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NUMERICAL INVESTIGATION OF THE EFFECT OF JET-FLAPS IN A TRANSONIC TURBINE CASCADE WITH SUPERSONIC OPERATING CONDITIONS

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Abstract
The objective of this part is to numerically analyze the effect of PS jet-flap design on the shock-boundary layer structure in a transonic HP turbine cascade, which is one of the usable flow control methods for variable-geometry turbine (VGT). With this purpose, the normal PS jet-flaps with different mass flow rate and slot width are used to consider the supersonic inflow condition. With two-dimensionally steady simulations, the PS jet-flap effectively changes cascade throat area and varies the shock-boundary layer structure, which will directly result in the difference of profile loss. Using a C_m=2% jet-flap with 1.025mm slot width and normal jet blowing direction, the income mass flow rate is diminished by 4.2% because of the new formed jet-boundary layer-shock structure, and the turning angle augmented by 0.48 degrees, but the energy loss coefficient is expanded slightly from 0.075 (no jets) to 0.085.

Key words: jet-flap; supersonic inflow; transonic High-Pressure turbine cascade; flow control

INTRODUCTION

Recent high-loading turbine often operates at transonic speeding due to the requirement of higher performances. By changing some components' shape, size and position, the new named variable-cycle engine (VCE) is achieved with the adjustable cycle parameters. This kind of engine can be effectively used at part-load or off-design conditions where the efficiencies are unacceptably bad with poor matching of the components owing to the fixed flow passage areas. But for transonic turbine, it will not be so easy to fit for different operations as described in reference [1] because of the shock-boundary layer interaction. So the variable-geometry flaps become much more essentially effective in transonic turbine cascades than in the subsonic inflow conditions.

With regard to variable-cycle engine (VCE), the off-design conditions can be improved by using variable-geometry turbine (VGT) which can alter the flow passage areas, which will then contribute to the variation of mass flow rate, which plays an very important role in the high-pressure (HP) turbines and makes the variable-cycle turbine one of the substantial components of the VCE, as described in references [1-5].

For a modern perspective, variable-geometry turbine (VGT) is one of critical methods used to change the throat areas of HP turbines, which then varies the turbine mass flow. The technique has been applied in VGT including nozzle guide vane (NGV) pivoting, inlet guide vanes, inlet-stator vanes, and real mechanical-flaps near the HP-turbine passage throat [2-4, 6], and so on. However, the real flaps cannot control the passage throat automatically and will bring more disadvantages at the design operating condition even though they are well performed at some off-design points. As a new method, the jet-flap was first introduced into the inner flow in 1971 by Stanley and John [7] in a 2D turbine cascade as a boundary-layer control device and as a variable-throat-area device. The results of their study showed a decrease of more than 10% main flow with the jet flow mass rate varying among 0-4%. In transonic conditions, a new approach with wall jet was used for blade cooling by Gehrer et al [8]. Though no details was demonstrated in their conclusion, the results showed a variation of 3.2% inflow when the mass flow rate of the cooling jet was 2%. Therefore, jet-flap can be introduced as a soft variable-throat-area device in not only the subsonic condition but also supersonic condition [9-14].

Referring to the serious problems of turbine cascade in supersonic conditions, shocks in the flow passage or forming at the leading edge of blades will lead to the boundary-layer separation and thus induce more flow losses. Meanwhile, the flow pattern with shock at supersonic inflow condition will be much more complicated with the blade boundary layer interaction [15]. This will also be harmful to turbines' performance. So historically many research have been done to concern about the shock-boundary layer structure and the shock-induced loss mechanism (seen references [15-17]), but we fail to find the work on the influence of jet on the shock-boundary layer structure and its influence on the variation of supersonic turbine performance.

As what we discussed in the previous work, with different inflow condition, the flow state seems to be clearly different. However, previous work just concentrates on the influence of jet-flap on the improvement of cascade performance without the changes of turbine cycle parameters. So In this part, when considering supersonic inflow, as one of the flow control methods, the effect of jet-flap, should lead to a really dramatic flow art which will make the shock-boundary layer structure totally different.

