Optimization of stator blade profile design for last stages of steam turbines based on the features of coarse droplets movement in inter-blade channels

R A Alekseev, V G Gribin, A A Tishchenko, I Yu Gavrilmov, V A Tishchenko and V V Popov
National Research University “Moscow Power Engineering Institute”, Krasnokazarmennaya 14, Moscow, 111250 Russia
E-mail: tishchenkoAA@mpei.ru

Abstract. Results of the investigation of coarse droplets movement in steam turbine blade passages are presented in the paper. The structure of generated streams of secondary droplets was considered. The analysis of the effect of these streams on the liquid film formation on the blade surfaces was performed. On the basis of obtained data, several recommendations for blade design operating in wet steam conditions were formulated. They were used to optimize the baseline profile geometry in order to control the coarse droplets streams and provide the increasing of liquid film suction effectiveness. The numerical and experimental comparison of the baseline and optimized geometries was performed.

1. Introduction
One of the main problems for blades operating in wet steam flow is the erosion wear. This process is caused by the impact of coarse erosion-hazardous droplets with the blade surfaces. The main source of these liquid particles is the water film separation and it’s further breakup downstream the blade trailing edge. The effective way of decreasing the intensity of material destruction is to arrange the suction of liquid film from the surfaces of stator blades in the last stages. The development of these methods has a big reserve in increasing their effectiveness. Experimental studies on operating wet steam turbine [1] have shown that the effectiveness of film suction depends on the different flow regime parameters. They influence the way how droplets interact with the surfaces of vane passages and take part in liquid film-forming. In [2] the complex process of the droplet impact on a surface has been studied. The main parameters of this interaction are the droplet impact velocity (normal to surface) and its mass (or diameter). The shape of a vane blade profile is curvilinear, as a result, the conditions of droplets impact are varied by the location. So, the optimization of blade geometry may be a very effective way to increase the effectiveness of liquid film suction systems in the vanes passages. At the moment the genetic optimization algorithms are widely used to increase the aerodynamic and thermodynamic (according to steam condensation and droplets nucleation) effectiveness of turbine blades [3, 4]. But these methods are limited in solving the current problem because it is still very difficult to obtain a full understanding of the features of liquid film formation due to the droplets deposition on the surfaces. This is connected with the complex behavior of the liquid phase movement in inter-blade channels. It is especially true for coarse droplets as their trajectories are sufficiently deviating from the steam streamlines and the impact of such drops on a surface may cause different scenarios. Nowadays we have
only an indirect representation of the processes with coarse drops taking place in a blade passage [5].
The experimentally obtained knowledge about coarse droplets movement and their interaction with
blade surfaces with further deposition and liquid film formation may allow to optimizing profile
gradient to control droplets streams and increase the effectiveness of liquid phase suction systems in
the last stages of steam turbines.

In this paper, we briefly discuss the results of a complex study of wet steam flow in turbine blade
cascades. For this propose the experimental investigations of droplets movement in blade passages were
performed [6] at different flow conditions. For this study, the flow laser diagnostics system with PTV
method was used. The obtained data were analyzed by the post-processing method developed in [7]. It
allows determining different streams of droplets originated from different zones in a blade passage. To
change the geometry of the blade profile, the parametric blade design method was developed [8]. It is
based on the Bezier curves. Summarized experimental and numerical results were used to optimize the
geometry of a baseline blade profile. Here we present the main outcomes of our work as a result of
which the profile geometry for wet steam flow has been developed.

