Controlling the coarse droplets streams by blade profile shape modification in the last stages of steam turbines

V Tishchenko¹, R Alekseev¹, I Gavrilov¹, V Gribin¹, A Tishchenko¹

¹National Research University "Moscow Power Engineering Institute", Krasnokazarmennaya 14, Moscow, 111250 Russia

Abstract. This work is devoted to investigation of wet steam flow in steam turbines blade passages. The methodology of flow laser diagnostic system application in order to study the trajectories and parameters distributions of coarse droplets in wet steam flow is presented. Obtained data was used to fit mathematical model of coarse droplets generation (as a result of droplet interaction with the blade surfaces) to experimental results. The calculation performed with this model allowed to optimize the shape of stator blade profile in order to control the streams of coarse droplets and minimize their diameters downstream the cascade.

1. Introduction

Presence of a liquid phase in the steam flow is the feature of the work of steam turbine last stages. It imposes strict requirements on the reliability and efficiency of the last stages operation conditions. The generation of discrete liquid phase intensifies a number of negative processes that affect the parameters of the steam flow. Detailed experimental and numeric studies have shown that the efficiency of the last stages is determined by the thermodynamic processes of condensation on the surfaces of fine droplets (the diameter of which are less than 1 μm) [1]. These phenomena are well studied [2, 3] and may be modeled using modern CFD codes. At the same time, the reliability of the rotor blades is affected by erosion damage caused by coarse droplets (with diameter more than 10 μm) which are formed upstream in stator blades passages. Currently, the extraction of liquid films from blade surfaces and erosion-resistant materials are used to minimize the negative effects connected with this process. However, the experience of steam turbines operation shows, despite the effectiveness of these methods, erosion damage remains one of the most important problems that must be solved in order to design efficient steam turbine flow path [4]. The profiling of stator blades shape with the aim of controlling the coarse droplets streams in blade passages seems to be a very effective method in the combination with the traditional ways of erosion damage reduction. But in order to implement this technique the understanding of coarse droplets development processes in blade cascades is needed.

The generation of erosion-hazardous drops is a complex process, which is realized due to several mechanisms. At the moment, there is only indirect knowledge about the nature of the formation and motion of coarse drops in the blade passages of steam turbines. It is connected with the difficulties of experimental investigations. It imposes a number of limitations on the possibility of minimizing erosion damage and improving the reliability of the blade. The generalized behavior of coarse droplets streams in a blade passage is shown in figure 1 (according to [5]).
It should be noted that the formation and movement of the liquid phase particles (except the primary droplets) is virtually impossible to model, because a lot of factors must be taken into consideration for its mathematical description [6]. But from another side the droplets interaction with dry and wetted solid surfaces is studied well in idealized laboratory conditions. And there are a lot of statistical models that describe the processes of droplet impact on surfaces [7] with the further effects: rebounding, splashing, depositing. The experience of these models applications has shown that their free parameters can be fitted to real engineering systems [8]. The application of modern experimental approaches, based on flow laser diagnostics systems, allows studying the features of motion of erosion-hazardous droplets in more detail [9]. On the basis of obtained experimental data, parameters of statistical models can be determined for the conditions of wet steam flow in steam turbines. Formulated by this way mathematical model of motion and generation of coarse droplets, can be used to optimize the shape of stator blade profile in order to control the streams of coarse droplets and minimize the erosion damage of rotor blades.

Figure 1. The scheme of movement of liquid phase particles in the nozzle blade cascade.

2. The experimental facility and object of study
In order to obtain the behavior of droplets motion in the nozzle blade cascade, the experimental studies were performed. The investigations were carried out in the experimental facility Wet Steam Circuit (WSC) in the turbine laboratory of the Moscow Power Engineering Institute (MPEI). This experimental plant is used to study the flow of superheated, saturated and wet steam in stationary channels. The main feature of this rig – steam for experimental investigations is extracted from the operating steam turbine. It was designed in order to study the polydisperse coarse droplets movement in wet steam flow.

