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An Experimental Investigation into the Influence of Diameter-Blade Height Ratios on Secondary Flow Losses in Annular Cascades with Leaned Blades

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ABSTRACT

Three groups of the annular turbine cascades with diameter-blade height ratios d/l=1.9, 3, and 5 respectively are tested. Each group includes five types of cascades equipped with different kinds of leaned blades. For each type of the cascades, the distributions of total pressure, static pressure and exit flow angle along the pitch and the blade height are surveyed in detail. The experimental results show that the smaller the diameter-blade height ratio of the cascade, the more effective application of positively leaned blade to reduce the secondary flow loss, when the inner and outer walls of the cascade are cylindrical. Under this condition the effect of the blade leaning on the energy loss distribution along the blade height is notable. There is an optimal lean angle corresponding to the minimum of the overall energy loss in each cascade with leaned blades. The function-relation between the optimal lean angle and the diameter-blade height ratio is monotonic.

NOMENCLATURE

b= Blade chord.
B= Blade axial chord.
d= Diameter.
γ= Ratio of specific heats.
l= Blade height.
N= Blade number.
P= Pressure.
t=Pitch of the cascade.
x= Distance of measured point from the hub of the blades
$\bar{t}$= Relative pitch of the cascade (t/b)
$\bar{l}$= Relative blade height (x/l)
$\bar{p}$= Static pressure coefficient behind the cascade

$$\bar{p} = \frac{p_i - p_a}{p_0{}^* - p_a}$$

ζ= Loss coefficient of energy in cascades

$$\zeta = \frac{\left(\frac{p_1}{p_1{}^*}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{p_1}{p_0{}^*}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{p_1}{p_0{}^*}\right)^{\frac{\gamma-1}{\gamma}}}$$

p_a= Pressure of atmosphere.
v= Airflow velocity.
σ= Deflection angle of streamlines in a meridional plane.
α= Airflow angle measured from a peripheral direction.
ε= Lean angle of blades.
ζ_t= Total loss coefficient of energy in cascades.
ζ_m= Pitch-averaged loss coefficient of energy in cascades.
ν= Kinematic coefficient of viscosity.

SUBSCRIPTS AND SUPERSCRIPTS

o= Parameter in front of a cascade (inlet parameter of a cascade).
1= Parameter in measured plane.
*= Stagnation parameter.
h= Hub of blades(parameter at a hub of blades).

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m= Averaged parameter.
t= Tip of blades(parameter at tip of blades).
opt= Optimal value.

INTRODUCTION

Since the method of curvilinear profiling blade in the turbine stator first was suggested in the early sixties [1] [2], researchers in other countries have shown great interest in conducting a study aimed at decreasing the energy loss in the cascades by utilizing straight leaned and curvilinear leaned blades. Our experimental results show [3] that for annular cascades with small diameter-blade height ratio the application of the positively leaned blades (characterized by a obtuse dihedral angle between the blade suction surface and the inner wall of the cascades) can effectively reduce the energy loss in a turbine stator, when the inner and outer walls of these cascades are cylindrical. The theoretical analysis of the calculation results demonstrates that the positive blade leaning can create the negative pressure gradient along the blade height inside the channel, which causes the boundary layer in the hub region to be sucked outward into the main stream region and the loss coefficient to be reduced [4].

Applying positively leaned blades to the cascades or stages with large diameter-blade height ratio the similar experimental results are obtained [5] [6]. In particular, for the rectangular cascades with aspect ratio of 1 (corresponding to the annular cascades with infinite diameter-blade length ratio) the experimental data obtained in Ref. [7] implies that on the side of an obtuse lean angle the secondary flow losses are reduced obviously as well and the beneficial effect of the obtuse corner could be introduced to both end walls by using curvilinear leaned blades. However, the experimental data obtained by a few authors have shown that the blade leaning has practically no effect on the turbine stage performance [8], and some specific tests have confirmed that the blade leaning can not improve the aerodynamic performance of the stage. Moreover, it can even lead to an increase in the energy loss in the stator cascades [9] in which the diameter-blade height ratio, according to our rough prediction, is equal about to 7. These experimental results seem to be contradictory among themselves. But we consider that no matter whether the energy loss is increased or reduced by employing leaned blades, the experimental results are all correct. The fact is that they have been obtained by different authors under different test conditions.

