HUMIDITY DISTRIBUTION IN A TWO DIMENSIONAL STATOR BLADE CASCADE OF STEAM TURBINE

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ABSTRACT

One of the most important properties of matter is its capacity to take different physical forms for different values of parameters such as temperature or pressure; for example, the condensation of the vapor forming droplets and that affect the behavior of the velocity triangles. A practical situation where the existence of water droplets creates problems is the behavior of steam in turbines. The temperature and pressure gradients are such that these droplets cause changes on the vector of absolute velocity and give, as a consequence, many problems with undesirable effects on the performance of the machine, including the erosion of the turbine blades due to the repeated impact on them. In this paper the calculation of the humidity distribution from input information about the streamline by means of physical characters of drops moving in a flow lines and by the boundary contact point is presented.

INTRODUCTION

The two-phase turbines have moderate efficiencies but a very high blade erosion rate due to impingement by high velocity, unsteady, individual liquid droplets. Due to the erosion of steam turbine blades has been one of the important technological problems in power generation systems, is necessary the analysis of path and collision of droplets that have brought severe erosion problems in steam turbine blades, causing a high cost of maintenance and repair as well as a safety problem and low efficiency of power generation.

NOMENCLATURE

$\vec{A}$: Lift strength.
B : Stream width.
c_{DO}: drop velocity
c_f : Friction coefficient.
c_{TO} : steam velocity
$\vec{G}$: Gravity force.

$\vec{K}_E$: Electrostatic forces.
K_K: Volume of the element.
$\vec{K}_P$: Field strength due to a pressure gradient.
m_T : drop mass
M_δ : local Mach number.
n: polytropic exponent
P : Pressure.
r : Time.
S_{ij} : Length of the element.
$\vec{T}$: Force of inertia.
U : Axial Velocity.
V : Peripheral Velocity.
$\vec{W}$: Strength.
$\vec{W}_M$: Strength due to additional movement along steam mass.
δ_1 : Displacement thickness.
δ_2 : Pulse loss thickness.
η_p: polytropic efficiency
σ : Density.
Φ : Friction Force.

DROPLETS IN STEAM TURBINES

Generally, depending of the conditions of work of the turbine, in the two or third rotor stage is found that the molecules nucleate as droplets onto surfaces. In the fourth stator stage can creates the primary nucleation toward the shroud. As flow expansion continues into the final stage, significant supercooling is again possible, leading to further secondary homogeneous nucleation along the final rotor stage.

Droplets in the last stage are entrained with sizes that are generally greater than 100 μm and have a considerable slip relative to the vapor. As is shown in the Fig.(1) the path of the
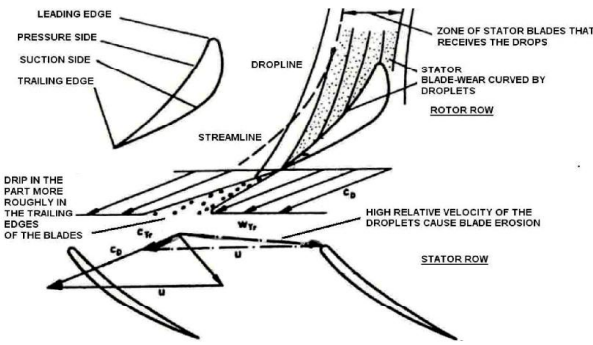
Figure 1 Droplet course in the channel of blade cascades.

droplets in the channel of the blade cascades can be different [3]. The part of the moisture that is deposited on the blade surface, form a fine liquid film less than 0.1 mm, which, under the action of the friction forces of the steam flow, is slipped slowly towards the trailing edges and impacts against the suction side of the rotor blade [4].

The erosion can affect a considerable percent of chord profile (25%) causing the loss of portion of the blade. Insignificant erosion even makes change the vibration characteristics and resistance of the blades, been the cause of the breakage and low performance of the stages.

Erosion is of significance when drops impact on a hard surface. The continuous impact of drops forms a liquid film on the surface, which would attenuate the forces during the impact at subsequent times and, hence, the long-term wear on the surface [5].

The existence of water droplets formation presents practical difficulty concerning the behavior of steam in turbines. The impact of droplets on the blade surfaces is essentially based in the range of particles with sizes affected by the forces of inertia. These droplets cannot follow the stream of the steam flow in the blade cascade. The water becomes to escape from the stator blades in form of large drops, generally toward the suction side of the following rotor blade, causing there erosion problems.