CASCADE CONFIGURATION

The linear transformed von Karman cascade, which was transformed from the profile design of the von Karman Institute, is investigated in the low-speed turbine cascade wind tunnel of the Northwestern Polytechnical University [18~20]. This cascade was named "FKM cascade" in reference [18]. In this paper, it will be simulated in order to cross-check the further experimental investigations in this wind tunnel. The geometry and main design features of the FKM cascade are given in Fig. 1 and table 1 [5, 15].

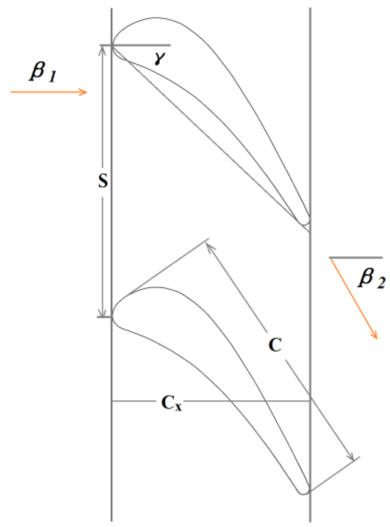


Fig. 1 Cascade configuration

Tab. 1 Cascade design parameters

Blade chord (C, mm)	64.6
Axial chord (C_x, mm)	47.628
Pitch (s, mm)	46.512
Height_simulation (mm)	30
Height_test (mm)	90
Solidity	1.38
Aspect ratio	1.47
Stagger angle (γ, degree)	42.5
Inlet metal angle (β_1, degree)	0
Exit metal angle (β_2, degree)	65.1

NUMERICAL APPROACH

Two-dimensional steady Reynolds-averaged Navier-Stokes equations were solved to simulate the flow in the turbine cascade with flaps in this paper using the commercial CFD software ANSYS CFX. The flow region was discretized using a finite volume method and the convection terms are analyzed using a second-order accurate upwind scheme. A coupled implicit time-marching algorithm was used to solve governing equations.

Turbulence Model

Considering the boundary layer separation on high-pressure turbine blades at subsonic conditions and the boundary layer separation bubble on the blade suction surface induced by the throat shock at transonic and supersonic operating conditions, Menter's SST two-equation turbulence model was used in the whole work. The performance of this model has been demonstrated in the literatures [21-22]. The computational methods of HP turbine cascade with jet-flap in this study are the same as in the references [9-10], which have been validated with experimental data of Bons [23], Lake [24] and Rouse [25].

Grid System

The topology of the computational grid is illustrated in Fig. 2. The grid consists of two kinds, H-grid and O-grid. The H-grid was used in the domains of inlet, outlet and passage, while the O-grid was used only around the blade for the higher demands of capturing the micro- and small-flow structure near the viscous blade wall.

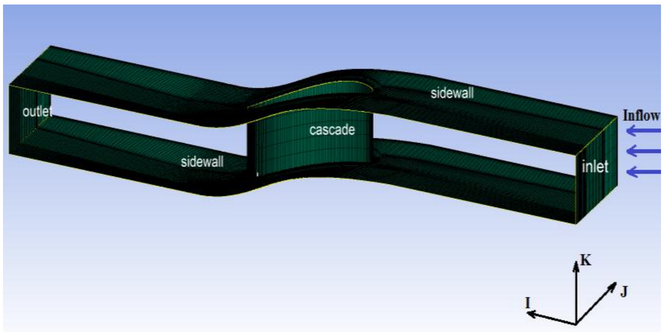


Fig. 2 computational domain and grids

Namely, for the O-grid, in the wall-normal direction, the 25 layers of quadrilateral grids were placed around the no-slip blade wall with y^+ equal to about 0.5 and the expansion ratio equal to 1.12 normal to the blade surface for the remaining nodes. The detailed gird information is entirely shown in table 2, with the total number of nodes almost 2e+5. Here, the I-index is along the axial direction, the J-index is in wall-normal direction for O-grids and in pitch-wise direction for H-grids, and the K-index is in span-wise direction.

