The main flow parameters characterising the liquid film suction process on the blade surface in a steam turbine

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Abstract. In this study, the process of liquid film suction from surfaces of steam blades is considered. The main goal of the investigation is to provide the list of nondimensional parameters characterizing this phenomenon. The complex nature of this process requires the consideration of various flow features occurring with the film. The influence of slot geometry, flow conditions and suction regimes are studied. As a result, the processes of film separation, transient breakup and interphase interaction are considered. Based on the obtained information, the set of nondimensional parameters is formulated. Their accounting will allow conducting correct research in laboratory conditions to transfer its results to a real turbine. The numerical modelling is performed to verify the findings, and the regime for the experimental rig providing the same non-dimensional parameters as for real turbine is selected.

1. Introduction

Steam turbines are widely used for power generation at combined cycles, nuclear and thermal power plants. One of the main features taking place in the steam turbine flow path is a condensation process. It causes generation of discrete phase in the form of droplets and liquid films. The appearance of the liquid medium significantly affects the efficiency and reliability of turbine blades working at these conditions. One of the negative effects induced by the multiphase flow is erosion wear of blades surfaces. It is intensified by the collision of coarse droplets with solid walls of blades passages. Liquid films developed on the surfaces are the main source of particles involved in the erosion process.

The interchannel liquid film suction is used to reduce the intensity of this negative effect. The suction system utilizes slots on blade surfaces. Through these slots, the liquid film is evacuated from the turbine flow path. The main aim of developing the film suction systems is to increase the mass flow rate of the evacuated liquid phase and decrease the mass flow rate of the separated working body (main flow is steam). For these purposes, an experimental and numerical investigation should be performed.

In view of this problem, investigations have been performed in the full-size steam turbine [1], and in laboratory conditions [2, 3, 4]. Obtained results allow understanding the processes proceeding during the suction. Especially it concerns the problem of determination of the optimal shape and operating regime of a suction slot. Based on these data several recommendations have been suggested [3]. But the main question about experimental studies performed in a laboratory is how can results be projected into the real turbine conditions? Due to the complex behaviour of the two-phase flow in a turbine blade passage, one should take into account the observance of the main nondimensional...
parameters while performing the investigation. So, it is important to specify the conditions providing the correct transition of laboratory results into full-scale turbines.

In current work, the process of liquid film suction through the slot is considered. Based on the literature review, the main nondimensional parameters characterizing this phenomenon are formulated. Compliance with these parameters should provide the correctness of performed experimental investigations. This work presents the first stage of the study of the liquid film suction process. The results presented here are based on the literature review and numerical modelling results.

2. The process of liquid film suction from the blade surface
The liquid film suction through a slot is a complex process which is determined by features of the liquid and gaseous phase flow and their interaction. Additionally, the geometry of a slot and its operating conditions are sources of aerodynamic disturbance. The general scheme of the liquid film suction process is presented in figure 1. The liquid film with thickness $h_f$ and average velocity $c_f$ driven by the main flow with velocity $c_g$ enters the slot with cross-section width $w_s$. The pressure of the medium from the main flow side at a slot section is $p_g$, while the pressure in a chamber connected to the slot is $p_s$.

![Figure 1. The scheme of the liquid film suction process.](image)

The nondimensional parameters of interest characterizing the suction slot performance are as follows [3]:

$$\psi_1 = \frac{G_{f,slot}}{G_f},$$
$$\psi_2 = \frac{G_{g,slot}}{G_g},$$

where $G_{f,slot}$ is the mass flow rate of the evacuated liquid film; $G_f$ is the mass flow rate of the liquid film on a blade surface; $G_{g,slot}$ is the mass flow rate of the main flow (steam) evacuated from a blade passage; and $G_g$ is the mass flow rate of the steam in a blade passage. It is important to note that equations 1 and 2 may be formulated in a different way by replacing the values in denominators. According to the marked expressions, the maximum suction slot performance will be provided when $\psi_2 = 0$ (the main working body doesn’t leave the turbine flow path) and $\psi_1 \geq 1$ (the value $\psi_1 > 1$ if in addition to complete film suction, droplets streams are partly evacuated through the slot). So, the correctness of the experimental investigation methodology may be achieved if these parameters match both for laboratory and real turbine conditions.