The object of study for current investigation was the flat nozzle blade cascade. The chord of the blades was determined on the basis of Reynolds number, and the number of blades is limited by the experimental facility dimensions. The geometry of the flat cascade, which consists of 5 blades, is shown in figure 2a.

In order to obtain the characteristics of liquid phase in the blade passage, laser diagnostic system “POLIS” was used. It implements the PTV (particle tracking velocimetry) method that allows to obtain instantaneous velocity vectors for each droplet detected by the method in studied flow domain. The optical scheme of laser diagnostic system is shown in figure 2b. 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 high-speed PIV camera takes photos of them. The obtained droplet 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 conditions. This allows detecting total amount of droplets approximately equal 20e6.
Operation conditions were controlled by measurement of total pressure \( p_0 \), total temperature \( T_0 \) and initial steam wetness \( y_0 \) upstream the experimental cascade and average static pressure \( p_1 \) downstream the blade cascade. Different operating conditions have been considered. In this article, we show results only for one of them: total pressure \( p_0 = 60000 \text{ Pa} \); theoretical Mach number downstream the nozzle blade cascade \( M_1 = 0.8 \); initial steam wetness \( y_0 = 3\% \); the liquid to vapor phase density ratio upstream the blade cascade \( \bar{\rho} = 2684.7 \). The \( \bar{\rho} \) parameter is determined as follows:

\[
\bar{\rho} = \frac{\rho_1}{\rho_g},
\]

where \( \rho_1 \)-initial liquid density, \( \rho_g \)-steam density.

\[\text{Figure 2. Geometry of the nozzle blade cascade (a); optical scheme of the laser diagnostic system (b).}\]
4. Mathematical model validation

In the current study we attempted to simulate the formation processes of secondary coarse droplets which are originated from the blade surfaces. The trajectories of coarse droplets were computed under the assumption that only aerodynamic force from the steam flow acts on the liquid particle. So the equation of motion is following:

$$\frac{1}{2}A_d C_x \rho_g |\vec{c}_g - \vec{c}_d| (c_g^2 - c_d^2) = \ddot{a}_d,$$

where \(A_d\) – cross-sectional area of the droplet; \(C_x\) - aerodynamic drag coefficient of spherical particles; \(c_g\) - velocity of the steam flow; \(c_d\) - droplet velocity; \(a_d\) - droplet acceleration; \(m_d\) - droplet mass.

Steam flow parameters were obtained by CFD code. In current study the reverse impact of liquid phase on main flow was not considered. According to flow operation conditions one can mark out 2 scenarios of droplets interaction with the blade surfaces [7]. They are presented in figure 4. The first one is a full splashing process: after the impact on the surface the primary liquid particle disintegrates and polydisperse stream of secondary droplets leaves the wall. At the second scenario a fraction of the droplet mass deposits on the wall and forms the liquid film.

![Figure 3](image)

**Figure 3.** Photo of illuminated droplets(a); instantaneous vector droplets velocity field (b); distribution of droplets velocities and angles in flow domain area (c).

![Figure 4](image)

**Figure 4.** Scenarios of droplet interaction with the surface.

In order to take into account these processes and calculate the interaction of primary droplets with the blade surfaces the Mundo model [11] was used. As input parameters for this model the initial velocity of the primary droplets (obtained by PTV method) and initial distribution of the primary droplets diameters (obtained by fingerprint probe) were used. The parameters of this model were fitted to the results obtained by PTV method. They were determined by comparing the parameters distributions of splashed droplets obtained by the experiment and the mathematical simulation. It is...
important to note that using such splashing model in wet steam flow conditions is a rough approximation. But this can help to estimate the behavior of the coarse droplets streams in turbines blade passages.

