Numerical simulation of the liquid film suction process through the slots of various geometry in the last stages of steam turbines

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Abstract. The liquid film suction process through the slot is considered. The stator blade row of the last stage of the steam turbine was used as an object of study. Based on the CFD modelling of two-phase flow in blades cascade the boundary conditions for slots modelling have been obtained. The numerical analyses of film removal were conducted in a domain including only a flow zone near the studied slot. The multi-phase VOF model was used to calculate the interaction between liquid and steam phases and model the interface evolution during the water removal process. Four different geometries of the slots were considered. For each of them, the unsteady calculations at two different operating regimes have been performed. The numerical results provide information about film suction details in a space of the slot. The behaviour of the film flow was analysed for each slot shape. The conditions of the film separation and its further breakup have been considered. For the studied slot designs efficiency analysis was performed. The results have shown how the way the liquid film moves in the slot effects on the removed water and steam mass flow rates.

1. Introduction

Liquid film suction process in a steam turbine blade passage remains a complex critical problem. The interchannel water removal provides the increase of last stages efficiency and reliability as it minimizes the intensity of erosion wear. For this reason, liquid film evacuation through the slots located on stator blades widely used in modern steam turbines. The main aim of designing such systems is to provide effective water removal from a blade surface with minimum working body (steam) losses.

For this purpose, several experimental and numerical studies dedicated to slots operating efficiency have been conducted. The process of water removal from the steam turbine flow path was studied in [1]. The results have shown that about 70% of the removed water comes from the water film and pressure conditions in the last stage are effective for water extraction at all operational modes of the turbine.

Detailed studies of the suction slot shape at an experimental rig have been conducted in [2]. The researchers considered several removal systems designs at different operating conditions and obtained information about the efficiency of water evacuation depending on different parameters. The suction slot operating conditions were studied in [3]. The authors have found that the optimum suction pressure ratio is in the range of 0.9-0.92. The studies of mass flow rate characteristics of different suction slots geometries have been performed in [4]. The results have shown that the main flow Mach
number, pressure drop on a slot and water film vaporization are the main factors determining the behaviour of the liquid film suction process. The work [5] is dedicated to influencing of the water removal process on liquid phase parameters downstream a vane blade. The main result of this study is that moisture removing systems reduce the number of droplets formed as a result of the interaction of water film on the surface of the blade with the wet steam flow in the inter-blade channel.

The described experimental studies provide the integral characteristics of the water removal process, which are necessary for designing effective interchannel film suction systems. But to understand this phenomenon in more detail, the numerical studies of liquid film evacuation behaviour are needed. It is very difficult to conduct such an investigation in experimental conditions.

In this article, the numerical study of the liquid film suction process is presented. Only the flow zone near the slot is considered. The boundary conditions as for liquid film as for the main flow were obtained by CFD modelling of two-phase flow in a stator blades row of the steam turbine last stage.

2. The object of study and numerical method

The studied geometries of suction slots are presented in figure 1(a). Suggested designs have been chosen during the literature review. One can point out several common features of the designs. The suction slots are oriented at 90, 60 and 45 degrees to the blade surface. The shape of the suction slot edge may be without smoothing or as an arc. The angle of the suction slots position varies from 90 to 45 degrees. To simulate the film evacuation process through the slot, the Volume of Fluid (VOF) model was used. This method provides the numerical analysis of immiscible fluids (liquid film on the surface and main flow) having the common interface. Multiphase flow modelling for each slot was performed in the computational domain, presented in figure 1(b). As one can see, only the area near the evacuation zone been simulated, higher the entire blade. It is because of the computational cost of the considered problem. For each slot design, the computational domain consists of about 10 mln cells. As one can see from figure 1(b) the boundary conditions of liquid film inlet and steam inlet are separated, also the periodic conditions are used as borders of the computational domain.