Tab. 2 Grids information of the FKM Cascade

Block's name	*Mesh type*	*Nodes*	*I-index*	*J-index*	*K-index*
Blade boundary layer	*O*	*44 400*	*296*	*25*	*6*
Passage	*H*	*56544*	*152*	*62*	*6*
Inlet	*H*	*44 352*	*84*	*88*	*6*
Outlet	*H*	*52800*	*100*	*88*	*6*
Total	*-*	*198 096*	*-*	*-*	*-*

Boundary Conditions

Periodic boundary conditions were applied in spanwise and pitchwise directions. Pressure-inlet and pressure-outlet boundary conditions were used with inlet total temperature and flow directions (angle of attack is 0 degree) given in the solver setting panel of the inlet domain. Since the jet is supplied by a compressor from the atmosphere, the flow in the jet flap has similar characteristics as the free stream. Therefore, a mass-inlet boundary condition can be imposed at the jet-flap inlet, with the jet blowing direction at different cases. The dynamic viscosity is computed from Sutherlands' formula.

DATA EVALUATION FOR FLOW CONTROL TECHNIQUES: PS JET-FLAP

Total pressure loss

Theoretically, the flow loss can be essential for the cascade performance analysis. Here, the local total pressure loss can be computed by

$$C_{P0}(x,y,z) = \frac{P_0(x,y,z) - P_{02}}{P_{02} - P_{s2}}$$

So, the total pressure loss coefficient of the passage can be performed as

$$C_{P0} = \frac{p_{01} - p_{02}}{p_{02} - p_{s2}}$$

where P_{01} is the inlet total pressure, and P_{02} is the exit total pressure and P_{s2} is exit static pressure.

Additionally, a mass flow weighted average method is used in all calculations by the integration perform to get the reasonable data for analysis.

Jet mass flow ratio

The mass flow rate of the inlet flow is

$$m_1 = \rho_1 V_1 A_1$$

Then, the mass rate of jet flow is

$$m_j = \rho_j V_j A_j$$

So the jet mass flow ratio of pressure-side (PS) jet-flap in our study can be defined by

$$C_m = m_j / m_1$$

Jet slot width

Considering the two-dimensional computational domain setting, there is no 3D effect in the flow region. The spanwise variation could be ignored, and here

$$A_j = dH$$

$$A_1 = sH$$

where d is the jet slot width, H is the height of the blade, and s is the cascade pitch.

So, the jet slot width is one of driving parameters to control the jet intensity, which will then contribute to a different mixing-effect between the jet and main flow. The jet slot width is described in Fig. 3 and ranges from 0.27mm to 1.025mm.

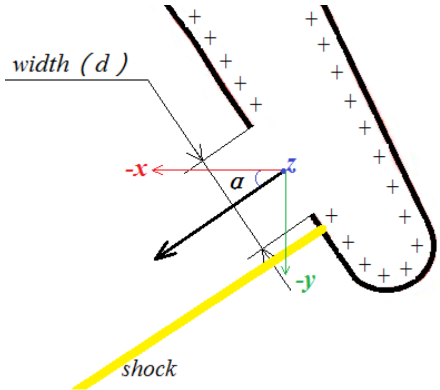


Fig. 3 The jet slot width and jet blowing direction of PS jet-flap

Wall shear stress

Due to the slip-wall condition, the flow has no velocity normal to the wall. So the wall shear stress is defined as the following:

$$\tau_w = \mu\sqrt{\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2}$$

Jet blowing direction

Because the jet flap is characterized by the high-momentum air jet, which is blown straight out of the airfoil wall at a controlled angle, the blowing direction of the jet-flap is one of the key characters determining the mixing effect of the jet and main flow. The jet blowing direction is defined by the jet blowing angle, α , as shown in Fig. 3.

In our former study [1], three kinds of jet-blowing directions ($\alpha = 0^\circ,\ 90^\circ\ and\ \alpha_{normal}\ (0^\circ < \alpha_{normal} < 90^\circ)$) were investigated and found that the counter-mainstream direction is more effective to deflect the mainstream and to vary the inlet mass flow. So in the transonic study of PS jet-flap, the direction which is normal to the blade wall (normal) is applied only.