As one can see from figure 1, during the evacuation through the slot a part of liquid film mass may separate from the edge of a sharp corner (with the angle $\alpha$), while another one remains attached to the wall. The way liquid phase separation proceeds depends on the ratio between inertial forces acting on the liquid film and surface tension [5]. If we neglect the gravity force, this ratio will look like:
\[ f_r = \frac{We_f \sin \alpha}{1 + \sin \alpha}, \]  

(3)

where \( We_f \) is the Weber number of the liquid film, which may be calculated as:

\[ We_f = \frac{\rho_f c_f^2 h_f}{\sigma}, \]  

(4)

where \( \rho_f \) is the water density, and \( \sigma \) is the surface tension coefficient. Figure 2 shows different possible cases caused both by geometry (suction slot shape) and by multiphase flow conditions. Depending on the value of \( f_r \), different cases may proceed. If \( f_r < 1 \) the film separation doesn’t occur. With the increase of \( f_r > 1 \) a part of film mass separates and another one remains attached to the wall after the edge. The correlation between \( f_r \) and the fraction of the separated film mass was obtained in [1].

**Figure 2.** Results of numerical modelling of liquid film suction for different cases: full film separation (a), partial film separation with reattachment (b), without separation (c).

The separated liquid film is injected into a space of suction slot and shattered by the high-speed steam flow. The velocity difference between both phases induces the Kelvin-Helmholtz instability that initiates the breakup process [6]. Several studies dedicated to the types of liquid phase breakup (liquid sheet, jet and wall stripping) have shown that the mechanism and the behaviour of the disintegration are different [7]. One of the main parameters describing the breakup process for all cases is the momentum flux ratio:

\[ M = \frac{\rho c^2}{\rho_f c_f^2}. \]  

(5)

In this work, the sheet breakup is considered. For this case, the value of \( M \) characterizes the behaviour of the disintegration process [5] whether it is a cellular breakup, stretched ligament breakup or torn-sheet breakup. In the case of the film suction through the slot (a wall-bounded film flow) the shearing air is encountered only on one side of the thin liquid sheet, while for the sheet breakup mechanism air is encountered from both sides. The film disintegration process is presented in figure 3(a). The studies of this phenomena have shown, that transient destabilization and breakup of the separated film may be characterized by the dimensionless breakup length (distance from the injection edge to the end of the continuous liquid) and Strouhal number [8]. The correlations based on experimental studies have been obtained in [9]:

\[ \frac{L_f}{h_f} = 6.51 M^{-0.68}, \]  

(6)

\[ St = 0.13 M^{0.38}. \]  

(7)

As one can see from Figure 3a, the process of separated film breakup is boarded by the suction side width, so, besides the ratio \( \frac{L_f}{h_f} \), the expression \( \frac{L_f}{w_s} \) should be taken into consideration. It should be noted that equations 6 and 7 utilize the momentum ratio as a parameter, while other studies take into account more parameters.
Figure 3. Comparison of slots operating conditions: $\pi = 0.9$ (a) and $\pi = 0.8$ (b).

In addition to the shear stress, acting from the main flow side, the separated liquid film moves under the transverse pressure gradient. It arises due to the difference between the pressure in a slot chamber and the pressure of the main flow (see figure 1). The ratio of these values describes a suction slot operating condition [3]:

$$\pi = \frac{p_s}{p_g}$$

(8)

Figure 3 presents the comparison of the film suction through the slot at different $\pi$. As one can see, the increase in the pressure drop leads to the deformation of the separated liquid film flow. At $\pi = 0.8$ the continuous liquid phase moves in the space of the suction slot, where the destabilization effect from the main flow is small due to the low velocity (the value of $M$ is close to zero). As a result, a disintegration process does not occur.

The considered parameters (equations 3-8 and $L_f/w_s$ ratio) specify the liquid film evacuation process through the suction slot. In other words, the equality of these quantities for different operating conditions of the multiphase flow in a blade passage leads to the equality of the slot efficiency parameters (see equations 1 and 2) for considered regimes. Presented relations are obtained according to the literature review and should be verified experimentally.

3. The comparison of the liquid film suction regimes

In accordance with the previous section, the correctness of experimental study of the suction slot is achieved in the case of an equality of dimensionless quantities described earlier. At this condition, the results of the study may reflect the features of the flow in a full-scale steam turbine flow path.