The application of the positively leaned blades is suitable only for cases of relatively short blades and relatively long blades, where the secondary flow losses occupy a considerable proportion of the overall energy loss. In the first case, the secondary flow is mainly the crossflow from the blade pressure surface to the suction surface along the end walls. The loss of energy caused by the above-cited secondary flow forms a significant portion of the overall loss. In the second case, in addition to the cross-flow in the boundary layer, there is a radial flow of the boundary layer along the blade surface from the tip to the hub of the cascades. The radial secondary flow loss can exceed that of the crosswise secondary flow in the annular cascades with long blades. As to the blades of the moderate height, there is little necessity of utilizing the leaned blade due to the fact that the secondary flow loss in such blades only accounts for a relatively small proportion of the overall loss. Moreover, with the blade leaning, the blade profile on the revolutionary surface, in general, will fail to be optimal, resulting in an increased profile loss, which, in turn, will lead to a higher level of overall energy loss. Therefore experimental investigation into the influence of the diameter-blade height ratio on the energy loss in the cascades with long leaned blades has important practical significance.

EXPERIMENTAL MODELS

The experiments were carried out in a low speed annular tunnel of Harbin Institute of Technology. The power of the blower is 132 KW. The models tested consist of three groups of annular cascades with different diameter-blade height ratios, and their geometrical characteristics are listed in table 1. Each type

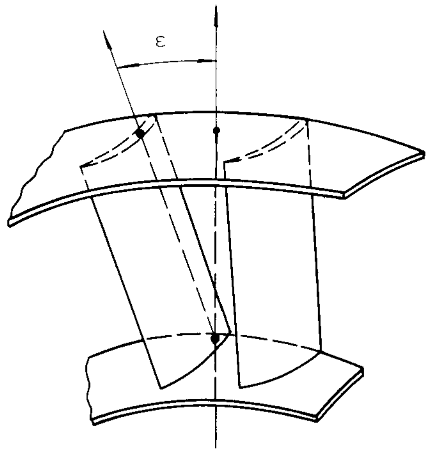


Fig 1. Lean angle ε of blade

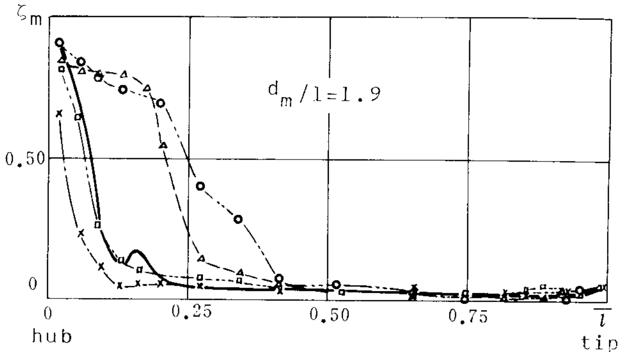
includes five types of cascades equipped with different kinds of leaned blade:No.1--radial conventional blade; No.2--and NO.3-- positively leaned blade with lean angles of 10° and 20°, respectively (Fig.1); No.4-- and No.5-- negatively leaned blade with lean angles of 10° and 20°, respectively.The positively or negatively leaned blades correspond to the obtuse or acute dihedral angles between suction surface and the inner wall respectively. The number of cascades used for the experiments altogether is 15. The measured plane is parallel to the outlet plane of the cascade and is located 10mm from the cascade outlet edge. The total pressure, the static pressure and the direction of the flow are measured with five-hole spherical probes. The total pressure in front of the cascade is 815mm WC (pressure above atmospheric pressure). At the mean diameter of the cascades exit the Reynolds Number $Re=4.46\times10^5$, where the characteristic length of the Reynolds Number is the blade chord b.

