Effect of Turning Angle on Flow Field Performance of Linear Bowed Stator in Compressor at Low Mach Number

ZHANG Yong-jun, CHEN Fu, FENG Guo-tai, SU Jie-xian

(Energy Science and Engineering School, Harbin Institute of Technology, Harbin 150001, China)

Abstract: A comparison of the results of a computational simulation and an experimental measurement indicates a good agreement between them: the bowed blade lowers the energy loss coefficient of engine by 11% in the simulation and by 13% in the measurement. To further discuss the application conditions of bowed blade in compressor, with incidence equal to zero and other boundary conditions unchanged, a computational investigations on four series of linear stators with different aerofoil turning angles are achieved. It is found that the bowed blade has much positive effect in high airfoil turning angle cascade, for example, the optimal retrofit of 30° bow angle highly reduces the energy loss coefficient by 17.9%, when the aerofoil turning angle is 59.5°. But the optimal retrofit of 15° has only 0.7% reduction when the aerofoil turning angle is 39.5°, or even the compressor performance will get worse with the bow angle gradually increasing. Consequently, it is verified that the turning angle is one of the important factors to decide whether to apply the bowed blade into compressor at low Mach number.

Key words: compressor airfoil; turning angle; computation study; bowed blade; low Mach number

Since the idea of using bowed-twisted-blades was proposed by Filippov and Wang, et al[1] in early 1960’s, the bowed blade theory research and application have undergone a satisfying development in turbine design and application. However, up to now the effects of bowed blade in the filed of compressor are of uncertainty. Some research reports[2,3] indicated that the bowed blade was two-fold in compressor application: benefit and cost in flow field performance.

With regard to how the bowed stators were used to control the three-dimensional flow and reduced the end-wall losses in axial compressors, there were some discussions in the past years. Breugelmans[4] demonstrated that in compressors the prime driver for using “bow” was to add a radial blade force to produce a new radial equilibrium of the flow between hub and casing. The early discus-
sion about the bow angle effect on the radial equi-
librium by Smith\cite{5} showed that the effect on the
radial pressure gradient was proportional to the tan-
gent of the bow angle. Gradually a common under-
standing in the mechanism that how the bowed
stator reduces the end-wall losses was getting fairly
clear. V. Gümmer and U. Wenger\cite{6} expatiated that
the radial blade force could change the stream-tube
height and static pressure, and that consequently the
end-wall diffusion was alleviated. Also, they re-
ported that the bowed blade had little effect on the
qualitative characteristics of classical secondary
flow but significantly reduced the extent of
3D-separations and re-distributed the flow within
the passage in those blade rows dominated by 3D
end-wall boundary layer separations rather than
classical secondary flows.

This study is aimed at further searching for ap-
lication conditions of the bowed blade in improv-
ing the compressor performance and at discussing
the mechanisms of the application conditions, espe-
cially, the effects of turning angle.

1 Computation Scheme

NUMECA simulation code for the
turbo-machinery applications (FINE/TURBO) is
used. The code turbulence is modeled by an alge-
braic Baldwin-Lomax model. The space and time
discretization schemes are two-stage TVD upwind
scheme and four-stage explicit Runge-Kutta scheme
respectively. For convergence acceleration to steady
state, the combination of multi-grid and implicit
residual averaging is applied.

The boundary conditions are inlet total pres-
sure of 103 355 Pa, inlet total temperature of 294
K, incidence of zero degree and outlet static pres-
sure of 101 325 Pa. The inlet Mach number is about
0.2 (\(<0.3\)), so a preconditioning\cite{7} technique is
used to resolve the problems of slow convergence
and reliability. The computation grid is shown in
Fig.1. Since the stagger angle of the cascade is
little (\(<20^\circ\)), H-type grid is used and the total node
is 545 025.