The ability to follow these rules is tested numerically for the experimental rig CWS (circuit of wet steam) [10]. It allows studying the flow of superheated, saturated and wet steam in elements of the turbine’s flow path. Dimension and working body flow rate limits allow investigating the scaled models. Figure 4 represents the geometry of the 2D section of the vanes row of a steam turbine’s last stage. The scale factor for studied passage in experimental conditions is 0.252.

Figure 4. The geometry of studied vanes cascade.
In addition, the difference between the droplets sizes takes place. Figure 5 shows the comparison of the discrete phase coarse droplets sizes spectra. As one can see particles diameters generated in the experimental rig are lower in contrast with the real turbine. Also, the types of probability functions describing presented distributions are different.

![Figure 5](image-url)  
Figure 5. Comparison of coarse droplets size upstream the cascade for the real steam turbine (a) and experimental rig (b).

It is important to note that the liquid film development on blade passage surfaces is a complex process. The main source of the mass flow rate of this flow is a collision of droplets with the walls. It is difficult to analytically predict velocity and thickness of the liquid film at the suction slot, due to the polydisperse composition of discrete phase moving in steam flow. For this reason, the numerical modelling was performed [11]. The used method calculates the movement of liquid coarse droplets in the main flow and their interaction with blade passage walls. The collision of discrete droplets with surfaces is a source of liquid film development. Film movement was calculated by solving the system of conservation equations. As a result, the distribution of liquid film thickness and velocity along the blade profile may be obtained. This data is needed to calculate considered nondimensional parameters.

The boundary conditions for the full-size section correspond to those measured in operating steam turbine. At the same time, for the experimental rig conditions, only the theoretical Mach number ($M_{1t}$) downstream the cascade and the slot pressure ratio ($\pi$) were equal to reference values. Total pressure at the inlet ($p_0$) and initial wetness ($y_0$) were varied depending on the experimental rig capacity. Droplets sizes for turbine and experimental rig correspond to that presented in figure 5. It should be noted that the current study is concentrated only on the flow regimes of film suction process. The position of the slot is shown in figure 4 – it is placed on the blade pressure side at the axial coordinate $L_x = 0.76$. The corner angle of the slot $\alpha = 90$ degrees and the width $w_x = 2$ mm (see figure 1). Table 1 shows the comparison between the considered parameters for the reference regime (for the full-size turbine) and laboratory condition. As one can see from the presented table, different regimes of the flow (for real turbine and experimental rig) may lead to the match of considered nondimensional parameters. But at the same time, the main flow regime parameter of initial wetness ($y_0$) doesn’t match between the laboratory and real turbine conditions. Also, the suction slot width ($w_s$) was scaled by the factor not equal to the global one. Thus, to experimentally study the liquid film evacuation phenomena, the local flow characteristics should be taken into account.

| Condition   | $p_0$, kPa | $M_{1t}$ | $y_0$ | $w_x$, mm | $\pi$ | $f_r$ | $M$ | $L_f$ | $h_f$ | $St$ | $L_f/w_s$ |
|-------------|------------|----------|-------|----------|-------|-------|-----|-------|-------|------|-----------|
| Real turbine| 28         | 0.78     | 0.02  | 2        | 0.9   | 0.505 | 8.98| 1.46  | 0.3   | 0.073 |
| Experiment  | 60         | 0.78     | 0.04  | 1.5      | 0.9   | 0.803 | 8.78| 1.49  | 0.3   | 0.072 |
One should remember that the equations 6, 7 correspond to the case of the main flow encountered from both sides of the liquid sheet, while in our case the high-speed steam flows from one side.

Conclusions
The analysis of the liquid film suction through the slot has been carried out. A complex interaction between liquid phase, main flow and blade surfaces leads to a combination of different processes during the film evacuation. Separation and breakup phenomena of the continuous liquid phase have been studied. As a result, 7 nondimensional parameters have been specified. Taking them into account while performing the laboratory investigations allows projecting the results on the real turbine conditions. The numerical modelling was performed to calculate liquid film parameters distribution along the surfaces of the studied blade. Based on the obtained data the experimental rig regime for scaled blade geometry has been determined. The clarified conditions correspond to a full-scale turbine for the process of liquid film suction through the slot. The suggested method may be applied to other experimental conditions and rig. Presented results should be verified and clarified by the experimental studies.

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