The results of droplets motion simulation for studied condition are presented in figure 5a. The primary droplets correspond to the red trajectories and the secondary droplets correspond to green trajectories. The structure of the liquid phase motion in the blade passage obtained by numerical investigation is in a good agreement with the experimental data (see figure 3a). As an example, the comparisons of experimental (obtained by PTV method) and numerical liquid particles parameters (velocity and angle) distributions in the area, marked as blue square in figure 5a, are shown in figures 5b and 5c. As one can see they don’t match but have the same behavior.

![Figure 5](image)

**Figure 5.** Results of simulation of droplets in the studied blade passage (a); comparison of droplets angles distribution (b); comparison of droplets velocities distribution (c).

5. **Strategy of the blade modification**

Based on the experimental and numerical data described in sections 3 and 4, one can pick out the following features of coarse secondary droplets movement in the blade passage.

Droplets in “fountain” which originate from the leading edge near the suction side leave the blade passage without interaction with the surfaces. So, they cannot be evacuated from turbine flow path by means of separation system.

Secondary droplets formed due to the splashing process on the blade pressure side, move inside the “two-phase boundary layer” and doesn’t leave it. The experiment investigation carried out in [12] has shown that separation slots on the blade surface effectively extract the liquid film but they are not able to evacuate these coarse droplets moving above the liquid film surface.

So, in the nozzle blade passage the coarse erosion-hazard droplets are generated and they cannot be influenced by the steam turbine liquid phase separation system. In order to minimize the erosion damage of rotor blades caused by these droplets we have to decrease the size of secondary droplets and increase the fraction of the primary droplet mass which deposits on the wall and forms the liquid film. It can be achieved by changing the shape of the blade profile. As was derived in [13], the part of primary droplet which remains on the wall after splashing process can be termed as:

$$\frac{M_{spl}}{M_0} = \min\left[2.9 \cdot 10^{-4}\sqrt{Re_n(We - We_c)}, 0.75\right],$$  \hspace{1cm} (3)

where $M_0$ - primary droplet mass; $M_{spl}$ - mass of secondary droplets generated by splashing process; $Re_n$ - droplet normal Reynolds number; $We$ - Weber number of droplet; $We_c$ - the critical Weber
number, defines the minimum droplet impact energy which is needed for intensification of splashing process. As one can see from the equation 3, in order to minimize the total mass of secondary droplets, the normal component of the primary liquid particle velocity vector should be decreased. This can be achieved by decreasing the angle between the surface normal and droplet velocity vector (see figure 4). This statement was used to optimize the geometry of nozzle blade profile. Modification of the baseline blade profile (see figure 2a) has been carried out by the blade parameterization method, described in [14]. Using the obtained in this study model of coarse droplets movement it is necessary to achieve the reduction of droplets diameters downstream the blade cascade. In figure 6 the modified profiles which meet this requirement are shown. These two modifications have a pronounced inlet area where the curvature of suction and pressure sides varies insignificantly (compared with the baseline geometry). The angle of the tangent to the surface in this region is close to average inlet angle of the primary droplets. The shape of the pressure sides for the modified profiles has a more uniform distribution of curvature in comparison with the baseline geometry. And the change in the tangent angle is closest to change in the angle of the droplet trajectories in the channel. As one can see from figure 6 the suction side shape of the modified profiles differs considerably. It was done in order to experimentally study the impact of the main flow pressure distribution on the processes of liquid film formation. It is important to note that in order to confirm the efficiency of the chosen approach the experimental investigations for these new profiles geometries are needed. It will be done in the future.

![Baseline profile](image)

**Figure 6.** Geometry of the modified profiles.

### 6. Conclusions

The following conclusions can be made:

1. The new method of experimental investigation of coarse droplets movement in steam turbines blade passages has been presented in this study.
2. Model which describes the interaction between droplets and solid surfaces has been fitted to experimental results with a good agreement.
3. The possibility of controlling streams of coarse droplets by optimizing the profile geometry is shown.

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