Investigation of the influence of intra-channel liquid film suction on the structure of the droplet flow downstream a stator blades cascade of a steam turbine

R A Alekseev, V G Gribin, A A Tishchenko, I Yu Gavrilov, V A Tishchenko and V V Popov

National Research University “Moscow Power Engineering Institute”, Krasnokazarmennaya 14, Moscow, 111250 Russia

E-mail: popovvv@mpei.ru

Abstract. The work is devoted to the study of the effect of intra-channel liquid film suction on the characteristics of the wet steam flow downstream a stator blades cascade of a steam turbine. The moisture removal system consisted of two slots on the pressure side of the blade. Each slot was connected to an individual suction chamber. The investigations were carried out with a theoretical Mach number downstream the cascade \( M_{1t} = 0.78 \) and an initial steam wetness \( y_0 = 3 \% \). The main feature of the research was the use of a "PIV-IT" flow laser diagnostics system in which the PTV method was realized. This allowed conducting a detailed study of the structure of a polydisperse wet steam flow. During the investigation an idea of the complex structure of droplets flows downstream the turbine cascade was generated. The analysis of the obtained data allowed us to reveal the main features of the influence of intra-channel liquid film suction on the flows of the liquid particles. It is established that moisture removal does not have a significant effect on the velocity characteristics of the liquid phase. At the same time, the results of studies have shown that intra-channel liquid film suction systems reduce the number of coarse erosion-hazardous droplets downstream a stator blades cascade.

1. Introduction
The growth of electric power industry market requires the creation of high-power steam turbines. These units must have high technical and economic characteristics. A large reserve for increasing the efficiency and reliability of turbomachines is associated with the improvement of working conditions of the blades in their wet-steam flow path. The presence of a liquid phase leads to such negative effects as erosion and a decrease in the efficiency of the turbine stages. The use of various types of moisture removing devices is quite an effective way to solve these problems.

Disruption of the water film from the surface of stator blades leads to the formation of coarse droplets. These droplets are the main cause of erosion and the source of additional losses in the turbine stage. Intra-channel liquid film suction systems allow evacuating the liquid film from the flow path of the turbine and reducing the amount of erosion-hazardous droplets. Effective application of moisture removal requires a reliable data about the structure of the wet steam flow in the turbine stage and the influence of the liquid film suction process on it.

To date, quite a lot of data on the study of intra-channel moisture removing has been published. The studies were carried out both in laboratory conditions [1, 2, 3, 4], and on real turbines [5, 6]. At the moment, there is data on the impact of the turbine operating conditions on the moisture removal...
efficiency [5]. The influence of the pressure drop in the suction slot, as well as its geometry and location on the efficiency of moisture removal, has been studied quite well [3, 4]. There is data on the effects of intra-channel moisture suction from the surface of the blade on the kinetic energy loss [1], the process of liquid film disruption structure from the trailing edge of the stator blades [2] and the intensity of erosion wear in the turbine stage [6]. Despite the large number of research on the method of improving the efficiency and reliability of turbine units, many questions related to the features of its work remain open.

Adaptation of modern methods of laser diagnostics for the study of wet steam flows opens opportunities for determining the effect of moisture evacuation on a wet steam flow. The work [7] describes the results of a comprehensive study of intra-channel liquid film suction in a stator blades turbine cascade in a wet-steam flow. The influence of the pressure drop on the moisture removing slots on the number of evacuated liquid and steam is determined. Evaluation of the impact of the moisture removal system on the characteristics of liquid particles in the trailing edge wake of the stator blade was carried out using the PIV method. This method uses a regular grid to obtain velocity vector fields. This causes the presence of certain limitations on the accuracy and details of the results [8]. At the same time, the PTV method allows one to study in more detail the structure of a two-phase flow and to identify individual flows of droplets that have different properties and origins [9].

This paper presents the results of an experimental study of the effect of intra-channel liquid film suction through the slots located on the pressure side of the turbine blade on the wet steam flow downstream the stator blades cascade. The studies were carried out using the "PIV-IT" flow laser diagnostics system, in which the PTV method was realized. So it is possible to obtain a detailed understanding of the droplet flows downstream the cascade and assess the impact of the intra-channel moisture removing on them.

2. Experimental facility and object of investigation

The investigations were carried out in the experimental facility Wet Steam Circuit (WSC) in the turbine laboratory of the MPEI. The applied measurement system allows separately determining mass flow rates of steam and liquid that was removed from the flow (figure 1). The methodology for these measurements is described in detail in [7]. The design features of the WSC and the working section provide for the possibility of using the flow laser diagnostics system. This system allows obtaining the characteristics of liquid phase particles. The experiments were performed with the theoretical Mach number downstream the stator blades cascade $M_{1t} = 0.78$ and the initial steam wetness $y_0 = 3\%$. Size distribution of droplets at the inlet of the stator blades cascade is presented in [7].