The movement of water on the blade channel is the distribution of velocity and local density of steam. As condition for the calculation of the drop movement, first the velocity field of the steam in the blade cascade must be known. The calculation of the velocity distribution in the subsonic region permits the treatment of the mesh in the curvature. In these cases for the calculation of the velocity field in the mesh a procedure suitable for transonic conditions is needed.

COMPUTING METHOD

For an unrestricted calculation of the transonic stream, the time step procedure is suitable. In future, the ideal gas with constant relationship of the specific thermal capacities k is accepted for a medium of flow, and the isentropic state change and the well-known gas dynamics basic relations are described. If this condition prevails in $t = 0$ and if is kept as constant $t > 0$, then an iterated transition adjusts itself to a stationary condition, which is the flowing state searched. The theory determines this temporal transition, which offers the advantage that the problem receives a parabolic character everywhere in

the field, since the solution in the time $t + \Delta t$ from t, is sufficiently closed in the final state. However, first the law of change of state is accepted as polytropic, in accordance with

$$p_\kappa = p_1 \left(\frac{\rho_\kappa}{\rho_1} \right)^n , \qquad (1)$$

the index 1 always refers about flow condition. The polytropic exponent n is given by

$$\frac{n}{n-1} = \frac{1}{\eta_p} \frac{\kappa}{\kappa-1} . \qquad (2)$$

In each case, the base factors serve to the Mach number and speed sound in the flow, which provide the index 1, and the small quantities with the index R.

$$a_1 = \sqrt{\kappa \frac{p_1}{\rho_1}} , \qquad (3)$$

$$M_1 = \frac{c_1}{a_1} , \qquad (4)$$

$$p_R = p_1 \cdot \left(1 + \frac{\kappa-1}{2} \cdot M_1^2 \right)^{\frac{\kappa}{\kappa-1}} , \qquad (5)$$

$$\rho_R = \rho_1 \left(\frac{p_R}{p_1} \right)^{\frac{1}{\kappa}} . \qquad (6)$$

A condition for the application of the Eq.(6) is that the function of the mesh and the leading edge crossing compression shocks are weak.

It is accepted that in the flow, the angle β_l takes place. In the zone of flow of the mesh profile the velocities of the compressible stream with the given variables of state become pressure and density of inlet and outlet plane after the relationship

$$c^2 = \frac{2\kappa}{\kappa-1} \cdot \frac{p_R}{\rho_R} \cdot \left[1 - \left(\frac{p}{p_R} \right)^{\frac{\kappa-1}{\kappa}} \right] , \qquad (7)$$

is calculated. In the outline of the profile the condition is fulfilled if the velocity is tangential. Thus is possible if the velocity, pressure and density of the fields regarding the size in the inlet and outlet plane linear can be interpolated.

In the closest section l_{min} the exit angle β_2 in the following form can be written:

$$\sin \beta_{2is} = \frac{l_{min}}{t} \left(\frac{\kappa+1}{2} \right)^{-\frac{1}{2}\frac{\kappa+1}{\kappa-1}} \left[M_{2is} \left(1 + \frac{\kappa-1}{2} M_{2is}^2 \right)^{-\frac{1}{2}\frac{\kappa+1}{\kappa-1}} \right]^{-1} , \qquad (8)$$

The velocity, pressure and density fields are introduced as initial values for the iterative methods. The pressure sizes p_1 and p_2 are well-known from the given state of flow. Also is known c_1 and c_2 in each case with p_1 and p_2 from the Eq.(7).

Conservation laws

In Eq.(2) the polytropic efficiency η_p considers the friction in summary way and allows to understand the friction strength

constantly distributed in the area. It can suppose the field strength per mass unit, in the direction of the increasing meridian coordinate against the each point n´. Then is

$$\delta F = \left(1 - \eta_p\right) \frac{|\Delta p|}{\overline{\rho}\Delta n'}, \qquad (9)$$

where $\overline{\rho}$ is an average value of the density. Thus, the polytropic exponent n and the friction force δF can be determined for a given η_p. For the transition the continuity equation applied on the volume element ΔV_k reads

$$\frac{\partial \rho_\kappa}{\partial t} \frac{1}{\Delta V_\kappa} \int \rho\left(c_x \sin\gamma - c_y \cos\gamma\right) b ds \cdot \qquad (10)$$

