An experimental study of the integral characteristics of the intrachannel liquid film suction in a turbine stator blades cascade

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Abstract. This paper presents the results of an experimental study of the integral characteristics of the intrachannel liquid film suction in a flat cascade of turbine stator blades. Two slots for removing the liquid film from the interblade channel were arranged on the pressure surface of the stator blade. The experiments were carried out with initial steam wetness $\gamma_0 = 3 \div 9.5 \%$ and theoretical Mach number downstream the cascade $M_{1t} = 0.6 \div 0.78$. The operation mode of the moisture removal system was determined by the relative pressure drop on the moisture-removing slots and varied over a wide range. The investigations were carried out for both the operation of the moisture-removing slots one at a time and the combined suction of the liquid film simultaneously through both slots. The measurement system used in the experiments allowed separately determining the mass flow rates of steam and liquid removed from the interblade channel. The obtained integral characteristics served to evaluate the influence of various factors on the efficiency of the intrachannel moisture removal system. Based on the analysis of the research results, recommendations on the design and operation of intrachannel moisture removal systems have been formulated.

1. Introduction
Generation of cheap electricity is one of the main factors that allow for economic growth and increase the competitiveness of enterprises. To reduce the cost of electricity production the creation of turbines with high technical and economic characteristics is required. A significant part of the generating capacity of modern power plants falls on steam turbines. The presence of a liquid phase in their flow parts leads to erosion wear and a significant decrease in the efficiency and reliability of operation.

When wet steam moves in the interblade channels of the turbine stages, a liquid film forms on the surfaces of the blades. Breaking into the main flow, it forms large drops of liquid. These particles make the main contribution to the deterioration of the working conditions of the turbine blades and leads to their destruction by erosion wear.

At present, intrachannel liquid film suction is widely used to solve problems associated with the presence of liquid phase in the flow paths of turbomachines. This method allows you to remove the liquid film from the surfaces of the interblade channel and reduce the number of generated large erosion-hazardous droplets. To the current moment, a large amount of knowledge has been accumulated, which allows us to talk about the effectiveness of intrachannel moisture removal as a method to reduce erosion wear of the turbine blades [1].
The use of modern laser diagnostic methods to investigate wet steam flows allowed studying the effect of intrachannel moisture removing on the flow structure behind the stator blades cascade. In [2], the impact of the moisture removal system on characteristics of liquid particles in the edge droplet wake was evaluated using the PIV method. The development of this study was conducted using the PTV method in [3]. PTV provides for a more detailed study of droplet motion in the flow downstream the stator blades cascade. Its application in [3] allowed establishing a decrease in the fraction of large erosion-hazardous droplets due to the operation of the intrachannel moisture removal system with the suction of a liquid film from the surface of the interblade channel.

Despite the large number of published research results on the problems of intrachannel liquid film suction, many questions remain open. First of all, to design effective systems to prevent erosion in the flow paths of turbomachines based on the intrachannel moisture removal method, information is required on the amount of the liquid and steam removed from the flow part. These values are greatly influenced by both the operating mode and design of the moisture removal system, and the initial and operating parameters of the turbine stage. Obtaining such reliable experimental data would make it possible to formulate recommendations on the design and operation of intrachannel moisture removal systems.

In this experimental study the mass flow rates of steam and liquid removed from the interblade channel were determined separately. The studies were carried out in the wide range of initial and operation parameters. The dependences of the mass flow rates of steam and liquid, removed from the main flow, on the relative pressure drop on the suction slot have been obtained. The presented results can be used both for the design of intrachannel moisture removal systems and for the refinement of methods for numerical modeling of intrachannel liquid film suction.

2. Experimental facility and object of study

The investigations were carried out in the turbine laboratory of the Steam and Gas turbine department of the MPEI. To obtain the integral characteristics of the intrachannel liquid film suction in a turbine stator blades cascade the experimental facility, i.e. Wet Steam Circuit (WSC) was used. The measurement system of this stand allows separately determining mass flow rates of steam and liquid, removed from the flow (figure 1). The applied methodology of measurements is described in detail in [2,4]. The experiments were performed with the inlet total pressure \( P_0 = 40 \) kPa, the theoretical Mach number downstream the stator blades cascade \( M_2 = 0.6 \div 0.78 \) and the initial steam wetness \( y_0 = 3 \div 9.5 \% \). The mean diameter of the droplets produced by the feed water sprayers is 30 \( \mu m \). Size distribution of droplets at the inlet of the working section presented in [2].

A flat cascade of stator turbine blades with intrachannel liquid film removing system was chosen as the object of study. Figure 2 illustrates the main geometry features of these cascade. On the pressure side of the blades two slots for suction of the liquid film were arranged. Each slot was connected to individual separation chamber. The geometry and location of these slots are presented in figure 2.