DESIGN OF PS JET-FLAP

As what narrated in the introduction, the purpose of this part in our study is to investigate the changes of turbine aerodynamic performance and the shock-boundary layer structure with different PS jet-flap design under supersonic inflow in the transonic HP Turbine cascade. With this purpose, the design parameters discussed in this part are jet slot width and jet mass flow rate, while the jet slot location is fixed on the cascade's pressure side (PS) and the jet direction is normal to the blade wall, as shown in figure 3. In figure 3, the yellow line represents for the location of passage throat shock. The jet-flap is located in the front of the passage throat shock.

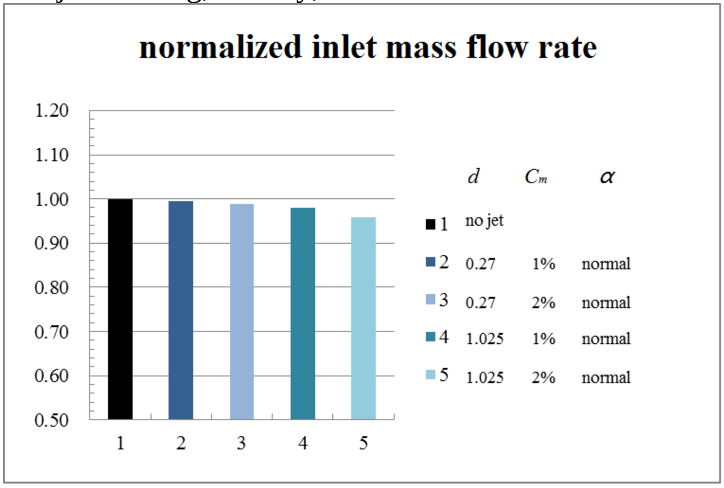
Tab. 3 Design parameters of PS jet-flap for supersonic inflow

Design / *case*	*d*	C_m	α
1	*no jet*		
2	0.27mm	1%	normal
3	0.27mm	2%	normal
4	1.025mm	1%	normal
5	1.025mm	2%	normal

