As seen in Fig. 5, with increasing  $AVDR$ , ( I ) the normally err

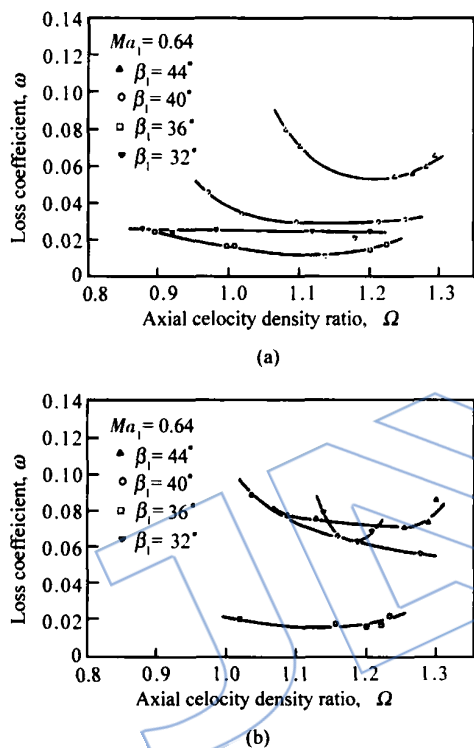


Fig. 5 Diversified loss variation trends with  $AVDR$ <sup>[6]</sup>

countered loss drop, ( II ) parabolic loss variation, ( III ) nearly constant losses. They also tested with three different sidewall slot opening configurations and found that the  $AVDR$  influence differed from one configuration to another. Stark and Hoheisel<sup>[7]</sup> investigated the combined effect of  $AVDR$  and  $AR$  (Aspect Ratio). They found that it was  $AR$  that defined the axial velocity distribution through the cascade at a given wall shape and contraction ratio, and it was the axial velocity distribution that decisively determined the local values of pressure distributions as well as the cascade overall parameters. This research indicates that  $AVDR$  may not be reactive enough

to the change of the flow that accounts for the performance variation.

## 2 Later cascade tests

There is little focused research on  $AVDR$  appeared in the open literature since the above-mentioned earlier efforts. But the importance of  $AVDR$  in cascade testing received sufficient attention and many published papers included  $AVDR$  data.

### 2.1 Subsonic/ transonic compressor cascade

Hobbs and Weingold<sup>[8]</sup> developed a series of Controlled Diffusion Airfoils (CDA) for multi-stage compressor application. The cascades were designed with an inlet Mach number of 0.7, inlet flow angle of  $30^\circ$ , flow turning  $13.6^\circ$ ,  $AVDR$  1.07, and solidity of 0.933. Cascade test results demonstrated lower losses and wider low-loss incidence range of the CDAs than conventional NACA-series airfoils and Multiple Circular Arc (MCA) airfoils. They compared blade surface Mach number results between the design and tests and found that the tested blade surface Mach number was higher than the design values. Then they adjusted the design  $AVDR$  to match the test and hence obtained better agreement. It is seen that  $AVDR$  played an important role in validating new blade designs.

Hoheisel and Seyb<sup>[9]</sup> presented a theoretical and experimental investigation of the boundary layer and loss behavior on a high turning Double Circular Airfoil (DCA) compressor cascade. The cascade was designed to achieve flow turning of  $50^\circ$  at an inlet Mach number of 0.85. The blade had a high camber of  $56.8^\circ$  and the cascade had a high solidity of 2.2. The experiments were carried out in the high speed cascade wind tunnel of DLR. In cascade tests, Hoheisel and Seyb obtained different variation trends of losses with  $AVDR$  for a wide  $AVDR$  range of 0.9~1.3 and inlet Mach number range of 0.3~0.9, similar to what was found by Starken et al.<sup>[6]</sup>

Schreiber and Starken<sup>[10]</sup> performed an intensive experimental analysis on a transonic compressor rotor cascade, in order to elucidate

the flow behavior and determine the performance in the whole operating range. The design relative inlet Mach number was 1.09 and the flow turning was  $12.5^\circ$ . Experiments were conducted for an inlet Mach number range from 0.8 to 1.1 and inlet flow angles from choking to stalling flow condition. *AVDR* was controlled by endwall suction during the tests. The total pressure loss data obtained from the cascade tests agreed well with those obtained behind the corresponding blade element of the transonic compressor rotor. Steirert et al.<sup>[11]</sup> designed a CDA cascade ( $M_{a1} = 0.62$ ,  $\alpha_2 - \alpha_1 = 26.4^\circ$ ,  $\alpha = 1.47^\circ$ ). The cascade wind tunnel test confirmed very low losses of the blade due to optimum suction surface velocity distribution (leading to separation-free operation). Both of these two works show that although the blade surface pressure distribution was considerably influenced by *AVDR*, the total pressure losses changed little. Thus, the loss development characteristics with inlet Mach number and incidence angle were tested with solid sidewalls, without the control of *AVDR*. These two examples shed light on how to flexibly handle the *AVDR* issue, with both test quality and convenience in consideration.