EXPERIMENTAL RESULTS

The above-mentioned three groups of annular stator cascades with diameter-blade height ratios of 1.9,3 and 5 respectively, equipped with different kinds of leaned blades, were tested in the aerodynamic tunnel. For each of the 15 experimental programs, the distribution of the total and the static pressure and the outlet angle along the pitch and the blade height are measured. The aerodynamic parameters obtained by the experiments given out in the form of the pitchwise averaged values.

TABLE **I**, Geometrical parameters of experimental models

Name of geometrical parameters	1^{st} group	2^{nd} group	3^{rd} group
Diameter-blade height ratio dm/l	1.9	3.0	5.0
Tip diameter, d_t(mm)	404	404	404
Hub diameter, d_h(mm)	126	200	200
Blade height, l(mm)	139	102	50
Blade chord, b(mm)	79	73	73
Blade axial chord B(mm)	40.05	48.05	48.05
Aspect ratio, l/b	2.89	2.12	1.04
Pitch-chord ratio, t/b	0.64	0.72	0.60
Blade number, N	18	18	18
Inlet angle α_0	90°	90°	90°
Outlet angle α_1	19°	19°	19°
Position angle α_p	41°53'	41°53'	41°53'



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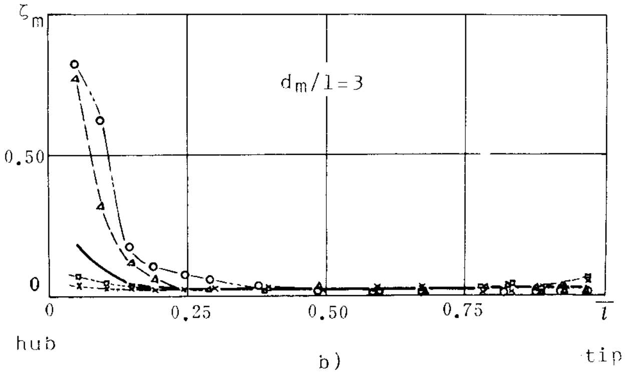

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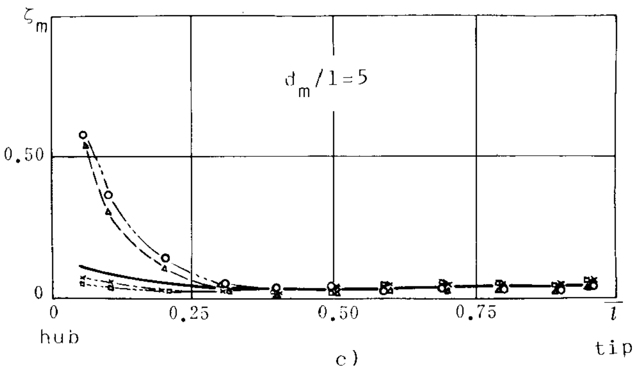


c)

Fig.2 Distribution of the energy loss coefficient along the blade height. ——— radial blade -x-x-x- leaned blade with $\varepsilon=+10^0$; -▫-▫-▫- leaned blade with $\varepsilon=+20^0$; -Δ-Δ-Δ- leaned blade with $\varepsilon=-10^0$; -o-o-o- leaned blade with $\varepsilon=-20^0$.

Fig. 2(a) represents the distribution of the pitchwise averaged loss along the blade height for the cascades with the diameter-blade height ratio 1.9. This figure shows that the energy loss coefficients in the hub region of the five cascades with different leaned blades have considerable different values. The reason for these differences is that there is obvious distinction of the pressure gradient in the hub regions. In the channel of the cascade with the radial straight blade cascade, especially in its rear part, there is the greatest positive pressure gradient along the blade height. Under the action of this pressure gradient, the low momentum gas in the boundary layer flows from the tip to the hub, which gives rise to an accumulation and separation of the boundary layer in the hub region of the cascades. As a result, the hub region of the higher energy loss is expanded and the energy loss coefficient is increased. In the channel of the positively leaned blade cascade, however, the radial positive pressure gradient has either a very small or negative value [4] . Under this condition, the radial flow in the boundary layer to the hub region is reduced or the boundary layer in the hub region is sucked into the main stream zone. Therefore, the secondary flow loss is decreased notably, and there is a marked drop in the energy loss coefficient near the hub.