Thus the impulse equation

$$\frac{\partial (\rho_\kappa c_{xk})}{\partial t} = \frac{1}{\Delta V_\kappa} \int \left[\rho\left(c_x \sin\gamma - c_y \cos\gamma\right)c_x + p\sin\gamma\right] b ds - \rho_\kappa \delta F. \quad (11)$$

In the same way the impulse equation in tangential direction is deduced itself.

$$\frac{\partial (\rho_\kappa c_{xk})}{\partial t} = \frac{1}{\Delta V_\kappa} \int \left[\rho\left(c_x \sin\gamma - c_y \cos\gamma\right)c_y + p\cos\gamma\right] b ds \quad (12)$$

The circulations can be represented as sums of the connected distances Δs_{ij}, in each case are multiplied by the average value integrating along the distance. The Eq.(16) is

$$\frac{1}{2}\sum \left[\rho_i(c_{xi}\sin\gamma_{ij} - c_{yi}\cos\gamma_{ij})\Delta b_i + \rho_j(c_{xj}\sin\gamma_{ij} - c_{yj}\cos\gamma_{ij})\Delta b_j\right]\Delta s_{ij},$$

where γ_{ij} is the angle of inclination of the side that connects the points designated with i and j. For the representation of the calculation procedure, the dimensionless formulation may be introduced in addition of the following definition:

$B = \dfrac{\delta b}{\delta b_1}$: Stream width.

$S_{ij} = \dfrac{\Delta s_{ij}}{l_a}$: Length of the element.

$K_\kappa = \dfrac{\Delta V_\kappa}{l_a^2 \delta b_1}$: Volume of the element.

$r = \dfrac{a_1 t}{l_a}$: Time.

$P = \dfrac{p}{\rho_1 a_1^2 M_1}$: Pressure.   (13)

$\sigma = \dfrac{\rho}{\rho_1}$: Density.

$\Phi = \dfrac{l_a \delta F}{c_1^2}$: Friction Force.

$U = \dfrac{\rho c_x}{\rho_1 c_1}$: Axial Velocity.

$V = \dfrac{\rho c_y}{\rho_1 c_1}$: Peripheral Velocity.

On the basis of U, V, P and σ into all points in the mesh in a stream value τ the temporal derivatives can be calculated

$$U_\kappa(\tau + \Delta\tau) = U_\kappa(\tau) + \frac{\partial U_\kappa}{\partial_\tau}\Delta\tau, \qquad (14)$$

$$V_\kappa(\tau + \Delta\tau) = V_\kappa(\tau) + \frac{\partial V_\kappa}{\partial\tau}\Delta\tau, \qquad (15)$$

$$\sigma_\kappa(\tau + \Delta\tau) = \sigma_\kappa(\kappa) + \frac{\partial\sigma_\kappa}{\partial\tau}\Delta\tau, \qquad (16)$$

and the magnitude of U_k, V_k, σ_k in the time $\tau + \Delta\tau$ are associated to P_k. The consequence to receive the function values is the smooth, in order to avoid instabilities in the calculation, on which the calculation around a further interval $\Delta\tau$.

BALANCE EQUATIONS

In the proximity of the surface of the wet body the drop movement is affected by the velocity profile of the boundary layer. The integral condition for the impulse as the force equilibrium in x-direction, averaged over the boundary layer thickness δ:

$$\frac{d\delta_2}{dx} + \delta_2\left(2 + \frac{\delta_1}{\delta_2} - M_\delta^2\right)\frac{du_\delta/dx}{u_\delta} - \frac{c_f}{2} = 0, \qquad (17)$$

with the definitions

$\delta_1 = \int_0^\delta \left(1 - \dfrac{\rho u}{\rho_\delta u_\delta}\right)dy$:   Displacement thickness.   (18)

$\delta_2 = \int_0^\delta \dfrac{\rho u}{\rho_\delta u_\delta}\left(1 - \dfrac{u}{u_\delta}\right)dy$:   Pulse loss thickness.   (19)

$c_f = \tau_w / \dfrac{\rho_\delta}{2}u_\delta^2$:   Friction coefficient.   (20)

$\tau_w = \left(\mu \dfrac{\partial u}{\partial y}\right)_{y=0}$

$M_\delta = \dfrac{u_\delta(x)}{a_\delta(x)}$:   local Mach number.   (21)

Motion of individual drop

The general beginning for the calculation of an unsteady drop movement proceeds from the force equilibrium:

$$\sum \vec{K} = 0. \qquad (22)$$

The sum of all forces around a drop is zero. The resulting strength is developed itself generally

$$\sum \vec{K} = \vec{W} + \vec{T} + \vec{A} + \vec{G} + \vec{W}_M + \vec{K}_P + \vec{K}_E. \qquad (23)$$

Therein mean

$\vec{W}$: Strength.