Katoh et al.<sup>[12]</sup> conducted cascade testing on profiles of NACA-65 and CDA designed for the near hub section of two compressor stators. The design condition was:  $M_{a1} = 0.8$ ,  $\alpha_2 - \alpha_1 = 11^\circ$ ,  $Re = 5.79 \times 10^5$ ,  $\sigma = 0.93$ ,  $AVDR = 1.07$ . Experiments in the cascade wind tunnel provided detailed blade performance information, such as blade surface velocity distribution, total pressure losses, and the boundary layer, which revealed the loss reduction from NACA-65 to CDA was due to the elimination of the shock waves on the blade suction surface. Katoh et al. did not employ sidewall air removal to control *AVDR* in their tests of the cascades as *AVDR* hardly changed in the tested inlet Mach number range (0.60~0.87). Although *AVDR* varied between 1.05 and 1.15 for different inlet flow angles, the two cascades had similar *AVDR* values at each inlet flow angle. Therefore, they argued that the experi-

mental evaluation of the performances of the two cascades was free of the *AVDR* influence, and the performance change observed was due to the blade profile instead of being biased by *AVDR*. Katoh's work showcased another example of the application of solid sidewall testing in performance evaluation.

Schreiber et al.<sup>[13]</sup> employed slotted sidewall suction to control *AVDR* in an experimental investigation of the effects of Reynolds number and freestream turbulence on boundary layer transition in a compressor cascade. In this award-winning paper, it is seen that *AVDR* was carefully controlled to be very close to unity and the tested blade surface Mach number almost perfectly agreed with the calculated values. This work exemplified the importance of *AVDR* control in a sophisticated study on flow physics, in which the agreement between experiment and calculation was emphasized. Note that the same author did not use *AVDR* control in another research[10]. The question then comes up, in dealing with the *AVDR* issue in cascade testing, control it or not? High quality control needed or not? A proper answer should be "it depends."

## 2.2 Supersonic compressor cascade

Tweedt et al.<sup>[14]</sup> tested a supersonic compressor cascade. The cascade was designed with inlet Mach number of 1.61. The blade had a negative camber angle of  $-2.89^\circ$ . Cascade tests were performed for an inlet Mach number range from 1.30 to 1.71, with blade chord Reynolds number in the range  $1.1 \times 10^6$  to  $1.4 \times 10^6$ . End-wall boundary layer suction was used to reduce secondary flow effects and to control *AVDR*. The shock wave pattern in the entrance region was measured using a laser anemometer. The influence of *AVDR* on the blade performance was experimentally investigated. As shown in Fig. 6, with increasing *AVDR*, losses and blade surface Mach number decrease, and shock waves move forward in the blade passage. It can be understood that blade surface Mach number takes the opposite variation trend in comparison with the subsonic case. Higher *AVDR* means more con-

vergence of the mid-span flow tube, the flow speed would decrease in the supersonic regime. Similar *AVDR* effects on supersonic cascade performance were seen from other two studies shown below.

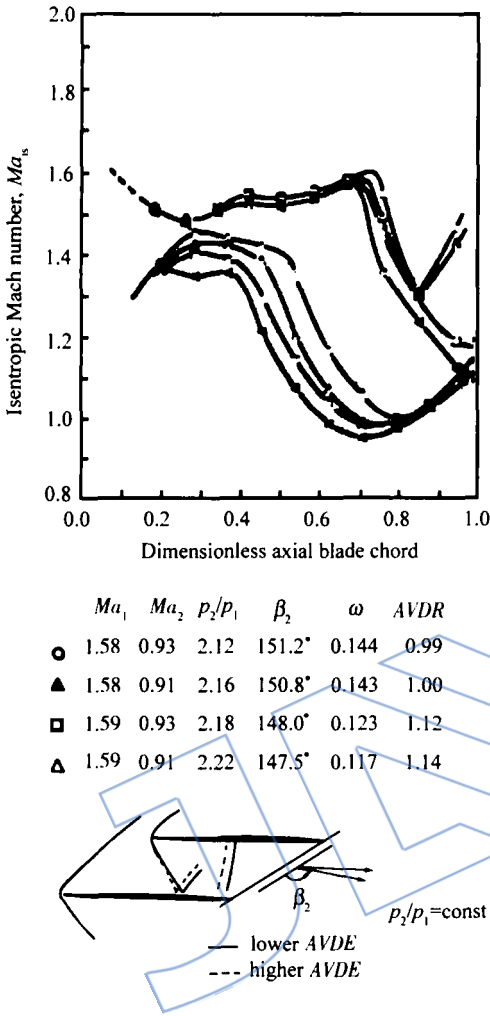


Fig. 6 *AVDR* effect in a supersonic cascade<sup>[14]</sup>

Kusters and Schreiber<sup>[15]</sup> successfully applied a two dimensional multiblock Navier-Stokes solver to a supersonic compressor cascade flow with strong shock wave/boundary layer interaction. The cascade was typical of a fan blade section with precompression design, low flow turning, and static pressure ratio around 2.0. Investigations were conducted at inlet Mach number between 1.28 and 1.53. The results were compared with previous cascade wind tunnel testing data. Schreiber and Starken<sup>[16,17]</sup> investigated the flow phenomena and loss mechanism of a strong shock wave turbulent boundary layer interaction in a supersonic compressor cascade.