![Figure 1. Schematic diagram of WSC.](image-url)
A flat cascade of stator turbine blades was chosen as the object of study. The geometry features of the cascade are presented in figure 2 (a). Slots for suction of the liquid film were arranged on the pressure side of the blades. Each slot was connected to individual suction chamber. Regime of intra-channel liquid film suction was determined by the pressure drop on the slot $\pi = P_{ch} / P_{st}$. In all the cases considered in the paper, moisture removal was carried out simultaneously through both slots. During the processing on the results of measuring of the separated steam and liquid mass flow rates, the moisture removing coefficient $\psi_2 = G_{liq} / G_{liq0}$ ($G_{liq}$ – mass flow rate of the liquid removed through the slot; $G_{liq0}$ – mass flow rate of the liquid through the channel section along the height of the slot) and the relative amount of separated steam $\psi_3 = G_{st} / G_0$ ($G_{st}$ – mass flow rate of the steam removed through the slot; $G_0$ – mass flow rate of the main flow through the channel section along the height of the slot) were calculated.

![Figure 2. Object of study (a) and scheme of PTV measurements along the pitch (b).](image)

The optical method of PTV, unlike PIV, allows obtaining the velocity and direction of each droplet, trapped in the plane of the laser sheet. Due to this, using various averaging methods, it is possible to determine the average velocity and angle of exit of the droplets along the pitch downstream the blades cascade [10]. A 1 mm wide area was chosen along the pitch of the cascade (1 mm × 74.3 mm) at a distance of 10% of the blade chord (0.1$b$) downstream the trailing edge (figure 2 (b)). Here and below, $\overline{t} = \frac{x}{t}$ is the relative coordinate along the pitch of the cascade ($x$ – coordinate along the measurement line; $t$ – pitch of the cascade). The pitch was divided into 70 elementary areas. In each area, the number of droplets $n_i$ was determined, the velocity vectors of the droplets were sampled and the averaged velocities $C_d$ and exit angles $\alpha_d$ of the discrete phase were determined:

$$C_d = \frac{\Sigma_{i=1}^{n_i} C_{d,i}}{n_i},$$

$$\alpha_d = \frac{\Sigma_{i=1}^{n_i} \alpha_{d,i}}{n_i},$$

where $C_{d,i}$ is the velocity of the droplet and $\alpha_{d,i}$ is the exit angle of the droplet.

3. Amount of water and steam removed through the suction slots

Figure 3 shows the distribution of the moisture removing coefficient $\psi_2$ and the relative amount of the removed steam $\psi_3$, depending on the pressure drop on the suction slot $\pi$. The mass flow rate of the liquid separated through the slot I is much less than that through the slot II and does not depend on the parameter $\pi$. The mass flow rate of the liquid separated through the slot II reduces with reduction of $\pi$. It is related to the differences of the liquid film parameters in the regions of the slot I and II. Unlike liquid flow, steam consumption through both slots is the same. This is due to the small gradient of static pressure along the pressure side of the blade between the slots. The amount of removed steam decreases with increasing parameter $\pi$. This results agree well with the data obtained in paper [7].
4. Investigation of liquid phase parameters downstream of the flat stator blades cascade

For preliminary analysis of experimental data, the PIV method was used. This allowed quickly obtaining the averaged velocity vector fields for regime without intra-channel liquid film suction and estimating the flow structure downstream the investigated cascade. In figure 4, two regions of motion of droplets with low velocities are clearly visible. A similar picture of the flow was observed in work [7].

Part of droplets in area 1 is formed by the disruption of liquid film from the blade trailing edge. And another part of them are formed as a result of the interaction of the water film on the pressure side of the blade with the wet-steam flow in the inter-blade channel [11]. As shown in [12], droplets that move in area 2 have a different origin. Some of them are the primary liquid particles that cross the channel of the cascade without interacting with the blades. Others are formed as a result of the interaction of the flow of droplets with the inlet edge of the blade. Both leave the cascade with a large exit angles and cross the trailing edge wake.

