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Numerical modeling of the mechanism of coarse droplets deposition on surfaces of a steam turbine nozzle blade cascade

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Abstract. The numerical model describing the interaction of coarse droplets with the surfaces of inter-blade channels is presented. This method uses a statistical approach to simulate the splashing process of primary droplet after its collision with the wall. This technique was verified by experimental investigation of wet steam flow in the studied nozzle blade cascade using the flow laser diagnostics system and PTV method. Numerical studies of wet steam were performed in order to investigate the structure of liquid particles streams and liquid film formation conditions in the nozzle blade passage. The influence of primary droplets inlet angle and steam density on the liquid phase parameters has been considered.

1. Introduction

The erosion processes in the last stages of steam turbines remain one of the most important problems for energy generation business. It imposes a strict requirement on the reliability and efficiency of the turbine operating conditions. Erosion damage is caused by the presence of coarse liquid droplets in a flow. Moving at high relative velocities and colliding with the rotor blades they intensify the wear of surfaces. In order to decrease or degenerate this negative effect, different active and passive methods are used. The understanding of coarse droplets generation and movement may help to increase the efficiency of these techniques (for example, liquid film separation from the surface of nozzle blade). Despite the fact that a lot of studies have been performed on this issue [1, 2], we don't have enough information about the coarse droplets formation process in the steam turbines flow paths. It is connected with the difficulties of investigation of two-phase polydisperse flows. It is well known that the erosion damage is basically caused by droplets generated by liquid film disintegrated at the blade trailing edge [3]. Liquid film is formed by depositing of particles on the surfaces of inter-blade channels. And this process is accompanied by the complex splashing mechanism resulting in generation of secondary droplets leaving the surface [4]. So, in order to describe the liquid film flow and its disintegration at the blade trailing edge it is very important to develop a model which would correctly consider the impact of coarse primary droplets on the surfaces. This problem has been thoroughly studied for the cases of the collision of single drops with walls. On the basis of experimental investigations, the statistical models have been developed [5]. The application of these approaches to modeling the wet steam flow in steam turbines is extremely promising. Using modern experimental techniques of flow laser diagnostics systems [6] allows verifying this model.

In current study we present the numerical model which allows computing the impact process of liquid particles on the surfaces of nozzle blade cascade passages. It allows simulating the streams of coarse particles and obtaining the main parameters needed to calculate the liquid film flow on the surfaces (the water film modeling problem itself is not considered in this paper). This model was used to study the influence of some wet steam flow conditions on the behavior of liquid phase structure in the nozzle blade cascade passage.

2. Numerical model of coarse droplets motion and interaction with the surfaces

Current numerical model describes movement of droplets due to the interaction with the main flow (steam) and also an interaction of liquid particles with solid surfaces of steam turbines inter-blade channels. Only coarse droplets are taken into consideration. Their trajectories substantially deviate from steam pathlines. At the current stage of development this method works with two-dimensional flows and doesn`t consider the simulation of liquid film formed on the surfaces of blade passages.
The motion equation of liquid droplet is the following:

$$\frac{d\overrightarrow{c_d}}{dt} = \frac{3}{4}\frac{\mu_s C_x}{d_d^2 \rho_d}\overline{Re}_d(\overrightarrow{c_s} - \overrightarrow{c_d}), \quad (1)$$

where indices d and s denote droplet and steam parameters respectively, c is the velocity, d is the droplet diameter, μ is the dynamic viscosity, ρ is the density, C_x is the spherical droplet drag coefficient, $\overline{Re}_d$ is the relative droplet Reynolds number. All parameters of a steam phase in this equation were calculated using CFD code separately from equation (1). So, the main flow in this model is presented as a background for the processes described in this paper. The effect of liquid particles movement on the parameters of steam phase is not considered. Current model simulates the streams of liquid particles, that is to say, each trajectory corresponds to the certain number of droplets having the same velocities and diameters.
Current model describes 2 scenarios of the process of liquid particle colliding with a blade surface: full deposition of droplet (primary droplet) on a surface and formation of liquid film (see Fig.1a); and splashing process, which results in a fact that part of primary droplet mass leaves a surface in a form of secondary drops (see Fig 1b).