2. The structure of droplets streams in a vane blades passage

In the current study, we consider the movement of coarse droplets which trajectories significantly
deviate from the steam streamlines. So, they interact with the blade passage walls and participate in the
formation of the liquid film. For the flow conditions specific for the last stages of steam turbines
diameter of such droplets is bigger than 5 μm. Recent experimental studies performed with wet steam
in a turbine blade passage have shown that there are several streams of coarse droplets [6, 9]. They are
generated due to the interaction of liquid particles with the blade surfaces and affect the characteristics
droplets upstream the rotor blades. Figure 1 shows common streams of coarse droplets in a blade
passage. Primary droplets (1) come from the upstream turbine stage and interact with the surfaces. As a
result, the liquid film (3) is formed on the pressure and suction sides of the blade. The value of the
impact energy of these liquid particles during the collision (with the surface) may be sufficient to
generate the secondary droplets due to the splashing process. So, the part of a primary droplet mass is
involved in a liquid film formation and another one leaves the surface as secondary droplets. As a result,
two streams of coarse secondary droplets take place in the blade passage: a “fountain” (2) generated at
the leading edge and a “two-phase boundary layer” (5) along the pressure side. Another source of coarse
droplets is the separation and the breakup of the liquid film from the blade surface (6). This process at
the trailing edge generates the erosion-hazardous droplets with big diameters. They collide with rotor
blade surfaces at high relative velocities and perform the material wear.

![Figure 1. Structure of coarse droplets streams in a vanes cascade passage.](image)

So, the main aim of reducing the intensity of erosion process is to effectively remove the liquid film
from the blade surface. The experimental studies with the use of flow laser diagnostics systems have
shown that the streams of secondary droplets have a significant influence on the processes of the liquid
film formation [6]. A lot of different flow and geometry parameters have an effect on the trajectories of
these particles [10]: inlet angle of primary droplets, densities ratio (between gas and liquid phases),

geometry parameters of blade profiles, etc. On the basis of performed experimental studies results, three important factors should be mentioned.

The impact of the droplet on the blade surface or the liquid film should be considered for different zones of the blade. The conditions of this process (droplet impact velocity, droplet diameter, and impact angle) determine the growing of the liquid film mass flow rate. One can estimate the part of the primary droplet mass which leaves the surface in a form of secondary droplets [11]:

\[
\begin{align*}
\frac{M_1}{M_0} &= \min\{A\sqrt{Re_{on}}(We_{on} - We_{on*}); B\},
\end{align*}
\]

where \(M_0\) is the mass of primary droplet which impacts the surface; \(M_1\) is the mass of secondary droplets generated after the collision; \(We_{on}\) and \(Re_{on}\) are the primary droplet’s Weber and Reynolds numbers, defined by normal to surface component of droplet velocity; \(We_{on*}\) is the critical Weber number which determines the level of impact energy needed to produce the secondary droplets; A and B are the empirical constants. So, one of the main parameters which has a significant effect on the liquid film formation is the impact angle (between primary droplet velocity vector and the normal to the blade surface). Since the surfaces of turbine blades have a substantially curved shape, this quantity changes in a broad range. The impact angle also influences the initial direction of secondary droplets. The bigger its value for the primary droplet - the bigger this parameter for the generated particles.

The secondary droplets moving in a “fountain” (see figure 1 position 2) are originated at the blade leading edge. This area is characterized by minimal impact angles and relatively high impact energy. So, the most of the mass of primary droplets interacted with a leading edge leaves the surface in a form of secondary droplets. The leading edge of common vane cascade occupies about 8-15% of the pitch, so the mass flow rate of secondary droplets in the “fountain” is about 5-9% of primary droplets flow rate entering the cascade. This stream can significantly effect the liquid film formation. As shown in figure 1 secondary droplets in the “fountain” originated near the suction side cross the blade passage and can deposit on the pressure side near the trailing edge. As a result, the mass flow rate of the liquid film near the separation area (on a trailing edge) increases. This leads to growth of erosion-hazardous droplets downstream the trailing edge (see figure 1 position 6). It is impossible to remove liquid film in this area through the slots. Thus, the “fountain” of secondary droplets may have a very critical effect on the formation of erosion-hazardous droplets downstream the vane cascade.

As was shown in previous study [6], the “two-phase boundary layer” (see figure 1 position 5) consists of secondary droplets originated from the pressure side. They move along this surface and their diameters and velocity vectors vary in a broad range. The concentration of droplets in this area is the biggest downstream the vane cascade [10]. These liquid particles cannot be removed by the suction system due to their inertia and sizes of the slots. Coarse primary droplets can generate relatively big secondary particles in certain pressure side zones. This stream appears to be the second most important source of erosion-hazardous droplets in a steam turbine flow path (after the droplets formed during the liquid film breakup at the trailing edge).