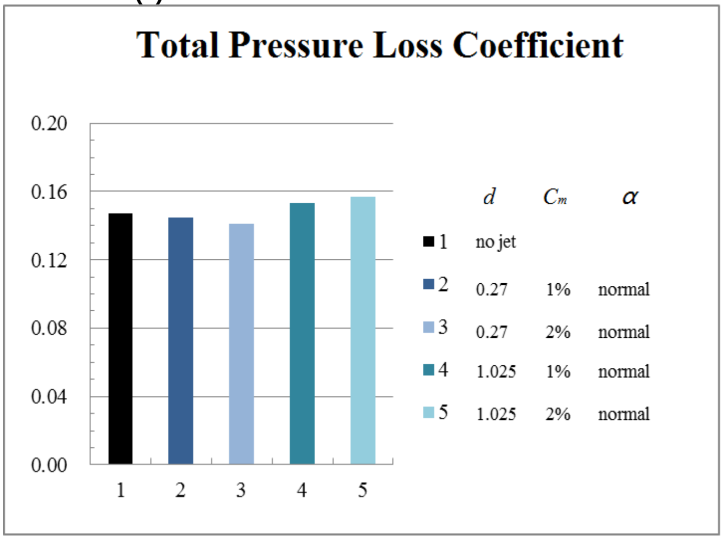
RESULTS AND ANALYSIS

Effect of PS jet-flap on the performance of FKM cascade with supersonic inflow

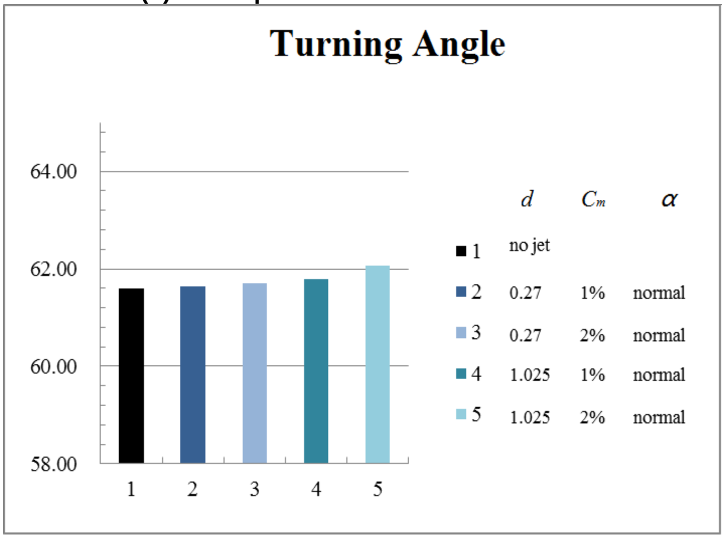
The performance changes of FKM cascades with different PS jet-flaps studied in this part are compared with the no-jet case at Ma_2=1.2. Here, the inlet mass flow rate is normalized by the original one without jet blowing, namely, case 1.



(a) Normalized inlet mass flow rate



(b) Total-pressure loss coefficient



(c) Turning angle

Fig. 4 Performances of FKM cascade with SS jet-flaps

In figure 4, the inlet mass flow rate is decreased with different PS jets, but the turning angle is increased by about 0.48 degree at most. The total-pressure loss coefficient is mostly increased with 1.025 mm jet slot width, but for the case 2 and 3 the loss is slightly decreased.

When compared the results with that of the subsonic condition, we can find that the tendencies of inlet mass flow rate and turning angle are alike when changing the jet mass flow ratio (as case 2 and 3, or 4 and 5), except for total-pressure loss coefficient. However, when separately changing the jet slot width (as case 3 and 5), compared with case 3 and 6 of PS jet-flap in reference [1], the tendencies of inlet mass flow rate, total-pressure loss coefficient and turning angle seem to be totally opposite.

In figure 5 and 6, the velocity distributions at passage throat line (PTL) and measurement line 1 (ML 1) are compared to analyze the effect differences of PS jet-flaps with different jet mass flow ratio and jet slot width at the passage throat and wake.