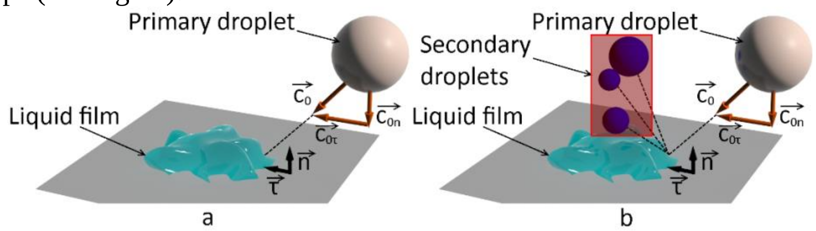

Figure 1. Full primary droplet deposition on the surface (a) and a splashing process (b).

The occurrence of one of these two processes depends on impact energy of primary droplet. It consists of primary droplet impact kinetic energy and surface tension energy of primary droplet and can be described as dimensionless parameter K [5]:

$$K = \sqrt{We_{0n}\sqrt{Re_{0n}}}, \quad (2)$$

where We_{0n} and Re_{0n} are primary droplet impact Weber and Reynolds numbers, respectively (defined by normal to surface component of droplet velocity c_{0n} in Fig. 1). If the value of K is greater than a certain critical value K_* - the slashing process takes place (see Fig 1b), otherwise primary droplet completely deposits on a surface.

In a case of splashing, the ratio of secondary droplets mass (M_1) leaving the surface to the mass of collided primary droplet (M_0) is estimated as follows [4]:

$$\frac{M_1}{M_0} = min\{A\sqrt{Re_{0n}}(We_{0n} - We_{0n*}); B\}, \quad (3)$$

where We_{0n*} is the critical Weber number (determined from equation 2 for $K = K_*$); A and B are the empirical constants. As a result of splashing process secondary droplets with different diameters and velocities vectors are generated. The number of secondary droplets streams formed after the splashing process is given as a constant value (for current study it is 6). For each stream of these droplets their size was determined randomly according to the Weibull probability distribution with the scale parameter [7]:

$$d_{max} = max\left\{\left(\frac{We_{0n*}}{We_{0n}}\right)^E; \frac{C}{We_{0n}}; D\right\}\frac{d_0}{F}, \tag{4}$$

where C, D, E, F are the empirical constants. And an initial velocity vector for each stream is determined as follows:

$$\overrightarrow{c_{\kappa\iota}} = c_{ifn}\vec{n} + \left[\left(0.12c_{0n} + c_{if\tau}\right)cos\Psi\right]\vec{\tau} + 0{,}8c_{0\tau}, \tag{5}$$

where c_{ifn} and $c_{if\tau}$ are random normal and tangential fluctuation of secondary droplet velocity (coordinate basis of vectors $\overline{n}$ and $\overline{\tau}$ is presented in Fig. 1): these values are obeyed the normal probability distribution; $c_{0\tau}$ is the tangential component of primary droplet velocity, Ψ is the random azimuth coefficient determined according the Nabier-Reitz probability distribution [8].

3. Object of study and validation of numerical model

In this paper the motion of liquid particles was studied in a flat turbine nozzle blade cascade which geometric parameters are presented in Fig. 2a. The computational domain is shown in Fig. 2b.

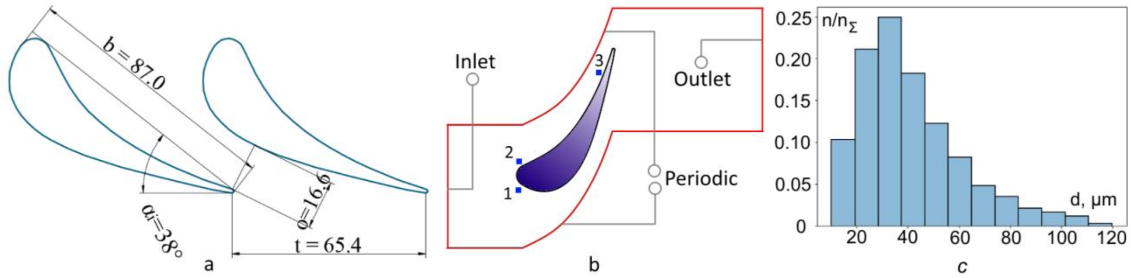

Figure 2. Geometry characteristics of the studied nozzle blade cascade (a), computational domain (b) and the spectrum of primary droplets diameters (c).