The cascade geometry was typical for a transonic fan tip section operating at a relative inlet Mach number of 1.5, a flow turning of about 3°, and a static pressure ratio of 2.15. Cascade experimental results showed a strong boundary layer separation on the blade suction surface occurred due to a complicated shock pattern and its interaction with the boundary layer. They claimed that in this research manipulating the cascade flow by different sidewall openings was no problem if the endwall effects were of minor influence on the mid-span flow region.

2.3 Turbine cascade

The *AVDR* issue is also encountered in turbine cascades as in compressor cascades. However, it is not as critical in turbine cascades as in compressor cascades. Unlike a compressor cascade that diffuses the flow and raises pressure, a turbine cascade accelerates the flow thus favorable pressure gradient across the cascade helps keep the sidewall boundary thin. Overall, the effect of sidewall boundary layer and secondary flow on the mid-span flow in a turbine cascade is relatively small compared to the compressor cascade. Probably due to this, there is less information available about the *AVDR* effects on turbine cascade performance in the open literature.

In turbine cascade testing, previous experience suggested that solid sidewalls could be adequate if the 3D effect was kept small. To achieve this, inlet boundary layer shall be kept thin and high aspect ratio is encouraged. Sieverding<sup>[18]</sup> recommended minimum aspect ratios to obtain reliable 2D mid-span performance data in turbine cascade tests from 1.6 to 2.2 based on different velocity ratios across the cascade, see Fig. 7.

In a recent testing of three subsonic turbine cascades, high aspect ratios of 3.8, 4.0, and 4.2 were used with solid sidewalls<sup>[19]</sup>. Good two dimensional flow was obtained. Fig. 8 shows a picture of blade surface flow visualization on one cascade, which confirmed good spanwise flow uniformity.

In testing two transonic turbine cascades, Jouini et al.<sup>[20,21]</sup> used a low aspect ratio of 1.525

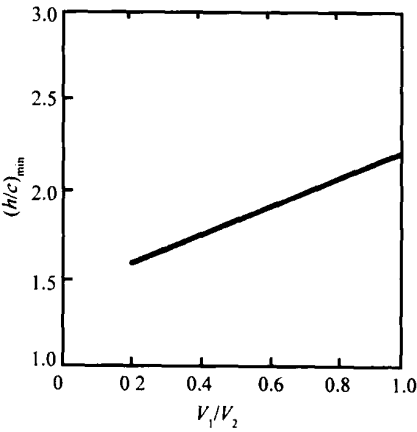


Fig. 7 Recommended minimum aspect ratio for reliable 2D performance measurements in turbine cascades<sup>[18]</sup>

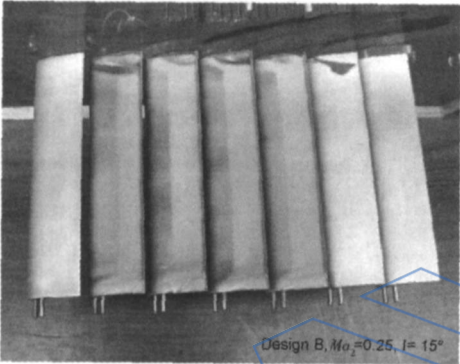


Fig. 8 Good spanwise flow uniformity of a turbine cascade with solid sidewalls<sup>[19]</sup>

in order to maximize blade chord. They used solid sidewall without controlling  $AVDR$ . Realizing the possible  $AVDR$  issue in their study, they recorded a lot of  $AVDR$  data and defended their results with respect to the  $AVDR$  influence. Figure 9 and 10 show their tested  $AVDR$  data at various incidence angles and exit Mach numbers. It is seen that  $AVDR$  is rather constant over the tested  $Ma_2$  range for all cases except for the second cascade at the highest incidence ( $14.5^\circ$ ), where  $AVDR$  decreased with increasing  $Ma_2$ . The dependence of  $AVDR$  on incidence is seen as a simple increase of  $AVDR$  with increasing incidence. The lowest  $AVDR$  is very close to or even slightly below unity for the first cascade.

In Fig. 9, they also included a computational study by Saroch<sup>[22]</sup> to show the effect of  $AVDR$  on losses of a transonic turbine cascade for the design incidence. For the subsonic and sonic case, losses barely changed with variation of

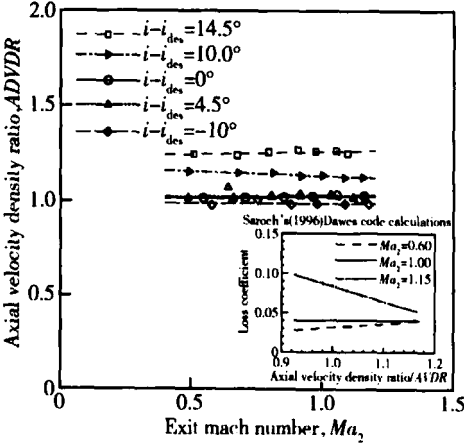


Fig. 9 Effects of Incidence and Mach number on  $AVDR$  in the first transonic turbine cascade<sup>[20]</sup>