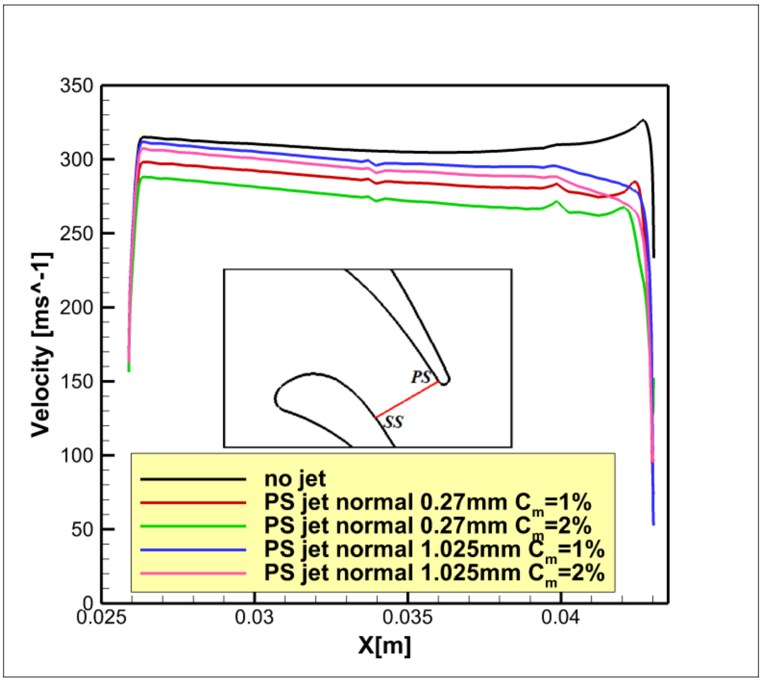


Fig. 5 Velocity distribution at PTL

In figure 5, with slight effect on the velocity of suction side boundary layer, the PS jet-flap obviously decreases the velocity of pressure side boundary layer. The difference of the effect with different design of jet-flap is on the velocity range: the thinner jet slot decreases the velocity of mainstream more than the wider one; and the bigger jet mass flow ratio can have a much significant influence on the reduction of mainstream velocity. There are two small stairs in figure 5, as the passage throat line (PTL) passes through the passage shock two times. When there is a jet-flap located at the trailing edge of blade pressure side, the structure of passage shock is changed by the interaction of shock, boundary layer and the jet flow, which can be obviously found in figure 7. In addition, since the passage mass flow rate is the integration of velocity distribution of throat multiplied with fluid density, the mass flow rate is decreased by PS jet-flap. This tendency can be obtained from figure 4a) as well.

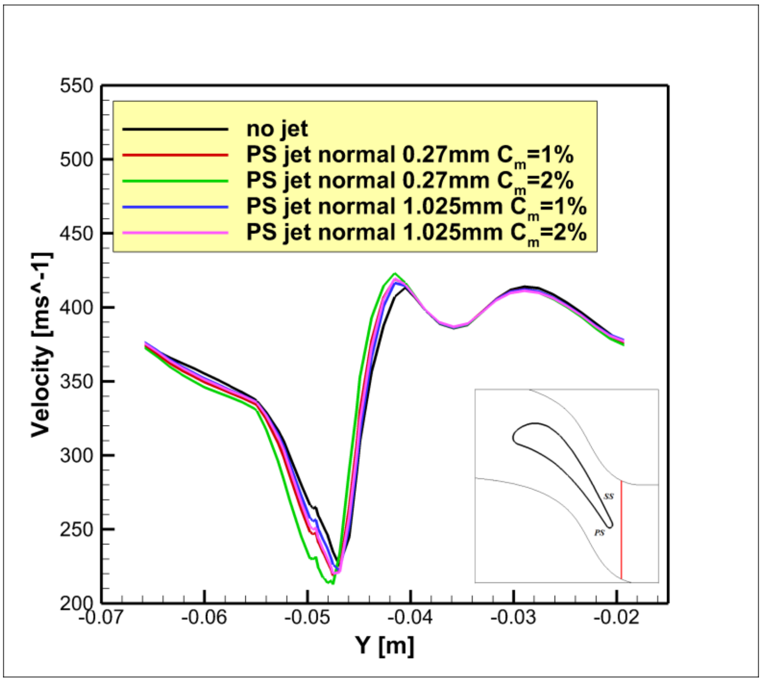
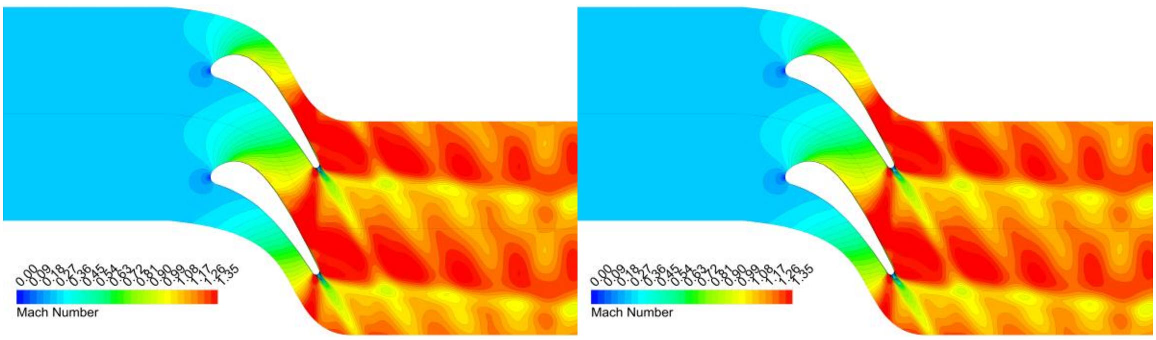