Experimental investigations were carried out in order to verify described mathematical model. They were performed using the experimental rig CWS designed to study the flow of wet steam in elements of steam turbine flow paths [9]. The spectrum of primary droplets diameters generated by this experimental plant is presented in Fig. 2c. The main aim of verification process was to compare liquid phase velocities in the studied blade passage. The laser diagnostic system with PTV method [10] was used to obtain velocity vectors of primary and secondary droplets in a wet steam flow. As an example, the comparisons of experimental and numerical results are presented in Fig. 3. The distributions of droplet velocity components in 3 zones (see square markers in Fig. 2b) are considered here. Gray contours represent experimental data and visualize a range of possible values of velocity droplet components in each area. Numerical results are presented as scatter plots for primary and secondary droplets. As one can see from Fig. 3 the results of simulation fit well the experimental data.

In this paper we use developed model to study the generation of secondary droplets streams in a nozzle blade passage. The effect of steam density ($\overline{\rho}_0$) and inlet angle of primary droplets (α_0) has been considered. The value of $\overline{\rho}_0$ is determined at the inlet of computational domain (see Fig 2b) as follows:

$$\overline{\rho}_0 = \frac{\rho_d}{\rho_s}. \tag{6}$$

The variation of $\overline{\rho}_0$ was achieved by changing wet steam total pressure at the inlet. The distribution of primary droplets sizes at the inlet corresponds to the one shown in Fig 2c. For all studied flow conditions the theoretical Mach number downstream the blade cascade was $M_{1t} = 0.70$ and inlet wetness $y_0 = 3\%$.

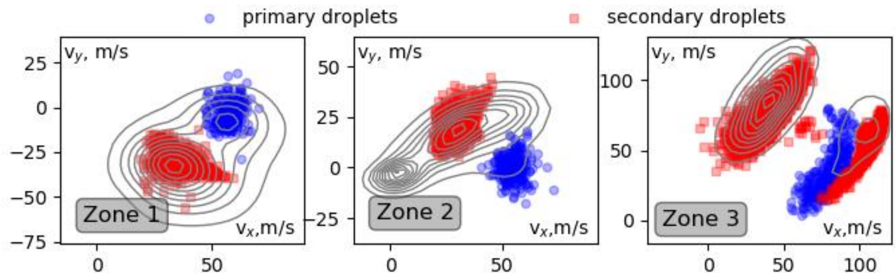

Figure 3. Comparison of numerical and experimental results.

4. Results of a numerical study

The structure of droplets streams in the studied blade passage is shown in Fig. 4, which presents trajectories of primary (red lines) and secondary (green lines) droplets. Two values of $\overline{\rho}_0$ at different drops inlet angles are considered. Current figure shows that all primary liquid particles are involved in the interaction with the profile walls and do not leave the blade passage. One can distinguish 3 specific zones of secondary droplets formation for all considered conditions (highlighted by blue squares in figure). The first one is a "fountain" of particles near the blade leading edge (areas 1 and 2). As can be seen from Fig. 4, blade pressure side is involved in an interaction with primary droplets on its entire length. Secondary droplets formed as a result of this process move along this surface and do not leave a certain region near it. We can say that they form a "steam-droplet boundary layer" (zone 3 in Fig. 4).

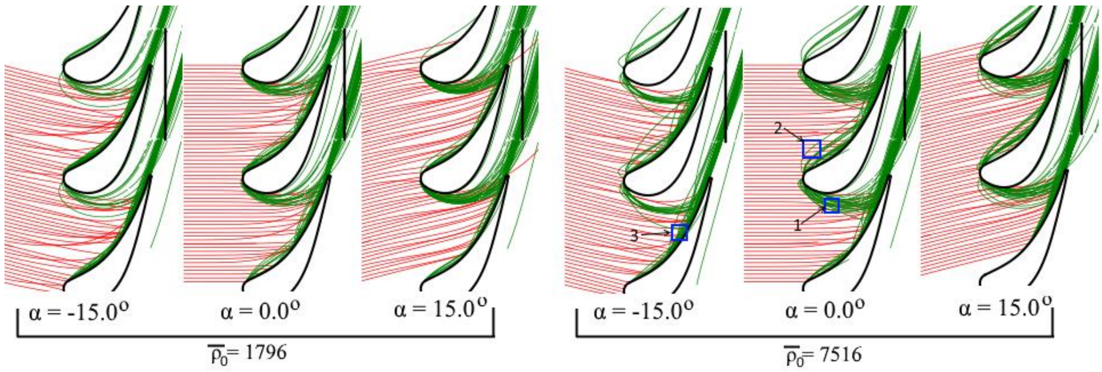

Figure 4. Primary and secondary droplets trajectories.