$\vec{T}$: Force of inertia.

$\vec{A}$: Lift strength.

$\vec{G}$: Gravity force.

$\vec{W}_M$: Strength due to additional movement along steam mass.

$\vec{K}_P$: Field strength due to a pressure gradient.

$\vec{K}_E$: Electrostatic forces.

In case of the movement of small drops in steam flow the relationship is simplified. The lift strength can be neglected if the densities of drops and flow medium are of large order. The force of gravity is neglected if cannot exert noticeable influence on the velocity. Finally, the electrostatic forces can be neglected in case of the steam flow.

The strength becomes

$$\vec{W} = c_W \cdot \frac{\rho}{2} \cdot w_{rel} \cdot \vec{w}_{rel} \cdot \pi \cdot r_T^2 , \qquad (24)$$

and the force of inertia is

$$\vec{T} = -m_T \cdot \frac{d\vec{w}_T}{dt} . \qquad (25)$$

Here c_w is the coefficient of drag, ρ is the steam density, r_T the drop radius and w_{rel} the relative velocity between steam and drop in accordance with

$$\vec{w}_{rel} = \vec{w}_D - \vec{w}_T . \qquad (26)$$

The drop mass m_T is calculated

$$m_T = \frac{4}{3} \pi \cdot \rho_T \cdot r_T^3 . \qquad (27)$$

From this the general differential equation for the drop movement

$$m_T \frac{d\vec{w}_T}{dt} = c_W \frac{\rho}{2} \cdot \vec{w}_{rel} \cdot w_{rel} \cdot \pi \cdot r_T^2 , \qquad (28)$$

the drops with a spherical shape are due to the force by the surface tension.

For the calculation of drop courses the velocity field must be given by drops moving with the help of the Eq.(27).

The droplet impact on the blade surface is essentially based in the range of particles with sizes affected by the forces of inertia. These droplets cannot follow the stream of the steam flow, as is showed in Fig.(2) by the courses $\psi_{T,i}$ and $\psi_{T,i+1}$ (remarked lines) in the blade channel. These large droplets become to escape from the stator blades, generally toward the suction side of the following rotor blade, causing there erosion problems. The drop distribution in the mesh outlet level is represented on the basis of a fundamental flow pattern in a blade channel. It provides that the drops before the mesh are homogeneous distributed and that the drop velocity and steam velocity are identical to c_{TO} and c_{DO} here. The stream condition continues homogeneous by p_0 and Y_0. The drop radius is r_{T0}.

Between the two drop courses $\psi_{T,i}$ and $\psi_{T,i+1}$ in the distance $\Delta t_{0,i}$, which are identical to the steam streamlines in the mesh and two surfaces parallel to the indication level $\Delta t_{0,1}$, the water mass flow is

$$\dot{m}_{T0,i} = Y_0 \cdot \dot{m}_{0,i} , \qquad (29)$$

whereby $\dot{m}_{0,i}$ is the total mass stream between the streamlines and Y_0 is the moisture content in the inlet. The number of drops in the flow is then