3. Blade profile optimization

According to the experimental and numerical results, described above, one can figure out several recommendations about the geometry of the blade profile to optimize it from the point of view of coarse droplets movement. The radius of the leading edge should be reduced as it’s possible (the aerodynamic properties of the blade must be taken into account). The transition region from the leading edge to the suction and pressure sides has to be with the constant curvature in order to increase the impact angle and decrease the intensity of secondary droplets generation in this area (as a result, the most part of primary droplets mass will turn into the liquid film on the surfaces). The pressure side of the blade profile should be designed using the information about primary droplets trajectories with average diameters to provide a big value of impact angle for these liquid particles. As a result, the height of “two-phase boundary layer” will be decreased and it will be possible to remove it from the turbine flow path using suction slots.
Using these recommendations, the baseline profile geometry was redesigned in order to create the blade with high liquid film suction effectiveness. The parametric blade design method was used for this propose [8]. Figure 2a illustrates the comparison of baseline and optimized blade shapes. Numerical study of the droplets movement in these blade passages was performed. For this propose method described in [10] was used. It allows to simulate droplets movement in a steam flow and their interaction with surfaces and generation of secondary liquid particles. Recent results of this investigation are shown in figures 2b and 2c.

The features of the droplet's interaction along the blade pressure side surface are presented here. The values of the \( \phi_1 \) and \( \phi_2 \) are calculated accordingly:

\[
\phi_1 = \frac{m_{qi}}{m_{qf}} \quad (2)
\]
\[
\phi_2 = \frac{m_{qi}}{m_{s}} \quad (3)
\]

where \( m_{qi} \) is the mass of primary droplets interacted with the surface at current coordinate; \( m_{qf} \) is the total mass of droplets impacted on a whole pressure side wall; \( m_{s} \) is the mass of secondary droplets generated after the splashing process at current coordinate; \( s \) is the nondimensional coordinate along curvilinear axis matching the pressure side (0 – near the leading edge, 1 – near the trailing edge).

![Figure 2. Comparison of baseline and optimized profile geometries.](image)

From figure 2b it is can be seen that as for baseline as for optimized profiles the maximum mass of droplets impacting the surface is located near the trailing edge (at \( s = 0.8-0.9 \)). The increase of liquid particles mass flow ratio in this zone is connected with a “fountain” (see figure 1, position 2). As was mentioned above, the droplets of this stream cross the blade passage and interact with surface near the trailing edge. At the same time the ratio of secondary droplets generation (\( \phi_2 \)) in this zone is minimal - about only 30% of primary droplets mass leave the surface (see figure 2c). So, the “fountain” of secondary droplets for both profiles intensifies the liquid film formation. And this water film cannot be removed by the suction slots. In the case of optimized geometry, the extremum of \( \phi_1 \) shifts to the leading edge (on 10% of pressure side length, see figure 2b) and the intensity of droplets mass flow impacted the surface in this area is decreased (by about 20%).

4. Experimental investigations

The experimental investigations for baseline and optimized profiles were carried out. The flat cascades of vane blades were manufactured and tested on the experimental rig which allows studying the flow of superheated, saturated and wet steam in elements of steam turbines flow paths. The main goal of the study is to compare the structure and characteristics of coarse droplets streams in blade passages and to confirm the proposed recommendations of blade profile geometry optimization. The experimental rig and scheme of measurements are presented in figure 3. The laser diagnostics system with PTV method
was used to study the droplets velocity vectors fields in the blade passages. The wet steam flow in the blade passage is illuminated by a plane laser knife formed by a dual impulse laser. It is directed through the endoscope into working part and illuminates droplets moving in the inter-blade channel. The PIV camera takes photos of them. The obtained droplets flow photos are used as initial data for the PTV method. This technique obtains irregular vector field for each pair of photos. In order to increase statistical significance of the results, 1000 photos were made for each studied condition. This allows detecting total amount of droplets approximately equal 20e6. Experimental investigations were performed for different flow conditions. The influence of theoretical Mach number, initial wetness, liquid to steam densities ratio were considered. In current paper we present the results for the regime with theoretical Mach number downstream the vane cascade 0.75 and initial wetness 4.5%.