Variation of $\overline{\rho}_0$ (in other words variation of total pressure) causes the changes of the intensity of interphase interaction. So, at $\overline{\rho}_0 = 1796$ trajectories of droplets are more curvilinear and closer to steam pathlines than those at$\overline{\rho}_0 = 7516$. More detailed analysis of the influence of the $\overline{\rho}_0$ is shown in [6]. Changing of primary droplets inlet angle affects the conditions of secondary droplets formation during the splashing process. Analysis of the data in the Fig. 4 has allowed representing the structure of secondary droplets streams in general (see Fig. 5a). Thus, trajectories of droplets formed in "fountain" near the blade leading edge can be separated into 4 specific groups. Group 1 consists of liquid particles depositing on the blade pressure side in the area close to the trailing edge. Group 2 consists of liquid particles crossing a trailing edge wake downstream the blade. Group 3 consists of liquid particles moving in flow core both in the blade passage and in a stream downstream the blade. Group 4 consists of liquid particles formed on the leading edge close to the suction side. As a rule, they deposit on the suction side subsequently. Droplets moving in "steam-droplet boundary layer" (group 5 in Fig. 5a) form another stream of secondary liquid particles. These droplets continue to move in a narrow area downstream the studied blade cascade.

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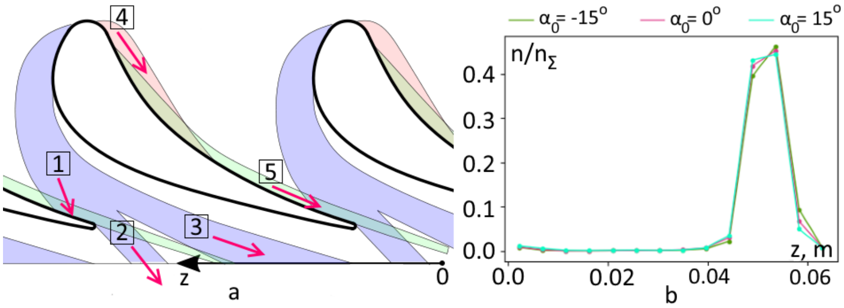

Figure 5. Structure of secondary droplets streams (a) and distribution of liquid droplets concentration downstream the studied blade cascade at $\overline{\rho}_0 = 3875$ (b).

The results of simulation have shown that the most concentration of droplets downstream the studied blade cascade takes place in the area of "steam-droplet boundary layer". It is shown in Fig. 5b, where the distribution of the n/n_Σ ratio along the line oriented in pitch-wise direction (this line and the corresponding coordinate system are shown in Fig. 5a) is presented. Here n is the number of droplets crossed the line in current coordinate; n_Σ is the total amount of droplets crossed the whole line. The "steam-droplet boundary layer" is situated within the range of $z = 0.45 - 0.062$.
The influence of the considered flow conditions on the mechanism of secondary droplets formation was studied for the blade pressure side. The distributions of the parameters of interaction between primary droplets and this surface for different liquid particles inlet angles are shown in Fig. 6.