The aerofoil used is NACA65 (Fig.2) with a
middle arc line of double circular arcs, whose equi-
tations\cite{9} are

\[
(x-a)^2 + (y-R_1)^2 = R_1^2 \quad (0 \leq x < a) \quad (1)
\]

\[
(x-a)^2 + (y-R_2)^2 = R_2^2 \quad (a \leq x \leq b) \quad (2)
\]

where \(R_1 = a \sin \chi_1; \ R_2 = (b-a) \sin \chi_2; \ \chi_1 = 0.6 \theta \)
\(\chi_2 = 0.4 \theta; \ a/b = 0.45\). After a value of turning
angle \(\theta\) is given, the corresponding middle arc line

Fig.1 Computation mesh in meridian plane

Fig.2 Aerofoil configuration and blade stacking line
will be gained; and then an aerofoil line can be got through adding NACA65 aerofoil thickness to the middle arc line. Finally, a computational cascade can also be obtained by using stagger angle’s formula

\[ \beta = \beta_i - \chi, \]  

where \( \beta_i = -9.75^\circ \) according to the experiment\[8\].

As shown in Fig.2 (b), the bowed blade stacking line is composed of three straight lines, among which a line is connected to it’s neighbor line with smooth curvature. The bowed blade is given by moving the end-wall sections perpendicular to the axis. The bow angle \( \gamma \) is defined by the angle between the pressure surface and the normal of end-wall.

2 Comparison of Results of Computation and Experiment

In the following text, a comparison of computational and experimental\[7\] results is achieved to validate the reliability of computation which is carried out with the same geometry, aerodynamic parameters and boundary conditions as the experiment. The comparison parameters are listed in Table 1 and other geometric parameters are shown in Table 2.

### Table 1  Geometry and aerodynamic parameters in comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experiment</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet geometry angle ( \beta_i ) ((^\circ))</td>
<td>49.75</td>
<td>59.5</td>
</tr>
<tr>
<td>Turning angle ( \theta ) ((^\circ))</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Stagger ( \beta_i ) ((^\circ))</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Incidence ( i ) ((^\circ))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reynolds number ( Re )</td>
<td>6.50 \times 10^3</td>
<td>6.53 \times 10^3</td>
</tr>
<tr>
<td>Inlet Boundary layer thickness ( \delta ) /mm</td>
<td>20.50</td>
<td>20.55</td>
</tr>
<tr>
<td>Displacement thickness ( \delta^* ) /mm</td>
<td>2.50</td>
<td>2.25</td>
</tr>
<tr>
<td>Momentum loss thickness ( \delta^{**} ) /mm</td>
<td>1.75</td>
<td>1.79</td>
</tr>
<tr>
<td>Bow angle ( \gamma ) ((^\circ))</td>
<td>0</td>
<td>25</td>
</tr>
</tbody>
</table>

A straight rectangular cascade and a bowed cascade with bow angle of 25\(^\circ\) were studied in the experiment. The total energy loss coefficients are compared in Table 3. And energy loss coefficient distributions along blade height are compared in Fig.3. Here the coefficient is defined as

\[ \xi = \frac{(p_i/p_0^*)^{0.2587} - (p_i/p_0)^{0.2587}}{1 - (p_i/p_0)^{0.2587/0.2587}} \quad (3) \]

where \( p_i \) is the static pressure; \( p_0^* \) is the local total pressure and \( p_0 \) is the inlet total pressure. The variation trends of the coefficient \( \xi \) for both results are fairly similar except for some differences in the absolute value, where exist possible reasons that there are some errors in the experiment measurements and computation codes and there are some differences between the post-process methods of the two research techniques. The variations of energy loss coefficient of bowed cascade show the bowed blade improves the cascade performance to high extent.