For the negatively leaned blade cascade, because there exists so much greater positive radial gradient of pressure in the hub region, the radial flow to the hub region in the boundary layer is intensified, and the high loss zone around the hub is expanded severely, even the reverse flow may appear therein, Thereby, it is certain that the energy loss coefficient is severely increased.

For each of the five experimental programs, in the tip region of the cascades, the energy loss coefficient is nearly the same, because the outer wall of the cascades is cylindrical and the flow there is accelerated. The radial positive gradient of pressure in the tip region may cause the boundary layer to the main stream zone. Thus, serious accumulation of the boundary layer in the tip region can not occur.

Fig.2(b) and Fig.2(c) represent the distribution of the pitchwise averaged loss coefficient of energy along the blade height for the cascades with diameter-blade height ratios of 3 and 5 respectively.

For each group including 5 types of cascades with different leaned blades, we have obtained the similar experimental curves. Comparing Fig.2(a) with Fig.2(b) or Fig.2(c), the distinction between them is that with the increase of the diameter-blade height ratio, the region of higher loss near the hub is reduced and the energy loss level is lowered. Our explaining to above-mentioned phenomena lies in that with the increase of the diameter-blade height ratio the radial pressure gradient is reduced and the radial secondary flow in the cascade is weakened, therefore the energy loss in the hub region of the cascade is reduced. In addition, from figures 1 it can also be seen that the greater the diameter-blade height ratio, the less the reduction of energy loss in the hub region of the cascades with the positively leaned blades in comparison with that of the corresponding radial blade. For three kinds of diameter-blade height ratio of 1.9,3 and 5, the reductions of the energy loss coefficient of the cascades, in the case of the optimal lean angle, are 30%, 25%, and 18%, successively, in contrast to that of cascade with radial conventional blade. From this it may be inferred that for cascade with moderate height blades, using the leaned blades should not give more effect to the reduction of the energy loss. The effectiveness of the application of the leaned blades depends on the proportion of the secondary flow loss (including radial and crosswise secondary flow losses)to the overall loss. Only when the secodary flow loss is dominant in the overall loss, characterized in the case of the cascades with long blade or short blade, blade leaning can have great influence on the energy loss in the cascades.For the cascades with moderate height blades, the application of the leaned blades probably does not produce great benefit.

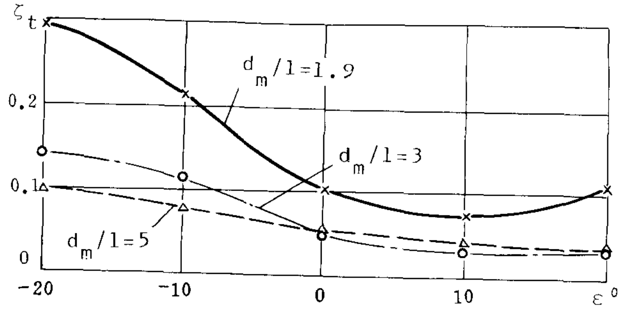


Fig.3 Variation of total loss coefficient of energy with the lean angle of blades

Fig.3 shows the curves of the variation of the total loss coefficient of energy in the cascades with the lean angle of the blades. From this figure it can be seen that with the increase of the diameter-blade height ratio, the curves become more and more level, which indicates that with the increase of the diameter-blade height ratio,the effect of blade leaning on the total loss coefficient of energy in the cascades is reduced. In addition, this figure demonstrates that there is a positive optimal lean angle for the each diameter-blade height ratio of the cascates with the leaned blades. When the diameter-blade height ratio is equal to 1.9, 3 or 5 respectively, the corresponding optimal lean angle is about 9^0,14^0 or 20^0. This indicates that for each of the diameter-blade height rations in the cascades there exists an optimal angle. The positive lean angle which is more than the optimum leads to an increase in energy loss, because of the increase of the positive pressure gradient on the blade to blade surface. Moreover, the greater the blade leaning angle, the further away from the optimal value the blade profile in the revolutionary plane will be. As a result, the blade outlet wake region is enlarged with the intensity of the vortex being enhanced. Consequently, the use of excessively leaned blades should be considerd as inadvisable. When the lean angle is less than the optimum, with the increase of the lean angle, the rate of reducing secondary flow loss is faster than the one of increasing the profile loss. Therefore the overall energy loss of the cascade is decreased.