During the experiments, we studied both the operation of the moisture-removing slots one at a time and the combined suction of the liquid film simultaneously through both slots. Regime of intrachannel separation through the slot was determined by the parameter \( \pi = P_{ch} / P_a \) (\( P_{ch} \) – pressure in individual separation chamber; \( P_a \) – static pressure on the surface of the blade in the section of the slot). This parameter characterized pressure drop on the slot and was investigated in the range of \( \pi = 0.75 \div 0.98 \). Within the limits of these values of parameter \( \pi \), the effect of steam condensation in the drains and separators of the liquid and steam flow measurement system is negligible due to high-quality thermal insulation.

As a result of experiment the mass flow rates of liquid \( G_{liq} \) removed through the slot and steam \( G_a \) were obtained. During the processing of measuring results the separation efficiency \( \eta_l = G_{liq} / G_a \) (\( G_{liq} \) – mass flow rate of the liquid removed through the slot), the separation coefficient \( \eta = G_{liq} / G_{liq} \) (\( G_{liq} \) – mass flow rate of the liquid through the channel section along the height of the slot) and the relative amount of separated steam \( \eta_s = G_a / G_0 \) (\( G_0 \) – mass flow rate of the main flow through the channel section along the height of the slot) were calculated.
3. Integral characteristics of the intrachannel moisture removing

During the study, various modes of operation of the moisture removal system were studied: the combined mode - when liquid film suction is carried out through both slots simultaneously; the mode when only slot I works; the mode when only slot II works. The graphs below show the measurement results for different modes of operation of the moisture removal system, which are indicated as follows:

- I – moisture removal only through slot I;
- II – moisture removal only through slot II;
- Ic – moisture is removed simultaneously through both slots, but the data are only for slot I;
- IIC – moisture is removed simultaneously through both slots, but the data are only for slot II.
Figure 3 (a) shows the distributions of the coefficient $\psi_3$ depending on the parameter $\pi$. The relative amount of the removed steam $\psi_3$ through slot II and slot I decrease with increasing parameter $\pi$. These data are in good agreement with previous experimental studies of the effect of the pressure drop in the separation slots on the separation characteristics [4]. The flow regime in the channel, characterized by the Mach number downstream the cascade, has a significant effect on the relative amount of the removed steam. With an increase of $M_{1t}$, the coefficient $\psi_3$ for both slots decreases. It is important to note that the relative amount of removed steam through both slots are almost at the same level for the same Mach numbers and does not depend on the value of initial steam wetness.

Figure 3 (b) shows the distributions of the absolute mass flow rates of the removed steam from the parameter $\pi$. The absolute mass flow rates of the removed steam are the same for both slots. Static pressure on the profile in the section of the separation slot has a significant effect on the mass flow rate of the removed steam [5]. In the studied range of Mach numbers, this parameter remains approximately constant. Therefore, the absolute amount of the removed steam with a change in the theoretical Mach number downstream the cascade remains approximately constant too. The decrease in relative amount of removed steam is associated with an increase in the amount of the main flow, which increases significantly.

Figure 4 (a) shows the dependences of the separation coefficient $\psi_2$ on the parameter $\pi$ for initial wetness $y_0 = 3$ % and different theoretical Mach number $M_{1t}$. The relative flow rate of removed liquid through slot I is less than through slot II. The flow rate through the slot I remains approximately constant. The flow rate through slit II increases with decreasing pressure drop across the slot corresponding to an increase in $\pi$. As it was shown in [2], this character of the influence of the parameter $\pi$ on the amount of removed moisture is associated with an increase in the steam flow rate through the slot and the sectional area of the slit occupied by the vapor phase. In [2], the occurrence of disturbances on the surface of the water film upstream of the suction slot was also revealed with an increase in the pressure drop on it. These disturbances led to an intensive breakdown of the liquid from the surface of the blade and its entrainment by the main flow. This secondary droplets flows could not be removed by the intrachannel liquid film suction system [6].

The distributions of $\psi_2$ show that the combined intrachannel moisture removing through slots I and II affects only the amount of liquid sucked through slot II, reducing it. Slot I completely removes the liquid film from the surface of the blade. Downstream the slot the film is formed again, but with a lower mass flow rate.

![Figure 3](image-url)
In the dependences presented in figure 4 (a), the influence of the Mach number on $\psi_2$ is observed, similar to the effect on $\psi_1$. An increase in the Mach number leads to a decrease in the relative amount of the removed liquid for both slits. The reason for this effect can be explained by analyzing the dependences of the separation efficiency $\psi_1$ on the parameter $\pi$ presented in figure 4 (b). Separation efficiency $\psi_1$ is equal for $M_{It}=0.6$ and $M_{It}=0.78$. The mass flow rate of the removed steam for all values of initial wetness and theoretical Mach number downstream of the cascade is the same. Analysis and comparison of the distributions in figures 4 and 5 allow evaluating the effect of the Mach number on the mass flow rate of the removed liquid. Thus, we can conclude that the Mach number $M_{It}$ in the studied range of relative velocities does not affect the amount of removed liquid.