### Table 2  Geometry parameters of computation cascade

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length ( b )/cm</td>
<td>16</td>
</tr>
<tr>
<td>Aspect ratio ( h/b )</td>
<td>1.00</td>
</tr>
<tr>
<td>Axial chord length ( B )/cm</td>
<td>15</td>
</tr>
<tr>
<td>Exit geometry angle ( \beta_i ) ((^\circ))</td>
<td>-9.75</td>
</tr>
<tr>
<td>Turning angle ( \theta ) ((^\circ))</td>
<td>59.5</td>
</tr>
<tr>
<td>Bow angle ( \gamma ) ((^\circ))</td>
<td>(5, 10, 15, 20, 25, 30)</td>
</tr>
<tr>
<td>Pitch length ( e )/cm</td>
<td>8</td>
</tr>
<tr>
<td>Blade height ( h )/cm</td>
<td>16</td>
</tr>
<tr>
<td>Solidity ( b/t )</td>
<td>2.00</td>
</tr>
</tbody>
</table>

### Table 3  Comparison of total mass-average energy loss coefficients of computation and experiment

<table>
<thead>
<tr>
<th></th>
<th>Straight blade</th>
<th>Bowed blade</th>
<th>Relative reduction / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>0.137</td>
<td>0.119</td>
<td>13</td>
</tr>
<tr>
<td>Computation</td>
<td>0.110</td>
<td>0.098</td>
<td>11</td>
</tr>
</tbody>
</table>

![Fig.3](image-url)
The contours of energy loss coefficients at exit plane are given in Fig. 4. The distributions obtained from experiment and those obtained from computation are similar to each other. There are two high loss regions near the lower corner and the upper corner of the straight blade, while the two loss regions of the bowed blade become much smaller. Besides, the energy loss values and the positions of the loss cores are changed: the values are reduced by 9% and the positions moved to the middle span.

The contours of axial velocities near suction side are shown in Fig. 5. In incompressible flow motion, it is known that the axial velocity decides the magnitude of the flow capacity and the low velocity region corresponds to the high loss region. As shown in Fig. 5, there are two back flow regions near the suction/end-wall corners in the passage of straight cascade. While the back flow regions are removed after the bowed blade technique is applied. The comparison of experiment with computation indicates that the computational results are believable and accepted.

### 3 Study on Losses of Bowed Blade in Different Turning Angle Cascades

As learned from Fig. 6, the effect of the bowed blade in lowering loss of high turning angle cascades is more apparent than the effects in low turning angle cascades. In particular, the cascade loss coefficient of 30° bowed blade in 59.5° turning angle cascade is less than that of straight blade in 54.5° turning angle cascade.

In the following discussions on the effects of aerofoil turning angle, the abbreviations of STR595 and BOW595, STR395, BOW395 stand for straight blade with \( \theta = 59.5^\circ \) and bowed blade with \( \theta = 59.5^\circ \), straight blade with \( \theta = 39.5^\circ \), bowed blade with \( \theta = 39.5^\circ \), respectively.

The contours of axial velocities and vectors of secondary flow at exit plane in the two turning an-
gle cascades are compared in Fig.7. In Fig.7(a) and (b), the areas of low speed flow and back flow in the cascade BOW595 are evidently reduced and the trend of high speed flow’s immigration is obviously strengthened.

Accordingly, the effects of different aerofoil turning angle cascades on corner separation are different. As shown in Fig.8(a), the separation line on suction surface(S.S) of the cascade BOW595 is much nearer to trailing edge than that of the cascade STR595 and the separation region of BOW595 is much smaller than that of STR595. As seen in Fig.8(b), the variations of separation line and separation region of BOW395 are comparatively negligible to STR395.

4 Effects of Bowed Blade on Secondary Flow in High Speed Fluid

As proved in present paper, a better explanation for bowed blade to be effective in controlling the end-wall flow is the rise of static pressure on the end-walls together with the decrease of low energy fluid mass near the end-walls caused by high speed fluid immigration from the middle span. A schematic model of bowed blade’s controlling secondary flow is given in Fig.9. As shown in Fig.9(a), when high speed fluid flows through the cascade passage, it is subjected to a centrifugal force pointing to the pressure surface(P.S) due to cascade’s turning. If the cascade is straight, the secondary flow in high speed fluid does nearly not immigrate to the end-walls (as
seen in Fig. 9(b)). While if the cascade is bowed, the composition of a bowed blade force and the centrifugal force impels some high speed fluid to migrate to the end-walls (as seen in Fig. 9(c)) and the pitched mass-averaged streamlines turn to the end-walls in the rear part of passage (as seen in Fig. 10). These phenomena will result in: ① the total mass of high speed fluid is increased and the flow speed is raised so as to effectively control the accumulation or separation of low energy fluid near the end-walls; ② the rise of static pressure on the end-walls strengthens the radial immigration and weakens the crosswise immigration of low energy fluid in boundary layer, thus the accumulation or separation of low energy fluid is further controlled.