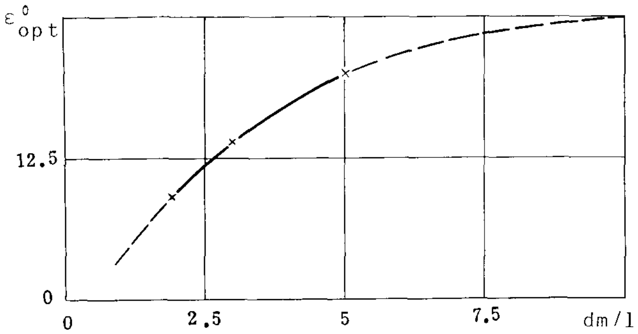
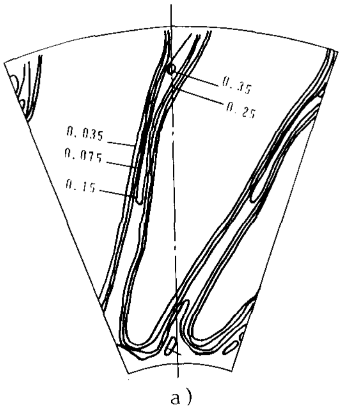


Fig.4 Variation of the optimal lean angle with the diameter-blade height ratios

Fig.4 represents the surves relating the optimal lean angles with the diameter-blade height ratios. From this figure it can be seen that the optimal lean angle is a monotonic function of the diameter-blade height ratio and its value increases with the increasing of the latter.



a)

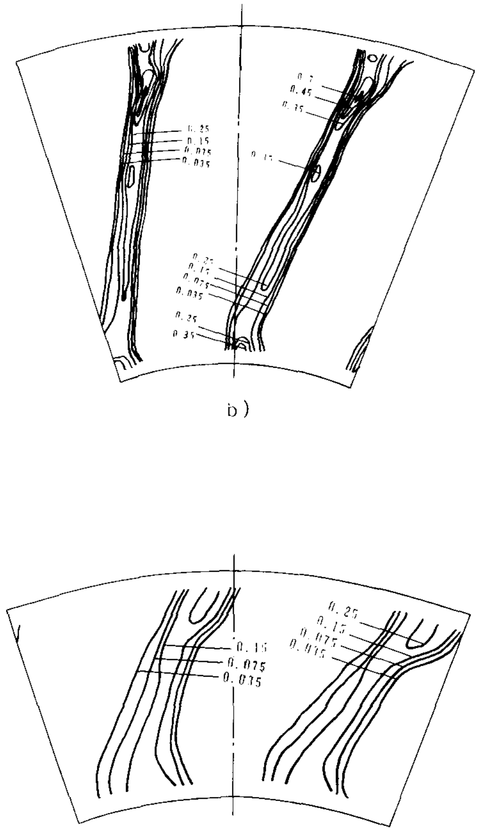


Fig.5, Contours of the equivalent local loss coefficient of energy with positively leaned blades
a)--d/l=1.9 and ε=10°
b)--d/l=3 and ε=20°
c)--d/l=5 and ε=20°

Fig.5 shows the contours of the equivalent local loss coefficient of energy in the cascades with the positively leaned blades.From Fig.5(a) it can be seen that when the diameter-blade height ratio is small(d/l = 1.9), even though the adopted lean angle is nearly equal to the optimal lean angle, there still is a thicker boundary layer in the hub region. However, when the diameter-blade height ratio is greater (d_m/l=3 or 5), by using the blades with the lean angle approaching the optimal one, not noly the radial secondary flow is eliminated, but also the boundary layer near the hub is partially sucked into the main stream zone. At this moment the boundary layer in this region is so thin that it can not be measured by a five-hole spherical probe(Fig.5 (b),(c)).