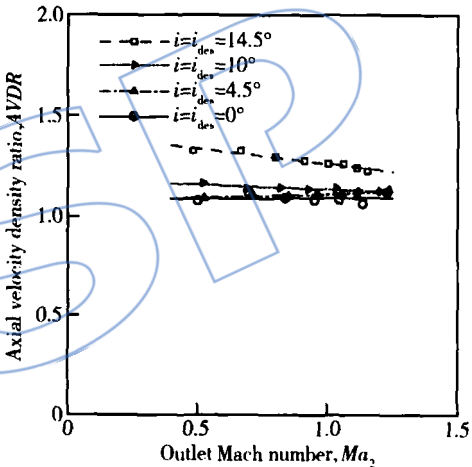


Fig. 10 Effects of Incidence and Mach number on  $AVDR$  in the second transonic turbine cascade<sup>[21]</sup>

$AVDR$ , similar to what was found on another supersonic turbine cascade<sup>[23]</sup>. For supersonic, losses decreased with increasing  $AVDR$ , which was in agreement with the trend seen from Ref[14].

### 3 A recent investigation

In a recent experimental and numerical investigation of modern supercritical compressor blades, efforts were extended to study the  $AVDR$  influence. Cascade testing was conducted in conjunction of 2-D and 3-D CFD analysis. The experiments were conducted in the Virginia Tech High Speed Cascade Wind Tunnel. The wind tunnel was a blowdown type. High speed steady flow was maintained for a short time span by a feedback control scheme. The control of  $AVDR$

was achieved by using slotted sidewalls. The slots were made in the rear part of the cascade passages, and were open to the ambient for air bleed. Choke plates of varying size were inserted in the exhaust to change the static pressure in the cascade, thus varying the rate of air bleed, which in turn controlled the  $AVDR$ . Testing was also conducted with solid sidewalls, which corresponded to the highest  $AVDR$  case at the same inlet flow condition.

Figure 11 illustrates the cascade nomenclature used in this study. Cascade geometry is listed in Table 1. The cascades were designed for application to the hub-section of a stator in a transonic fan stage with the pressure ratio being about 1.8. As such, the cascades have a high solidity and the blades are highly cambered. The aggressive design condition is:  $Ma_1 = 0.87$ ,  $\alpha_1 = 48.4^\circ$  (corresponding to  $I = 0^\circ$ ),  $DF = 0.55$ ,  $Re = 1.5 \times 10^6$ . Two blade profiles were used. The baseline is a CDA while the other is an optimized profile. 2D and 3D CFD solved steady Reynolds-Averaged Navier-Stokes (RANS) equations, with matching the flow conditions in the experiments. 2D CFD offered flow calculations for  $AVDR = 1$  while 3D simulated the flow through the test section with solid sidewalls.

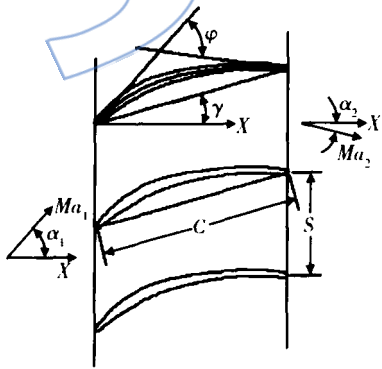


Fig. 11 Cascade nomenclature

Table 1 Cascade geometry

| Parameters                  | Value      |
|-----------------------------|------------|
| Blade Chord ( $C$ )         | 86 mm      |
| Aspect ratio ( $AR = L/C$ ) | 1.77       |
| Solidity ( $\sigma = C/S$ ) | 2          |
| Stagger Angle ( $\gamma$ )  | $15^\circ$ |
| Camber Angle ( $\varphi$ )  | $55^\circ$ |
| L. E. Circle Radius         | 1 mm       |

3.1 Effects of  $AVDR$  on performance

The effects of  $AVDR$  on losses are shown in Fig. 12 at the design inlet Mach number and two inlet flow angles. Both solid and slotted sidewall test results are included in the plot. The lowest  $AVDR$  data point of each blade was obtained with the maximum sidewall air removal that could be achieved, while the highest  $AVDR$  data point corresponded to solid sidewall condition. Although the same slot configuration and similar air bleed rate were used in the experiments, the values and effects of  $AVDR$  differed between two cascades and flow angles. The baseline exhibits the Normal  $AVDR$  Influence. The optimized blade has almost constant losses at one flow angle and the Normal  $AVDR$  Influence at the other. The flat loss trend with variation of  $AVDR$  was found on another optimized blade designed for the same condition<sup>[24]</sup>. These results indicate that the  $AVDR$  influence is coupled with different blade-to-blade flow characteristics due to different blade profile and inlet flow angle, similar to the findings of Ref[5]. It was found that the baseline has severe boundary layer separation while the optimized blade does not<sup>[25]</sup>. Despite the diversification of the  $AVDR$  influence, relative evaluation of the two blades can be made either by using solid sidewall test data or at the same  $AVDR$ .