Fig. 6 Velocity distribution at ML 1

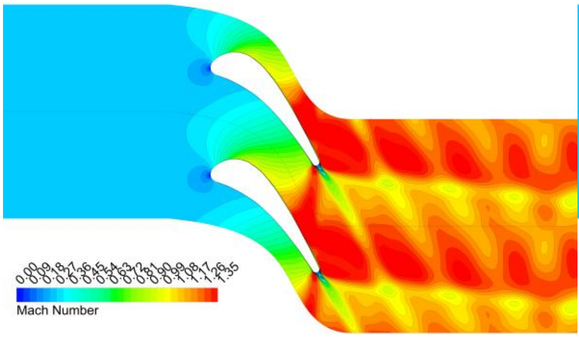
The velocity distribution of wake at ML 1(the red line in figure 6) represents for the profile loss due to wake. In figure 6, compared with the no-jet case, with jet flap, the width and depth of wake are augmented significantly. As a result, the profile loss is larger than the original case. Then, considering the changes of velocity in figure 6, we can conclude that the PS jet-flap can deflect the wake, so the turning angle in figure 4c) is augmented with the increasing jet mass flow rate.

Comparisons of Mach contour

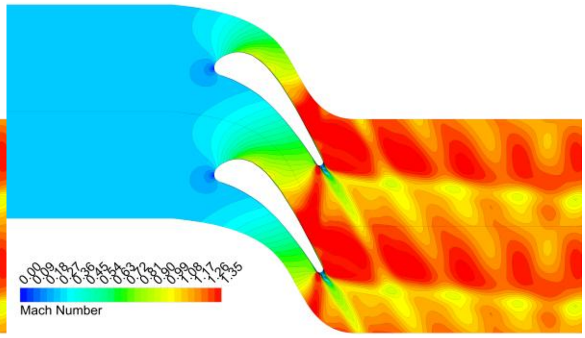
The flow-field Mach number distributions of the five cases are shown in figure 7. The conclusions from figure 5 and 6 can be exactly obtained from figure 7. With PS jet-flap, the range of peak Mach number in figure 7a) is minimized. This then affects the velocity distribution at the passage throat line (PTL) and shows the tendency in figure 5. The change of exit flow angle cannot be obviously obtained in figure 7, which is a check of the results of figure 4c) as well.



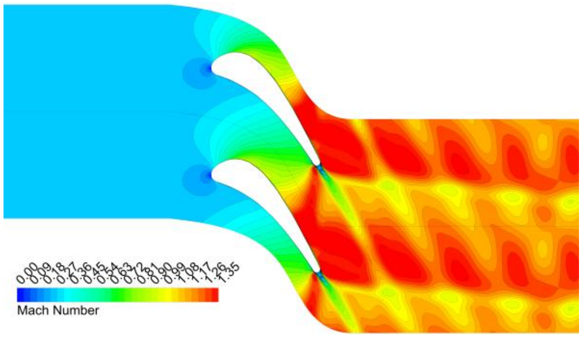
(a) Case 1: No jet **(b) Case 2**



(c) Case 3



(d) Case 4



(e) Case 5

Fig. 7 Comparisons of Mach number contours

The new finding in figure 7 is the changes of shock-boundary layer structure. Owing to the PS jet-flap, the location of passage throat shock is changed to adhere at the jet flow, like the wing of the jet. The shock will induce much thicker boundary layer of suction side, even leads to separation bubbles. So if the location and pattern of shock are changed, the boundary layer thickness will be also changed. When the shock is changed as the wing of the jet, its location is delayed along the axial direction. Then the boundary layer thickness is not fully developed after the incident shock, since the interaction between reflection shock and the trailing edge wake shock has play an essential expansion role on this region and the boundary layer does not continue to grow as a result. So in figure 7, with PS jet-flap, the high Mach number regions are decreased in general. Therefore, we can find that the loss induced by shock should be reduced, thus the flow losses with jet-flap of 0.27mm are decreased. For the jet-flap of 1.025mm, the flow losses are bigger than the no-jet case, which is mainly owing to the shock-jet flow interaction in the passage.