The comparison of instantaneous vector fields obtained by the PTV method is presented in figure 4. One can clearly see the matched above coarse droplets streams – the “fountain” (1) and the “two-phase boundary layer” (2). Secondary droplets in the “fountain” are stratified by velocities due to the polydisperse composition of generated liquid particles. Droplets situated in the “two-phase boundary layer” have relatively small velocities and move along the pressure side surface.

**Figure 3.** Experimental rig (a) and the measurement scheme (b).

**Figure 4.** Instantaneous vector fields of liquid droplets.
Developed in [7] post-processing method was used to analyze experimental data, obtained by PTV method. The trajectories of droplets moving in the considered streams were determined. They are presented in figure 5 for droplets with the diameter over 5 μm. Obtained results confirm the numerical investigations about the controlling the stream of coarse droplets in “fountain”. The impact zone of these particles on the pressure side is shifted closer to the leading edge and becomes narrower for the optimized profile. The geometry of developed profile allows arranging the suction slots in this zone for preventing the increase of the mass flow rate in the liquid film. The redesign of the blade pressure side shape leads to change of initial angles of secondary droplets originated from this surface in the “two-phase boundary layer” (see green trajectories in figure 5). As a result, the height of this layer decreases which can be seen in figure 6. Here the distribution of height (h) along the pressure side surface is shown. The zone at \( \bar{s} = 0.0-0.45 \) corresponds to the “fountain” of secondary droplets moving in the area along the pressure side (see figure 5). They deposit on the wall and don’t move into the blade passage core.

![Figure 5. Experimentally obtained trajectories of droplets streams in the blade passage.](image)

![Figure 6. Distribution of “two-phase boundary layer” height along the pressure side.](image)

Conclusions
In the current study, we briefly presented the results of our investigations dedicated to the movement of coarse droplets in turbine blade passages and finding ways to control them by optimizing the blade profile geometry. The main streams of these droplets (as primary as secondary) have been identified. One can figure out two main features of droplets movement to have a significant influence on the liquid film formation and further erosion wear: the "fountain" of secondary droplets originated from the blade leading edge and the “two-phase boundary layer” along the blade pressure side. The obtained results were used to optimize the geometry of baseline blade profile to increase the effectiveness of a film suction system. As a result, for the new shape the thickness of “two-phase boundary layer” is decreased
and secondary droplets of the "fountain" deposit closer to the leading edge. It leads to increasing of liquid film mass flow rate removed from the turbine flow path and decreasing of droplets diameters generated downstream the blade trailing edge.

Acknowledgments
This study was supported by Russian Science Foundation (project No. 16-19-10484).

References
1. Hoznedl M, Tajc L, Bednar L 2012 Proc. of Baumann Centenary Wet Steam Conference (Cambridge)
2. Mundo C, Sommerfeld M, Tropea C 1995 Int. J. Multiphase Flow 21 (1) 151–73
3. Abadi S M A N, Ahmadpour A, Abadi S M N R, Meyer J 2017 J. Applied Thermal Engineering 112 157589
4. Giordano M, Congedo P, Cinnela P, 2009 Proc. Of 19th AIAA Computational Fluid Dynamics (San Antonio, Texas)
5. Watanabe E, Ohyama H, Tsutsumi M, Maruyama T, Tabata S 2012 Proc. of Baumann Centenary Wet Steam Conference (Cambridge)
6. Gribin V, Gavrilov I, Tishchenko A, Tishchenko V, Popov V, Khomyakov S, Alexeev R 2018 Proc. IMechE Part A: J.Power and Energy 232 452–60
7. Alexeev R A, Gribin V G, Tishchenko A A, Gavrilov I Yu, Tishchenko V V, Popov V V 2018 J. of Physics: Conf. Series 1128 012093
8. Alexeev R A, Tishchenko V A, Gribin V G, Gavrilov I Yu 2017 J. of Physics: Conf. Series 891 012254
9. Gribin V G, Tishchenko A A, Tishchenko V A, Gavrilov I Y, Sorokin I Y, Alexeev R A 2017 Power Technology and Engineering 51 82–8
10. Tishchenko V A, Alekseev R A, Gavrilov I Y 2018 Thermal Engineering 65 885–92
11. Yarin A, Weiss D 1995 J. Fluid Mech 283 141–73