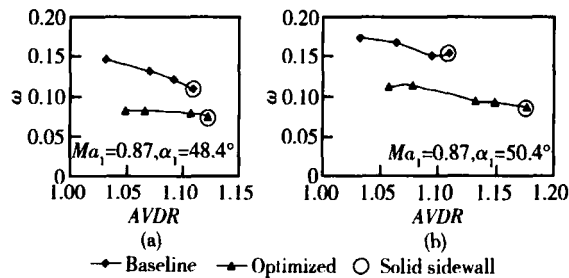


Fig. 12 Measured losses with variation of  $AVDR$ <sup>[26]</sup>

The dependency of  $AVDR$  on inlet flow angle (incidence) became clearer when testing negative off-design incidences. It was found that decreasing incidence from the design value, both experiment and 3D CFD showed the decrease of  $AVDR$ . At the incidence of  $-4^\circ$  ( $\alpha = 44.4^\circ$ ),  $AVDR$  was very close to unity with solid walls.

Apparently, slotted sidewall testing is unnecessary in such a case. Recall this trend of  $AVDR$  variation with incidence was also found on transonic turbine cascades as discussed earlier<sup>[20]</sup>.

Since the obtained  $AVDR$  ranges were different and did not reach unity, more efforts were tried to lower  $AVDR$ . The sidewall slots were lengthened to about 60% chord, i. e., extended more upstream compared to the original opening of 37% chord. This change failed to further decrease  $AVDR$ . Flow visualization by attaching tufts near the slots showed that air was drawn in the blade passage at upstream locations and bled out at downstream locations through the slots. Recall that Starken<sup>[6]</sup> had similar experience with different slot configurations. Figure 13 shows solid sidewall test results of losses and  $AVDR$  at different inlet Mach numbers at the design incidence. 2D CFD predicted losses are also shown for comparison. EXP  $AVDR$  variation is 1.03~ 1.14 for the baseline blade and 1.05~ 1.13 for the optimized blade.  $AVDR$  of 2D CFD is unity. Although the tested and CFD loss re-

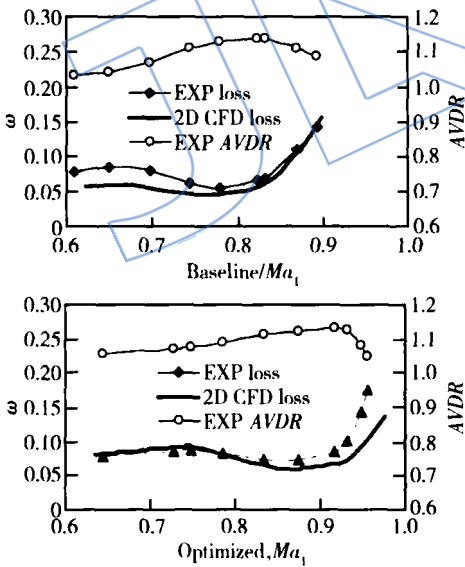


Fig. 13 Development of losses and  $AVDR$  with inlet Mach number for solid sidewall test<sup>[26]</sup>

sults are not in perfect agreement, both of them exhibit basically the same loss vs.  $Ma_1$  variation trend. When  $Ma_1$  reaches the critical value (0.83 for the baseline and 0.93 for the optimized), losses rise up drastically, where  $AVDR$  drops sharply. It was confirmed that boundary layer

separated when  $Ma_1$  was over the critical value. These results indicate that flow characteristics (separation) due to the blade profile and flow condition mostly drive the losses and  $AVDR$ , instead of vice versa. At the same inlet Mach number,  $AVDR$  of the two blades is close, allowing relative evaluation of the two blades. Recall this approach was used in Ref[12].

### 3.2 Blade surface Mach number

Figure 14 shows the experimental (with solid sidewalls) and 2D CFD blade surface Mach numbers at the design incidence for two inlet Mach numbers. In general, both EXP and CFD reflected the same variation of flow pattern/ blade loading with increasing inlet Mach number. The up-shifting of EXP blade surface Mach number agrees with the Normal  $AVDR$  Influence. At  $Ma_1 = 0.75$ , the optimized blade has an EXP  $AVDR$  (1.07) closer to unity, such that EXP and 2-D CFD are in good agreement, except for a slight up-shifting of EXP results aft of the blade. The same effect of  $AVDR$  on blade surface Mach number was seen on another optimized blade<sup>[24]</sup>.

It is seen that blade surface Mach number is sensitive to the variation of  $AVDR$ . Even for a case in which losses barely respond to the change of  $AVDR$ , such as the optimized blade (See Fig. 13, left graph), blade surface Mach number still reflects the change of the flow. It is seen that blade surface Mach number can serve as an excellent criterion to account for the  $AVDR$  effect on the cascade flow. The important role of blade surface Mach number as a flow diagnostic tool in cascade testing and turbomachinery development was showcased by Weingold and Behlke<sup>[27]</sup> and Steinert et al.<sup>[28]</sup>.