$$\dot{n}_{0,i} = \frac{\dot{m}_{T0,i}}{\frac{4}{3} \pi \cdot r_{T0}^3 \cdot \rho'} . \qquad (30)$$
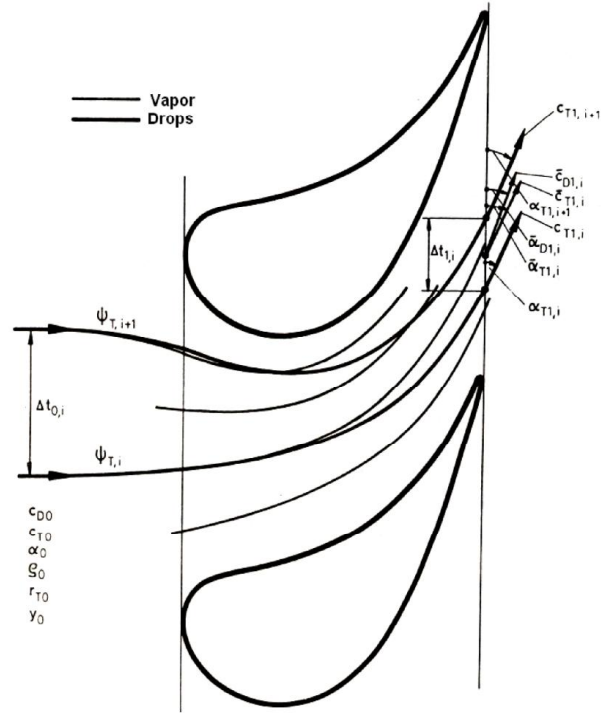

Figure 2 Moisture distribution in the mesh outlet plane.

A certain part of drops which flow between the pressure side of the blade enter in contact with the profile, all these drops are closed strongly in a very thin layer on the profile surface and are concentrated finally along the flow in a narrow volume of the trailing edge, forming a water film. The remaining drops leave from the mesh with a velocity which deviates in size and direction from the local steam velocity. In addition, they are distributed irregularly over the division. The local moisture content behind the mesh is

$$Y_{1,i} = \frac{\dot{m}_{T1,i}}{\dot{m}_{T1,i} + \dot{m}_{D1,i}} . \qquad (31)$$

Therein $\dot{m}_{T1,i}$ represents the quantity of water in the level 1 by the cross section of the level 1 between the courses $\psi_{T,i}$ and $\psi_{T,i+1}$. The zone of steam flow is presented from the calculation of the transonic stream. The quantity of water between the two drop courses in the level 1 is calculated by

$$\dot{m}_{T1,i} = \dot{n}_{1,i} \cdot \frac{4}{3} \pi \cdot r_{T1}^3 \cdot \rho_1' . \qquad (32)$$

The mid drop course in the steam flow between the courses $\psi_{T,i}$ and $\psi_{T,i+1}$ in the level 1 is:

$$\dot{m}_{D1,i} = \rho_1'' \cdot \bar{c}_{D1,i} \cdot \sin \bar{\alpha}_{D1,i} \cdot \Delta t_{1,i} \cdot 1 \cdot \cos(\bar{\alpha}_{T1,i} - \bar{\alpha}_{D1,i}) . \qquad (33)$$

Steam has a medium velocity $\bar{c}_{D1,i}$ in the level 1. This direction is given by $\bar{\alpha}_{D1,i}$. The term $\cos(\bar{\alpha}_{T1,i} - \bar{\alpha}_{D1,i})$ of the steam quantity is referred to the drop course direction.

Drop distribution

First, the lattice geometry and the mesh organization of the computational net are given. An estimated initial distribution of the searched flow parameters σ, P, U and V must be entered. With the progress of time, if the boundary conditions are kept constant, the distribution is approximately iterated more and more to the stationary solution of the zone of flow. If the difference of the flow functions is successively under a barrier which can be given, the approach to the stationary final state is terminated.

The solution functions σ, P, U and V of the iterated final state, must be converted in ρ, p, c_x and c_y. The first parameter ρ_1 is selected in such a way that the given pressure P_1 of the Eq.(1) fulfils the turbine design. Thus, inlet and outlet Mach number and the exit angle results from the calculation.

The positions of drops are relevant for the calculation of the drops distribution, and are calculated with a subroutine.

RESULTS

The approximate results of calculation to the stationary solution was effectuated several times and examined. For the demonstration of the possibility of the inflow angle changes and the influence of the stagnation point situation, an example of calculation for the lattice with the polytropic efficiency is presented. The results in Fig.(3) to (7) are showed. There is a clear difference between suction and pressure velocity and proves the effects of the rear stagnation point in the flow.

In Fig.(7) the border drop course for the blade pressure side is showed, i.e. the course of the drop affects directly before the outlet of the stator surface. The distance of the border drop course from the blade increases directly with the drop radius, showing the drops ejected to the pressure side directly.