![Figure 1](image)

**Figure 1.** Considered designs of the film suction slots (a) and the computational domain (b).

Values of boundary conditions for the computational domain were obtained using numerical modelling of the liquid film formation and development on the blade surface [6]. The geometry of the considered vanes passage is shown in figure 2(a). The location of the suction slot is also marked here. A CFD simulation of the main flow (steam) in a couple with the modelling of coarse droplets moving and interacting with walls, allows to numerically predict the development process of the liquid film on blade surfaces. Using this technique, the distribution of film average velocity and thickness have been obtained (see figures 2(b) and 2(c)). It should be noted that these quantities have a transient nature. Boundary conditions of the flow entering the blade passage for current calculation correspond to last stages of steam turbines at maximum initial wetness ($y_0 = 6\%$).
The results of two-phase medium flow simulation in the blade passage were used as boundary conditions for the suction slot computational domain (presented in figure 1(b)). Boundary conditions for the study are the following: steam total pressure (position 1 in figure 1(b)) \( p_0 = 20000 \) Pa, liquid film velocity (position 2 in figure 1(b)) \( u_f = 3 \) m/s, static pressure at the outlet (position 5 in figure 1(b)) \( p = 18000 \) Pa. Two operating conditions of the suction slot were considered. They are determined by the value of pressure ratio:

\[
\pi = \frac{p_s}{p},
\]

where \( p_s \) – the static pressure in a chamber of the slot. For the current study, calculations at \( \pi = 0.8 \) and \( \pi = 0.9 \) were performed. The height of the film inlet zone (position 2 in figure 1(b)) corresponds to the liquid film thickness upstream the studied slot and equals \( h_f = 40 \) \( \mu \)m.

3. Result of numerical modelling

Figure 3 shows the behaviour of the transient liquid film separation process for several shapes of the studied slots. These pictures were obtained from the midsection plane of the computational domain (see figure 1(b)). As one can see, a design of suction slot has a significant effect on the way the liquid film removed.

For the slot 2x90 (see figure 3(a)) the whole mass flow rate of the film separates from the slot edge. The continuous liquid medium is injected in the slot space and disturbed by the high-speed steam flow. The velocity difference between phases causes the Kelvin-Helmholtz instability [7]. As a result, the breakup process is observed (see figure 3(a) at \( t = 2.4e-4 \) s). The way the steam flow acts on the liquid film is the shear Main flow acts on the liquid medium by shear stress. For the considered case the separated film sheet periodically overlaps the section of the slot thereby reducing a mass flow rate of the main flow.

In contrast with the 2x90 slot, in the 1.5x45 geometry, the liquid film partly separates while the rest mass flow remains on the surface (see figure 3(b)). As one can see, the interaction process between these water streams is complex – the partial reattachment of the separated film sheet is observed.

The scenario of the way the liquid film will be evacuated is affected by the ratio between surface and inertia forces [8]. This parameter can be presented as follows (after neglecting the gravity force):

\[
f_r = \frac{We_f}{s_1 + \sin \alpha},
\]

where \( \alpha \) is the angle of a slot sharp edge, \( We_f \) is the Weber number of the liquid film, which may be calculated as:

\[
We_f = \frac{\rho u_f^2 h_f}{\sigma},
\]
where \( \rho_f \) is the water density, \( \sigma \) is the surface tension coefficient, \( h_f, c_f \) are the liquid film velocity and thickness respectively. The value of \( f_r \) correlates with the ratio of separated mass to the mass of liquid film.

As one can see from equation 2 and figures 3(a) and 3(c), the increase of the slot edge angle leads to the growth of separated liquid film mass. This phenomenon may be useful for slot performance. Because liquid sheet injected into a volume of slot represents a continuous medium which overlaps a slot section for the main flow. As a result, it should decrease the evacuated steam mass flow rate. But, as one can see from figure 3(a), the film breakup process violates the continuity of liquid medium. It can be seen from figure 3(c), where the evacuation process for the slot 1.5x45K is presented. The appearance of cavern upstream this slot leads to active disintegration of the separated film. Phases velocity difference induces the breakup process and its intensity mainly characterized by the momentum flux ratio [9]:

\[
M = \frac{\rho_g c_g^2}{\rho_l c_f^2}
\]  

(4)

where \( \rho_g, c_g \) are the steam density and velocity respectively. It should be noted that for the considered cases a shearing steam flow is encountered only on one side of the separated liquid sheet. Because in a space of suction slot the main flow velocity is much lower in a comparison with the flow in blade passage. The complete breakup of the separated liquid sheet in the slot 1.5x45K causes the formation of coarse droplets leaving the slot space and entering the main flow in a blade passage (see figure 3c at \( t = 8.0e-5 \) s). Also, a disintegrated jet does not provide a continuous barrier for the main flow on a way to the suction slot chamber.