### 3.3 Mid-span flow behavior

Strong three dimensionality of the cascade flow for the two blades under solid sidewall condition is exhibited by blade surface flow visualization and 3D CFD simulation, as shown in Fig. 15. 2D and 3D CFD Mach number contours of the two blades at the design condition are given in Fig 16. The contours of 3D CFD are made for

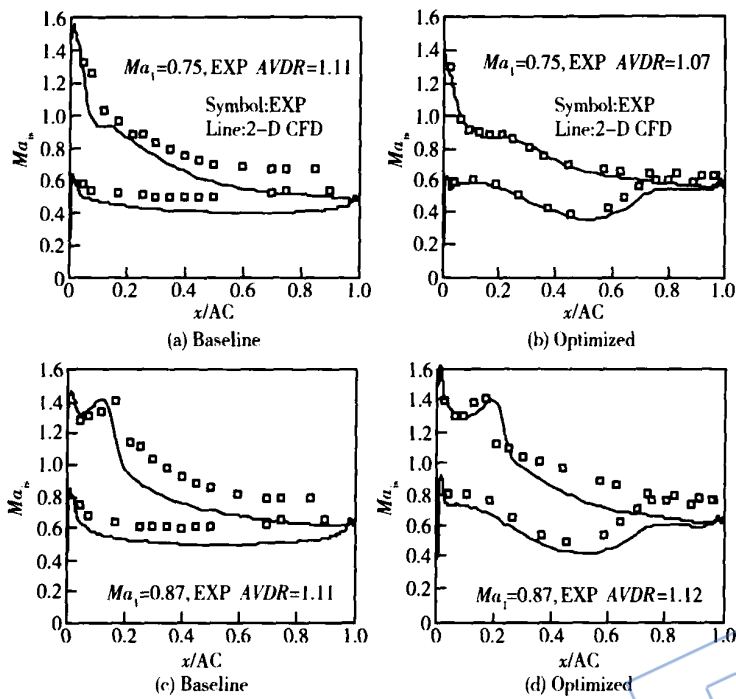


Fig. 14 Blade surface Mach number distribution<sup>[29]</sup>

the mid-span plane. Although significant flow contraction was predicted by 3D CFD as seen in Fig. 15 while 2D CFD gave completely two-dimensional results, both 2D and 3D CFD Mach number contours exhibit similar flow patterns for each blade respectively. The essential flow difference between the two blades was successfully predicted by both 2D and 3D CFD. The baseline blade has a stronger passage shock and suction surface boundary layer separation while the optimized blade has a stronger leading edge shock and attached flow on the suction surface. The quantitative discrepancy between 2D and 3D CFD results is due to the AVDR Influence: for 3D case in which AVDR is greater than unity, the passage shock shifts to a little more downstream, the boundary layer is thinner, and the overall losses are lower.

Although the cascade flow with solid sidewall condition has significant flow contraction cross the passage, the essential flow nature due to 2D blade profiles, such as boundary layer behavior and shock pattern are conserved in the mid-span, where the measurements are taken. This flow nature conservation in the mid-span makes relative evaluation of the two blades pos-

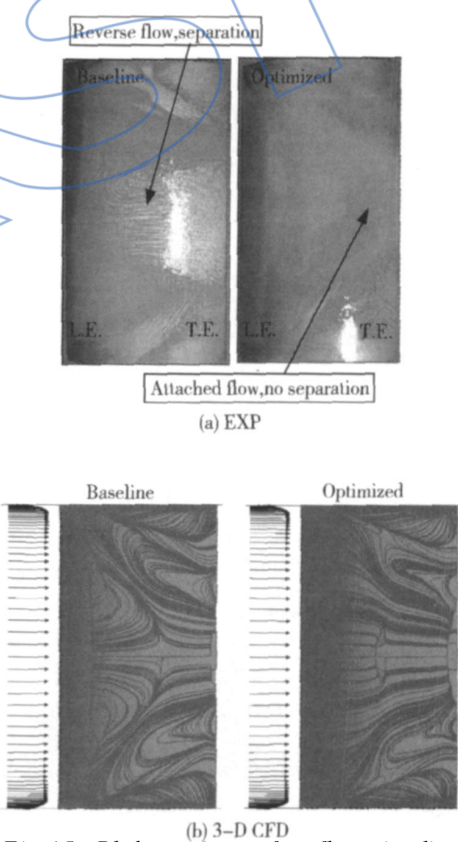


Fig. 15 Blade suction surface flow visualizations<sup>[26]</sup>

sible by solid sidewall testing. Similarly, prior research has shown that even with sidewall effects and the consequent overall flow contraction ( $AVDR > 1.0$ ), uniform flow could be still pres-