So, for instance, using a C_m=2% PS jet-flap with 1.025mm slot width and normal jet blowing direction, the income mass flow rate is minished by 4.2% because of the new formed jet-boundary layer-shock structure, and the turning angle augmented by 0.48 degrees, but the total-pressure loss coefficient is expanded slightly from 0.147 (no jet) to 0.157.

The wall shear stress distributions of each case are shown in figure 8.

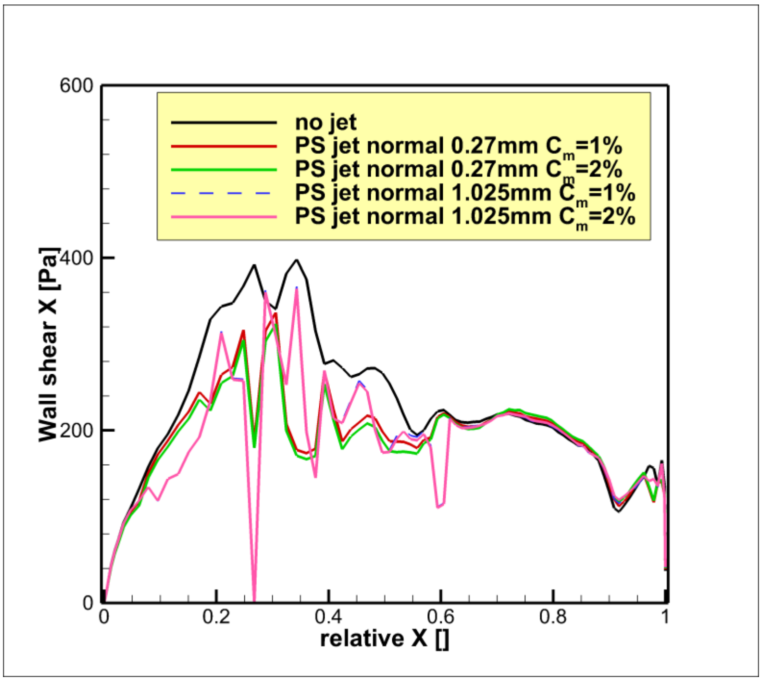


Fig. 8 Wall Shear Stress distributions of blade suction side

In figure 8, with jet-flaps, the wall shear stress is minished generally, especially between 20% and 60% axial chord. Then the wall shear stress appears to be similar with the no jet case, which actually means that the PS jet flap located in the trailing edge of pressure side has little effect on the wall shear stress distribution near the trailing edge of suction side. But at the rear end of the suction side, there is a change happened there, it can be represented for the pressure variation induced by the PS jet-flap in the dead region. Generally, there is no separation zone in each case.

CONCLUSIONS

As discussed in this part, the PS jet-flap seems to be quite effective to change the pattern of shock-boundary layer interaction under supersonic inflow in this numerical simulation. As a result, the boundary layer thickness induced by the shock-boundary layer interaction is diminished owing to the change of shock location. Like a wing of jet, the shock was reduced, which will then contribute to the reduction of throat area and a different transonic turbine performance.

With two-dimensionally steady simulations, the PS jet-flap can slightly change the deflection of the mainstream, which can be concluded from the velocity distribution at the measurement line 1 (ML 1) with PS jet-flap. Consequently, the passage mass flow rate is decreased by jet-flap as a result of the throat velocity distribution. Referring to the flow loss, with jet flap, the width and depth of wake are augmented significantly. As a result, the profile loss is larger than the original case.

Compared to the subsonic inflow, the influence of design parameters of PS jet-flap is not as significant as what is shown in Part I. Separately, the thinner jet slot decreases the velocity of mainstream more than the wider one; and the bigger jet mass flow ratio can have a much significant influence on the reduction of mainstream velocity.

Using a C_m=2% PS jet-flap with 1.025mm slot width and counter-axial (-x) jet blowing direction, the income mass flow rate is diminished by 4.2%, the turning angle augmented by 0.48 degree, but with an expanded total-pressure loss coefficient of 0.01.

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