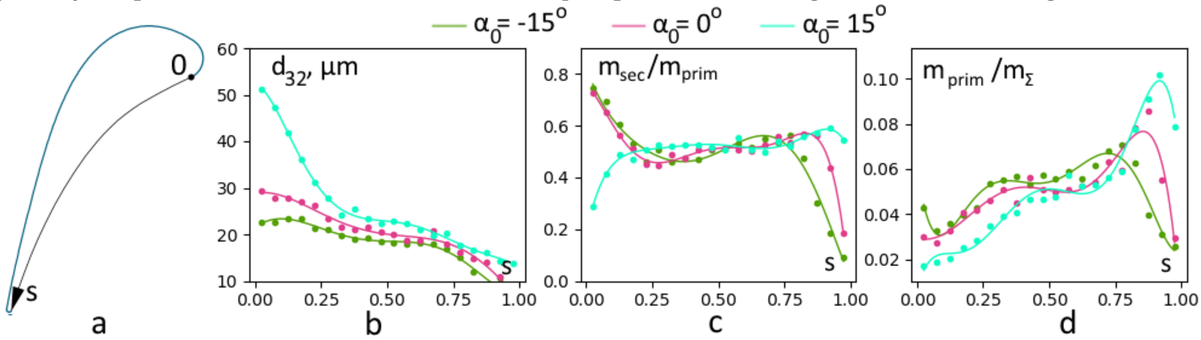

Figure 6. Distribution of splashing process parameters along the blade pressure side at different inlet angles and $\overline{\rho}_0 = 3875$

Here s is the dimensionless curvilinear coordinate coinciding with the blade pressure side (see Fig. 6a). As one can see from the presented data, the inlet angle of primary droplets has a significant influence on the interaction conditions. With the increase of α_0 Sauter mean diameter of secondary droplets formed after the splashing process near the blade leading edge (see Fig 6b at s = 0-0.25) increases. But the mass of liquid phase left the surface in the form of secondary droplets (m_{sec}) with respect to the mass of primary droplets impacted on the pressure side (m_{prim}) decreases (see Fig 6c). It means that the interaction between primary droplets and the surface in this zone at $\alpha_0 = 15^o$ causes the active formation of the liquid film. While for $\alpha_0 = -15^o$ and $\alpha_0 = 0^o$ the most mass of primary droplets converts to the secondary droplets formed after the splashing process. This is due to the fact that at $\alpha_0 = 15^o$ the normal component of the primary droplet velocity at the moment of collision is small. And for the most droplets the impact energy is smaller than the critical value needed for splashing process. Thus, only primary droplets with relatively high diameters (more than 80 μm) having a significant reserve of surface tension energy (see equation 2) are involved in the splashing process in this area. It causes a generation of secondary droplets with high diameters at s = 0-0.25.

Decreasing the α_0 leads to increasing of the intensity of secondary droplets formation (see Fig 6c) and decreasing of Sauter mean diameters of these particles (see Fig. 6b) in the considered pressure side section.

As one can see from Fig 6c, on the blade pressure side at s = 0.25-0.75 the value of primary droplets angle virtually has no effect on the process of generation of secondary droplets. The mass of deposited droplets (which forms the liquid film) is equal to mass leaving the pressure side in the form of secondary droplets.

The parameters distributions presented in Fig. 6 at s = 0.75 – 1 is quite interesting from the viewpoint of liquid particles streams which interact with this section of the blade pressure side. The intensity of secondary droplets generation at $\alpha_0 = -15^o$ and $\alpha_0 = 0^o$ significantly decreases (see Fig. 6c). This is due to the fact that this area of the blade pressure side is situated in an "aerodynamic shadow" for the most primary droplets originated from the inlet zone of the computational domain (see Fig. 2b). At the same time, as is obvious from Fig. 6d, in this zone the ratio of primary droplets mass which interacted with the pressure side (m_{prim}) to total mass of primary droplets collided with the whole surface (m_Σ) has a maximum. This behavior of considered distributions is explained by the fact that this section of the pressure side is located in the stream of secondary droplets of the "fountain" (see group 1 in Fig. 5a). They deposit on the surface without causing the splashing process. For the regime with $\alpha_0 = 15^o$ the area within the range of s = 0.75 – 1 is located outside the "aerodynamic shadow" so the intensity of splashing process remains constant (see Fig 6c).

Numerical study has shown that the main flow (steam) density variation has no significant effect on the conditions of droplets interaction with the blade surface.

5. Conclusions

The following conclusions can be drawn:

1. A numerical method which simulates the motion of coarse droplets in turbine blade cascades has been developed.
2. Inlet angles of primary droplets have a significant effect on the conditions of splashing processes occurred due to the collision of liquid particles with the surfaces. At the same time the variation of steam density virtually doesn`t influence this process.
3. When considering the process, one should pay attention on the area of blade pressure side near the trailing edge, where the intense liquid film formation occurs.

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