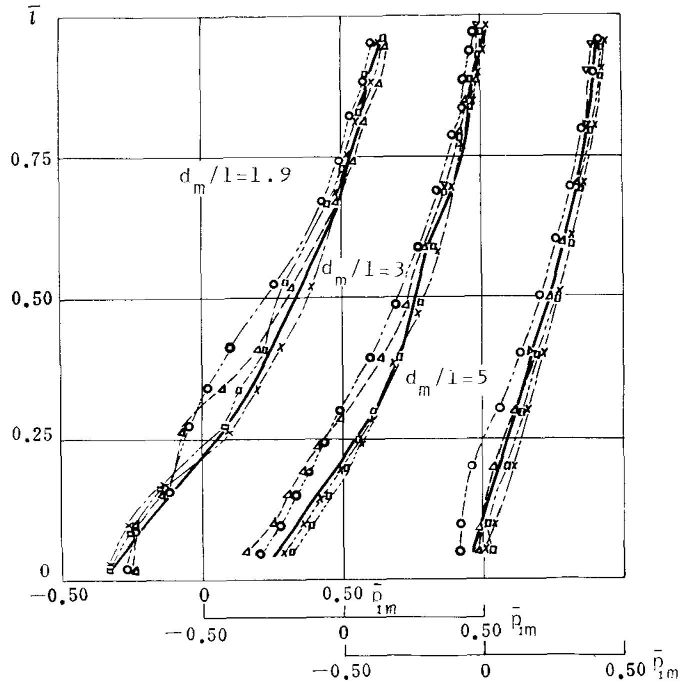


Fig.6 Distributions of the pitchwise averaged pressure coefficient

Fig.6 illustrates the distribution of the pitchwise averaged pressure coefficient along the blade height for three groups of tested cascades. Every one group includes five types of cascades with different leaned blades. From this figure we can observe clearly that for five types of cascades, with the same diameter-blade height ratio and different leaned blades, the differences of the static pressure distributions behind the cascades are not very obvious.A similar result is obtained for the distributions of the outlet angles behind the cascaes(Fig.7). This shows that the blade leaning does not have a notable effect on the flow parameters behind the cascades. Therefore, using leaned blades can effectively reduse the energy loss in the cascades, and does not bring great difficalty to designing the rotor blades.

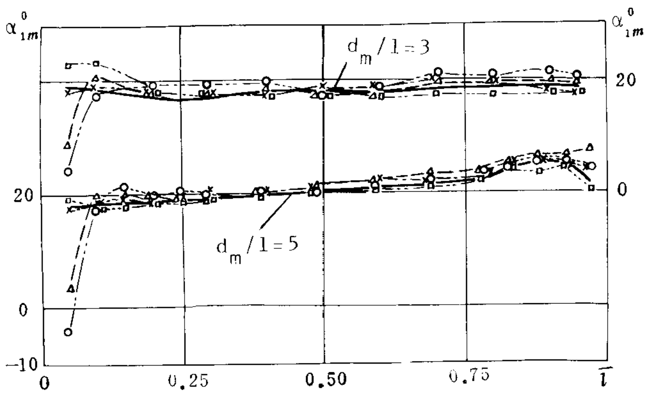


Fig.7 Distribution of the pitchwise averaged outlet angles

CONCLUSIONS

The conclusions of this paper can be outlined in three aspects as follows:

1. When the diameter-blade hight-ratio is less, using positively leaned blades has an obvious effect on reducing the secondary flow loss. With the increase of the diameter-blade height ratio, the effectiveness of using positively leaned blades on reducing the energy loss in the cascades can also be decreased gradually.

2. For the annular cascades equipped with leaned blades of different diameter-blade height ratios there are different optimal lean angles. There is a monotonous function-relationship between the optimal lean angle and the diameter-blade height ratio.

3. For the annular cascades with the suitable flow conditions behind them, the distributions of flow parameters behind the cascades with leaned blades can not be changed evidently, which is of great benefit to ensuring the design of the elements of the turbine stage locaded on the different height of the blades under the optimal velocity ratio u/v (where u=peripheral velocty).

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