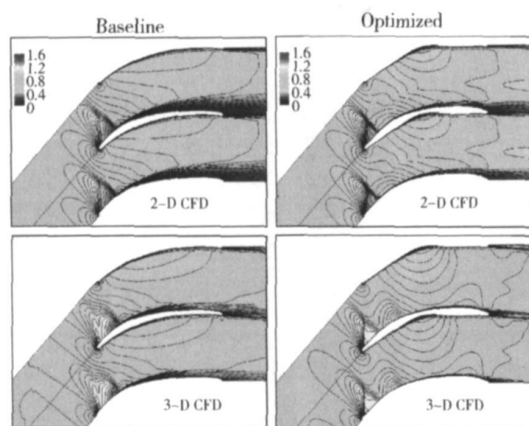


Fig. 16 CFD Mach number contours<sup>[26]</sup>

ent in the mid-span flow tube. Two examples are from Weber et al.<sup>[29]</sup> in a low turning transonic compressor cascade and Cyrus<sup>[30]</sup> in a subsonic compressor cascade. It should be pointed out that the *AVDR* influence does exist and cause the quantitative discrepancy, as shown in Fig. 16. Again, the necessity to control *AVDR* is dependent on the test purpose. In this case, for relative evaluation of the two blades, solid wall testing is acceptable. For a more accurate performance evaluation or validation of 2D design, *AVDR* control is certainly desired.

## 4 Conclusions and recommendations

*AVDR* serves as a helpful flow parameter that can be readily determined from measurements in linear cascade testing to account for the deviation of the tested cascade flow from the ideal 2D cascade model. Theoretically, *AVDR* is a necessary but not sufficient condition for 2D cascade flow. The influence of *AVDR* on cascade performance is complicated with many affecting factors, such as those related to cascade/blade geometry and flow conditions. The control of *AVDR* by sidewall air removal improves two dimensionality but by no means it is an absolute solution. The outcome is coupled with the intrinsic flow characteristics of the cascade and dependent on tunnel facility capability, test section configuration, sidewall air removal procedure, etc. The role of *AVDR* in cascade testing is case dependent and should be properly appraised relative to the test objective. There is no simple all-

purpose method or procedure to follow when dealing with the *AVDR* issue in linear cascade testing.

Despite the diversification of the issue in question, as seen from previous studies and published results, understanding is consolidated and recommendations are provided as the following:

The normal *AVDR* influence is mostly encountered, i. e., with increasing *AVDR*, losses decrease, blade surface Mach number increases for subsonic/ transonic cascades but decreases for supersonic cascades.

Blade surface Mach number is an excellent flow diagnostic criterion to help evaluate the 2D flow nature in addition to *AVDR*.

The *AVDR* issue is not as critical in turbine cascades as in compressor cascades.

It is necessary to control *AVDR* to obtain good 2D flow condition when comparing test data to 2D design. Test data with *AVDR* equal to unity is required for validating a 2D flow solver. When comparing cascade test data obtained from one tunnel facility to another, more rigorous test conditions with *AVDR* control need to be satisfied.

In addition to manipulating air removal, high aspect ratio is encouraged to use for improved 2D flow conditions if possible.

In the case that the tunnel facility does not have enough *AVDR* control capability, solid sidewall testing could be acceptable based on the prerequisite that the cascade flow nature due to blade profile was conserved in the mid-span. Additional flow diagnostic measurements and/ or and CFD analysis can help verify the prerequisite.

In some scenarios solid sidewall testing is adequate without bothering about the *AVDR* control, such as ( I ) *AVDR* is close to unity already, e. g., possibly in the case of high aspect ratio or negative incidence, ( II ) relative performance evaluation of cascades if *AVDR* differed little from cascade to cascade, ( III ) cascade experiments for flow mechanism study, as solid wall condition with *AVDR* greater than unity reflects real turbomachinery conditions.

AVDR is an important piece of information in linear cascade testing. It is encouraged to include AVDR information in the test report or publication, no matter what kind of sidewall is used.