CONCLUSIONS

The proceeding for a stator blade mesh by systematic deformations for transonic flow conditions, with respect to smaller drops of water, is introduced. It has been shown that the large secondary drops in the saturated steam stream are essentially responsible by the negative consequences. Being the liquid impact erosion a major technological problem in steam turbines, the interaction of drops, droplets or clusters, plays an important role in the low pressure section. The understanding of drops collision is pertinent due to the erosion that appears on the blades by the repetitive impact of the great droplets causes damages in the surface of them and, therefore, changes in the flow conditions of the stage.

With the calculations can be accomplished, whose results are communicated to the pressure and Mach number distribution, direction of flow and streamlines in the field, and drops distribution in the outlet of the stator blade mesh.

In the steam turbines is not possible to predict the real situation of the droplet size distribution in a correctly form, only with the turbine geometry and the inlet and outlet steam conditions, but the set of available information present in this work can be a tool to understand the distribution of droplets and the damages caused by them on the blades. Prevention of turbine blade erosion, which is mainly caused by the collision of the secondary droplets with the rotor blades, is the main motive of this research program.
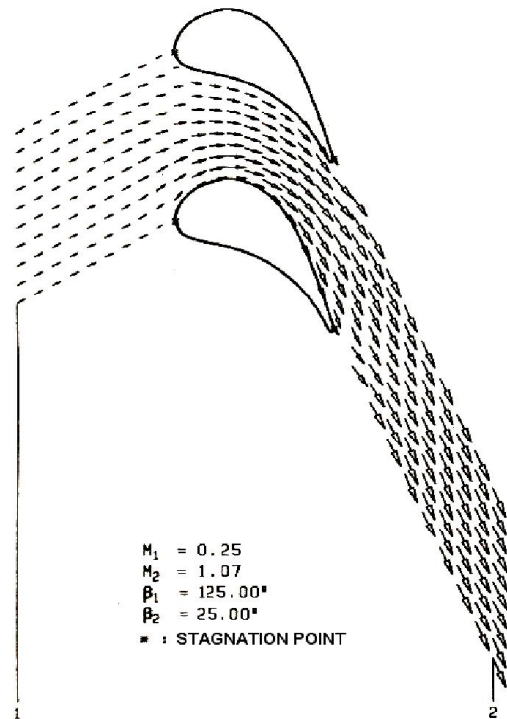

$M_1 = 0.25$
$M_2 = 1.07$
$\beta_1 = 125.00°$
$\beta_2 = 25.00°$
▪ : STAGNATION POINT

Figure 3 Direction of flow in calculated zone.

$M_1 = 0.25$
$M_2 = 1.05$
$\beta_1 = 120.00°$
$\beta_2 = 25.00°$
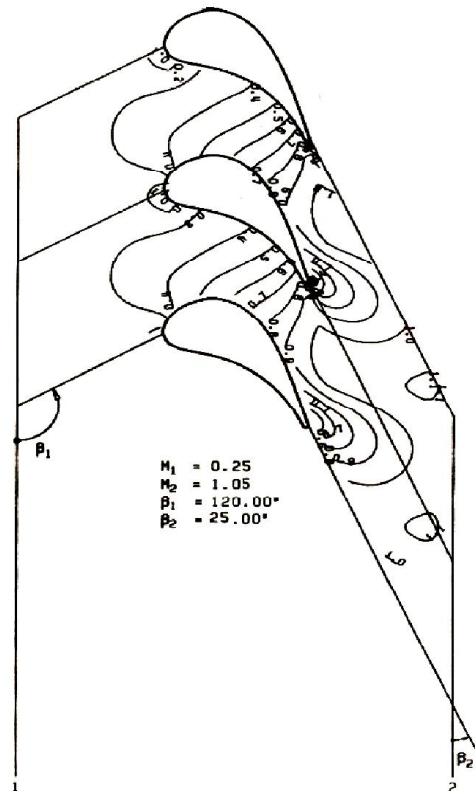
Figure 4 Velocity and pressure pattern