The common feature of considered suction slots designs is a presets of a sharp edge upstream the evacuation system. As a result, the separation process takes place. For the shape 1.5x60A, the liquid phase evacuation occurs with film remain on the slot surface (see figure 4(a)). For such geometry, the direction of inertia forces acting the liquid film is close to the tangent vector of the slot wall. But disturbances imposed by the main flow on the phases interface are observed in a form of capillary waves.
One should point out a complex nature of processes occurring on the interfaces between steam and liquid film for all considered cases. There is a two-way interaction here – the destabilized by shear stresses film surface causes the aerodynamic disturbances in a steam phase. One can verify this by analyzing the flow field in a zone near the considered suction slot. For example, the comparison of velocity contours is presented in figure 4(b) and 4(c). On the first picture, the case with liquid film suction is considered, while the second one corresponds to the one-phase flow (only a steam phase). It is seen that although the liquid film separation does not occur for this design, the main flow not uniformly distributed in the slot space.

![Figure 4](image)

**Figure 4.** Features of liquid film evacuation in slot 1.5x60A at $\pi = 0.9$: liquid film behaviour(a); multiphase velocity field (b) and steam velocity contours for the case without the liquid film (c).

### 4. Slots efficiency analysis

To analyze the considered slots performance the following characteristics were used [2]:

$$\Psi_2 = \frac{G_{gs}}{G_{g0}},$$

$$\Psi_3 = \frac{G_{fs}}{G_{f0}},$$

where $G_{gs}$ – the steam mass flow rate through the slot, $G_{g0}$ – the steam flow rate at the domain inlet (see position 1 in figure 1(b)), $G_{fs}$ – liquid phase mass flow rate through the slot, $G_{f0}$ – film mass flow rate at the domain inlet (see position 2 in figure 1(b)). According to the presented equations, the ideal slot shape and working conditions provide the $\Psi_2$ close to 0 (the main working body doesn’t leave the turbine flow path) and $\Psi_3 > 1$ (despite complete liquid film suction, water droplets may be evacuated from the flow path). Figure 5 presents the results of numerical investigations for the studied suction slots for two considered operation conditions: $\pi = 0.9$ and $\pi = 0.8$. The common feature for all designs – the decrease of parameter $\pi$ (the increase of the pressure drop on the suction slot) leads to an increase of the sucked steam mass flow rate.

![Figure 5](image)

**Figure 5.** Comparison of $\Psi_2$ (a) and $\Psi_3$ (b) for the considered slots designs.
The design 1.5x45K provides low performance due to liquid film disintegration during the evacuation process. As was pointed out above it leads to the high steam mass flow rate in the slot and coarse droplets generation in the blade passage. Designs without or with a partial liquid film separation provide complete water evacuation (see figure 5(b) for the slots 1.5x60A and 1.5x45). For these shapes, the liquid film maintains its continuity during the suction process (as a result, $\Psi_3$ equals 1). At the same time, the evacuated water doesn’t overlap slot cross-section for the steam flow. This is not typical for the 2x90 slot shape providing the lowest steam flow rate (see figure 5(a)). From another side, this slot doesn’t show the same performance for liquid phase flow rate as 1.5x60A and 1.5x45 do.

5. Conclusions
In this study, the numerical simulation using the VOF model was performed to investigate the mechanism of the liquid film suction in different shapes of the slots. The results have shown different scenarios of the water removal process depending on the suction system design. The appearance of film separation may lead to its disintegration during the movement in a slot space. As a result, the violation of jet continuity causes the increase of steam suction flow rate and coarse droplets generation (which leave the slot and enter the blade passage). These mechanisms are observed for the slot 1.5x45K. In the case of 2x90 design, the separated sheet breakup is not so active. As a result, this shape provides the lowest mass flow rate for the main phase. The slot 1.5x60A prevents film separation by curvilinear linking of blade surface with the slot wall. In this case, the liquid film is completely removed from the blade passage wall. The same results achieved for the slot 1.5x45 where the partial film separation appears.

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