Theoretically, if the bow angle, bow height of the bowed blade and the centrifugal force are great, the high energy fluid easily immigrates to the end-walls. But if the bow angle and height are extremely great, the loss of the surface friction obviously increases. Thereby in bowed cascade passage, the immigration capacity of high speed fluid mainly relies on the centrifugal force.

5 Effects of Bowed Blade on Different Turning Angle Cascade

In Fig. 11, a parameter mass-flow density $\phi$, local density $\rho$ multiplied by local axial velocity $v_z$, is defined to describe the flow capacity, i.e., the mass-flow in a unit area. As learned from Fig. 11, the mass-flow density along a radial line $A-A$ for the cascade BOW595 is much higher than that for the cascade STR595. While for the cascade BOW395 the mass-flow density is increased a little and the trend of high speed fluid’s immigration capacity is weak.

![Fig. 11 Distributions of mass-flow densities along the line](image)

The bowed blade can evidently control the separation, and consequently, obviously lower the losses at the suction and end-wall corners in high turning angle cascade. The contours of total pressure loss coefficients at outlets section are shown in Fig. 12. A high loss region with a loss coefficient of 0.700 in its core exists at the hub/suction corner and expands to 25% span-wise position in the cascade STR595. While in the cascade BOW595, there appear two high loss regions: the one is located at the hub/suction corner with a loss coefficient of 0.550 in its core, the other is located at the small zone between 30% and 40% span-wises also with a loss coefficient of 0.550 in its core. But unlike the high
turning angle cascade, the cascade BOW395 hardly improves the performance, and the total pressure loss coefficient is kept as a value of 0.650 in the loss core when compared to STR395. Actually the overall losses of low turning angle bowed blade are increased due to the increment of surface friction losses.

6 Conclusions

(1) The experimental and computational results both verify that the bowed blade has obvious effect in high turning angle cascade. The overall losses are lowered by 13% and 11% in experiment and computation respectively.

(2) In different turning angle cascades, the effects of bowed blade are different. In higher turning angle cascade, the bowed blade can lower the loss by 17.9% in maximum. While in lower turning angle cascade, the bowed blade can lower the loss by 0.7% in maximum.

(3) In different turning angle cascades, the bowed blade can strengthen the radial secondary flow and weaken the traverse secondary flow. Both of these two effects can lower the end-wall loss but increase the mid-span loss, so they can not explain why the effects of bowed blade are different in different turning angle cascades.

(4) An important effect of the bowed blade is to strengthen the flow capacity near the end-walls, of which the reasons include: ①radial immigration of low energy fluid in boundary layer; ②high speed fluid’s turning to the end-wall in meridian plane. Thus the strong flow capacity near the end-wall makes the anti-separation capacity stronger and thus lowers the pressure-difference loss. This is the main reason for the bowed blade to significantly lower the losses in high turning angle cascade.

(5) In low turning angle cascade, the bowed blade increases the mass-flow density comparatively less and the corner separation is much weaker. So the benefit of bowed blade in reducing losses is negligible.

References


Biographies:

ZHANG Yong-jun Born in 1977, he received B.S. and M.S. from Harbin Institute of Technology in 2000 and 2002 respectively. Now he is working for his doctoral degree in Harbin Institute of Technology. Tel: (0451) 86412433, 13030086504, E-mail: zhang_blestu@sina.com

CHEN Fu Born in 1970, he received the doctoral degree from Harbin Institute of Technology in 1997 and then became a teacher there. Now he is working as an professor in Energy Science and Engineering School of Harbin Institute of Technology. He has published several research papers in various periodicals. Tel: (0451) 86412368, E-mail: chenfu@hit.edu.cn