$M_1 = 0.20$
$M_2 = 1.07$
$\beta_1 = 120.00°$
$\beta_2 = 23.87°$

Mach number M ---------
Pressure P/P_{01} ————
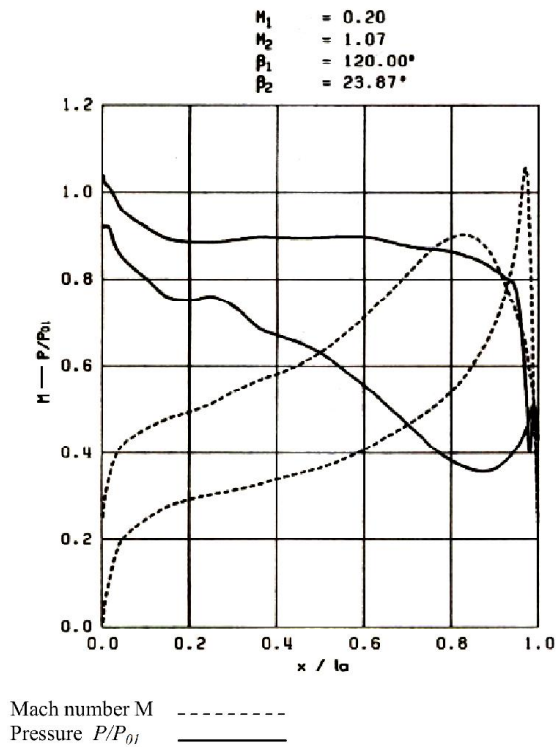
Figure 5 Velocity and pressure pattern.

$M_1 = 0.20$
$M_2 = 1.07$
$\beta_1 = 122.00°$
$\beta_2 = 23.87°$

———— : $h_{TOT}, \varkappa = 1.4$
-------- : Suction side
- - - - : Pressure side

Figure 6 Total enthalpy.

$M_1 = 0.20$
$M_2 = 1.07$
$\beta_1 = 122.00°$
$\beta_2 = 23.87°$

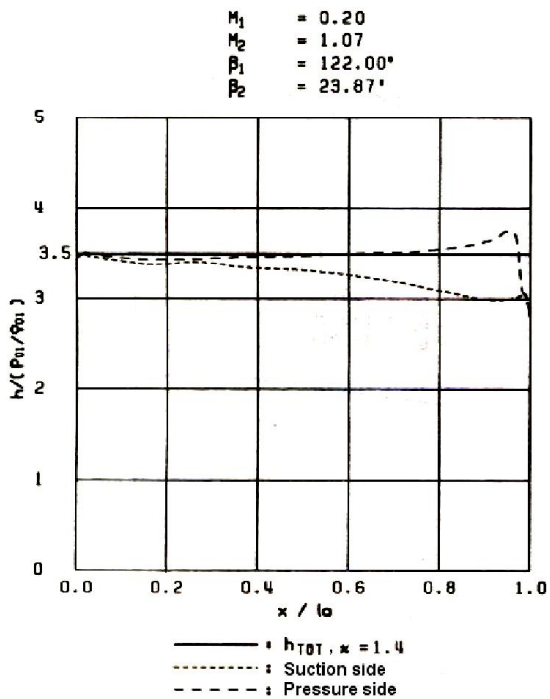———— : $h_{TOT}, \varkappa = 1.4$
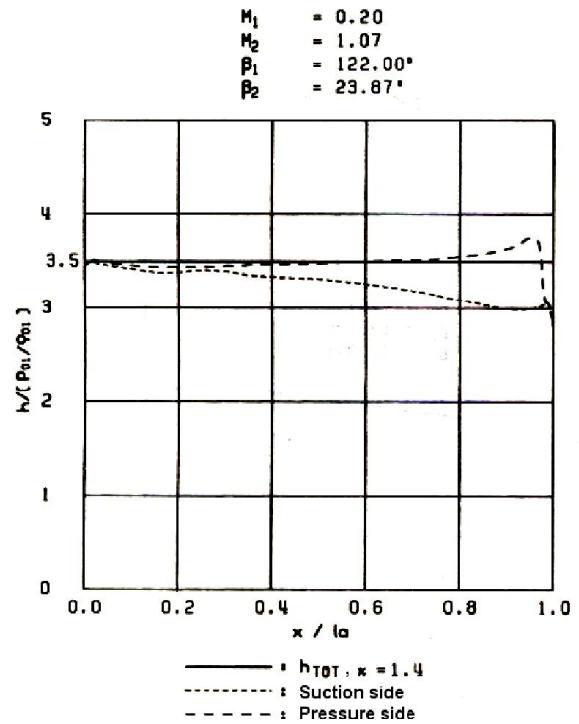-------- : Suction side
- - - - : Pressure side

Figure 7 Streamlines in blade cascades.

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