## References:

- [ 1 ] Gostelow J P. Cascade aerodynamics [ M ]. Pergamon Press, 1984.
- [ 2 ] Pollard D, Gostelow J P. Some experiments at low speed on compressor cascades[ J ]. ASME Journal of Engineering for Power, 1967, 89: 427-436.
- [ 3 ] Fottner L. Analytical approach for the loss and deflection behavior of cascades in transonic flow including axial mass flow variation[ R ]. AGARD-AG-164, Paper F7, 1972: 119-139.
- [ 4 ] Stark U. The effect of axial velocity density ratio on the aerodynamic coefficients of a compressor cascade in viscous flow [ R ]. AGARD-AG-164, Paper F12, 1972: 205-220.
- [ 5 ] Heilmann W. The influence of axial velocity density ratio on compressor cascade performance in compressible flow [ R ]. AGARD-AG-164, Paper F13, 1972: 221-240.
- [ 6 ] Starken H, Breugelmans F A E, Schimming P. Investigation of the axial velocity density ratio in a high turning cascade[ R ]. ASME Paper 75-GT-25, 1975.
- [ 7 ] Stark U, Hoheisel H. The combined effect of axial velocity density ratio and aspect ratio on compressor cascade performance[ J ]. ASME Journal of Engineering for Power, 1981, 103: 247-255.
- [ 8 ] Hobbs D E, Weingold H D. Development of controlled diffusion airfoils for multistage compressor application[ J ]. ASME Journal of Engineering for Gas Turbines and Power, 1984, 106: 271-278.
- [ 9 ] Hoheisel H, Seyb N J. The boundary layer behavior of highly loaded compressor cascade at transonic flow conditions[ R ]. Transonic and Supersonic Phenomena in Turbomachines, AGARD-CP-401, 1987.
- [ 10 ] Schreiber H A, Starken H. Experimental cascade analysis of a transonic compressor rotor blade section[ J ]. ASME Journal of Engineering for Gas Turbine and Power, 1984, 106: 288-294.
- [ 11 ] Steinert W, Eisenberg B, Starken H. Design and testing of a controlled diffusion airfoil cascade for industrial axial flow compressor application[ J ]. ASME Journal of Turbomachinery, 1991, 113: 583-590.
- [ 12 ] Katoh Y, Hamatake H, Kashiwabara Y. Investigation of the aerodynamic performance of a transonic inlet stage of an axial flow compressor[ R ]. AIAA 98-3415, 1998.
- [ 13 ] Schreiber H A, Steinert W, Kusters B. Effects of reynolds number and free stream turbulence on boundary layer transition in a compressor cascade[ J ]. ASME Journal of Turbomachinery, 2002, 124: F9.
- [ 14 ] Tweedt T L, Schreiber H A, Starken H. Experimental investigation of the performance of a supersonic compressor cascade[ R ]. ASME Paper 88-GT-306, 1988.
- [ 15 ] Kusters B, Schreiber H A. Compressor cascade flow with strong shock wave/boundary layer interaction[ J ]. AIAA Journal, 1998, 36(11): 2072-2078.
- [ 16 ] Schreiber H A, Starken H. An investigation of a strong shock wave turbulent boundary layer interaction in a supersonic compressor cascade[ J ]. ASME Journal of Turbomachinery, 1992, 114: 494-503.
- [ 17 ] Schreiber H A. Experimental investigations on shock losses of transonic and supersonic compressor cascades[ R ]. Transonic and Supersonic Phenomena in Turbomachines, AGARD-CP-401, 1987.
- [ 18 ] Sieverding C H. Subsonic choked (turbine) cascades[ R ]. Advanced Methods for Cascade Testing, AGARD-AG-328, 1993: 22-23.
- [ 19 ] Song B, Ng W, Cotroneo J A, et al. Aerodynamic design and testing of three low solidity steam turbine nozzle cascades[ R ]. ASME/IGTI Turbo Expo 2004, Vienna, Austria: GT-2004-53329, 2004.
- [ 20 ] Jouini D B M, Sjolander S A, Moustapha S H. Aerodynamic performance of a transonic turbine cascade at off design conditions[ R ]. ASME Turbo Expo 2000, Munich, Germany: 2000-GT-0482, 2000.
- [ 21 ] Jouini D B M, Sjolander S A, Moustapha S H. Midspan flow-field measurements for two transonic linear turbine cascades at off design conditions [ R ]. Proceedings of ASME Turbo Expo 2001, New Orleans, USA: 2001-GT-0493, 2001.
- [ 22 ] Saroch M F. Contributions to the study of turbomachinery: Part II: Computations of the effects of AVDR on transonic turbine cascades[ D ]. M. Eng. Thesis, Carleton University, Canada: January, 1996.
- [ 23 ] Kiock R, Lehthaus F, Baines N C, et al. The transonic flow through a plane turbine cascade as measured in four european wind tunnels[ J ]. ASME Journal of Engineering for Gas Turbines and Power, 1986, 108: 277-284.
- [ 24 ] Song B, Ng W. Performance and flow characteristics of an optimized supercritical compressor stator cascade [ J ]. ASME Journal of Turbomachinery, 2006, 128: 435-443.
- [ 25 ] Song B. Experimental and numerical investigations of optimized high turning supercritical compressor blades [ D ]. Ph. D. Dissertation, Virginia Polytechnic Institute and State University, 2003.
- [ 26 ] Song B, Ng W. Influence of axial velocity density ratio in cascade testing of supercritical compressor blades [ R ]. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Fort Lauderdale, Florida: AIAA-2004-3414, 2004.
- [ 27 ] Weingold H D, Behlke R F. The use of surface static pressure data as a diagnostic tool in multistage compressor development[ J ]. ASME Journal of Turbomachinery, 1987, 109: 123-129.
- [ 28 ] Steinert W, Fuchs R, Starken H. Inlet flow angle determination of transonic compressor cascades [ J ]. Journal of Turbomachinery, 1992, 114: 487-493.
- [ 29 ] Weber A, Schreiber H A, Fuchs R, et al. 3-D transonic flow in a compressor cascade with shock induced corner stall[ J ]. ASME Journal of Turbomachinery, 2002, 124: 358-366.
- [ 30 ] Cyrus V. The effect of the reynolds number on the three dimensional flow in a straight compressor cascade [ R ]. ASME 88-GT-269, 1988.