It should be noted that the dependences of the separation efficiency $\psi_1$ on the parameter $\pi$ are exponential and for slit I are more sloping than for slit II. This is due to the fact that the amount of liquid through the slot I does not change depending on $\pi$, in contrast to the slot II, while the removed steam mass flow rate through both slots decreases equally with decreasing pressure drop on them.

![Figure 4](image_url)

**Figure 4.** The separation coefficient $\psi_2$ (a) and separation efficiency $\psi_1$ (b) at initial steam wetness $y_0 = 3\%$ and different theoretical Mach number $M_{It}$.

Figure 5 shows the dependences of the separation coefficient $\psi_2$ and the separation efficiency $\psi_1$ on the parameter $\pi$ for initial wetness $y_0 = 6.5\%$ and different theoretical Mach number $M_{It}$. These dependences have a character similar to that for $y_0 = 3\%$. It should be noted that the separation coefficient $\psi_2$ during the transition $y_0$ from $3\%$ to $6.5\%$ slightly decreases. Moreover, the separation efficiency $\psi_1$ increases. This is due to the fact that the mass flow rate of the liquid removed through the slots grows slower than the amount of moisture in the channel.

![Figure 5](image_url)

**Figure 5.** The separation coefficient $\psi_2$ (a) and separation efficiency $\psi_1$ (b) at initial steam wetness $y_0 = 6.5\%$ and different theoretical Mach number $M_{It}$. 
Figure 6 shows the dependences of the separation coefficient $\psi_2$ and separation efficiency $\psi_1$ on the parameter $\pi$ for initial wetness $y_0 = 9.5\%$ and theoretical Mach number $M_{1t} = 0.6$. The influence of parameter $\pi$ for this regime has a character similar to that for $y_0 = 3\%$ and $y_0 = 6.5\%$. But dependences are becoming more sloping. The separation coefficient $\psi_2$ and the separation efficiency $\psi_1$ during the transition $y_0$ from 6.5\% to 9.5\% increase.

During the transition to the initial steam wetness $y_0 = 9.5\%$, the influence of the slot located upstream disappears. This effect is associated with the nature of the formation of the liquid film on the surface of the blade. The dispersed composition of the wet steam flow has a significant effect on this [7]. At $y_0 = 9.5\%$ the film on the blade is formed quite intensively. It increases the efficiency of the simultaneous operation of suction slots. Thus, the combined moisture removal system is appropriate.

Comparing the dependences of the separation coefficient $\psi_2$ on the parameter $\pi$ for different values of initial steam wetness, one can notice that with an increase in the $y_0$, the influence of the pressure drop on the slot decreases, and the character of the dependences becomes more sloping. In the transition from the initial wetness from $y_0 = 3\%$ to $y_0 = 6.5\%$, the relative amount of the removed liquid decreases slightly for both of the investigated slots. A further increase of wetness to $y_0 = 9.5\%$ leads to an increase in separation coefficients. The initial wetness has a stronger effect on the relative mass flow rate of liquid removed through slot $I$.

Estimating the distributions shown in figures 4 (b), 5 (b) and 6 (b) we can conclude that the efficiency of intrachannel moisture removing $\psi_1$ increases with decreasing pressure drop on the suction slot. The most effective modes are for $\pi > 0.9$. These regimes allow removing the maximum amount of liquid, with a minimum mass flow rate of suction steam. Also, a comparison of the distributions of the separation efficiency $\psi_1$ for various initial steam wetness shows that the amount of the removed liquid increases with increasing wetness upstream of the cascade.

**Conclusions**

The experimental study of the intrachannel liquid film suction in a flat turbine stator blades cascade has been carried out with initial steam wetness $y_0 = 3 \div 9.5\%$ and theoretical Mach number downstream the cascade $M_{1t} = 0.6 \div 0.78$. In the studied range of initial wetness $y_0$ and theoretical Mach number downstream the cascade $M_{1t}$ these parameters do not affect the amount of removed steam. Reducing the pressure drop on the suction slots reduces the amount of removed steam. For all investigated ranges of $y_0$ and $M_{1t}$ the relative amount of the removed liquid through slot $I$ is smaller than through slot $II$. The amount of removed liquid through slot $II$ increases with decreasing pressure drop on the slot. The amount of removed liquid through slot $I$ depends only on the $y_0$.

The most effective regimes of suction are the low pressure drops ($\pi > 0.9$) when the amount of the removed liquid is the highest and the amount of the sucked steam is the lowest. Simultaneous operation of suction slots reduces the amount of removed liquid through a slot located downstream
only at \( y_0 = 3 \div 6.5 \% \). This effect disappears during the transition to \( y_0 = 9.5 \% \) and the use of a combined moisture removal system becomes more effective.

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