A detailed study of the structure of the liquid phase flow downstream the stator blades cascade was carried out along the pitch (figure 2 (b)) for three regimes. These results are presented in figure 5. Regime 1 is without intra-channel liquid film suction. Regime 2 is with pressure drop on slot I $\pi_1 = 0.855$ and pressure drop on slot II $\pi_{II} = 0.861$. Regime 3 is pressure drop on slot I $\pi_1 = 0.795$ and pressure drop on slot II $\pi_{II} = 0.844$. For these regimes, slip coefficients $\nu = C_d / C_{st}$ ($C_{st}$ – steam flow velocity in the elementary area calculated in ANSYS Fluent) were shown in figure 5 (a) and an average mismatch of the angles of the steam and liquid phases $\Delta \alpha = \alpha_{st} - \alpha_d$ ($\alpha_{st}$ – steam flow exit angle in the elementary area
calculated in ANSYS Fluent) were shown in figure 5 (b). The amounts of removed steam and liquid for specific values of the parameter \( \pi \) correspond to the values given in figure 3.

Figure 5. The distribution of the averaged slip coefficients \( \nu \) of the droplets (a) and the average mismatch of the angles of the steam and liquid phases \( \Delta \alpha \) (b) along the pitch.

In the distributions of average slip coefficients \( \nu \), presented in figure 5 (a), two local minima are clearly visible. They correspond to two droplet flows moving at low velocities, which were distinguished on vector fields downstream the stator blades cascade in figure 4. It is possible to mark an area 2, disposed on \( \bar{t} = 0.3 – 0.5 \). In all the modes studied, the greatest mismatch of the phase angles \( \Delta \alpha \) and the smallest slip coefficients \( \nu \) correspond to this region.

Turning on the intra-channel liquid film suction system reduces the averaged slip coefficients \( \nu \) and an increase in the mismatch of steam and liquid phases exit angles only in the area 2 (figure 4). While in the area 1 and the flow core, the influence of moisture removal is insignificant. No effect of intra-channel moisture removing on velocity of droplets in the trailing edge wake was observed in [7].

For a detailed analysis of the intra-channel liquid film suction system influence on the droplet flow the elementary area located on \( \bar{t} = 0.42 \) was chosen. For this region two-dimensional distributions of the droplet velocity vector components \( C_x \) and \( C_y \) to their relative number \( n / \sum n \) were built (\( n \) – number of droplets with the current \( C_x \) and \( C_y \); \( \sum n \) – total number of droplets in the elementary area).

Figure 6. The two-dimensional distribution of vector components of the droplets velocity on their relative number in the elementary area located on \( \bar{t} = 0.42 \).
From the distributions in figure 6 it can be seen that there are two droplet streams with different velocity characteristics in this area. One stream of liquid particles moves at a sufficiently large exit angle, the average value of which is \( \alpha_d \approx 37^\circ \). This stream corresponds to slow droplets passing through the cascade without interaction with blades. As you can see, the work of the intra-channel liquid film suction system does not affect these droplets. To influence this flow there has to be a profiled blade for ensuring the maximum deposition of both primary and secondary particles of water [13]. The other flow of the liquid phase has a significantly lower average exit angle (\( \alpha_d \approx 16.7^\circ \)) and a higher velocity. This flow consists of droplets formed by the interaction of a wet-steam flow with a water film on the surface of the blade. It should be noted that the number of particles in the first stream is substantially greater than in the second. Under the influence of moisture removing system, the number of droplets in the second stream is significantly reduced.

An assessment of the effectiveness of intra-channel liquid film suction in terms of reducing erosion wear was made. To do this, the number of droplets with slip coefficients \( \nu \) <0.8 was determined. According to [14], these droplets are coarse and erosion-hazardous. For each elementary region, the ratio of the number of coarse droplets in it \( n_c \) to the total number of coarse droplets within a cascade pitch was determined:

\[
\bar{n} = \frac{n_c}{\sum_{i=1}^{m} n_c}
\]  

The distributions presented in figure 7 have two peaks. They correspond to the two areas of motion of coarse droplets downstream the stator blades cascade noted earlier (figure 4). Under the influence of moisture removing, the relative number of droplets is redistributed. In the trailing edge wake the concentration of droplets decreases. And in area 2, the relative amount of liquid particles increases. It is important to note that intra-channel liquid film suction does not affect the number of coarse droplets in the area near the pressure side of the blade. In this region, particles from steam-droplet layer are moving [11]. Intra-channel moisture removing system does not have any significant impact on them [12].

Conclusions
The characteristics of the motion of the liquid phase downstream of the turbine stator blades cascade with an intra-channel moisture removing system are investigated. The complex structure of the droplet flow was revealed. The data obtained allow to evaluate the effect of intra-channel moisture removing on the flow downstream the cascade. Intra-channel liquid film suction does not impact liquid particles path through the inter-blade channel without interaction with the surface of the blades. This problem
can be solved by modifying the shape of the blade and the inter-blade channel. For example profiling of the blade in order to maximize droplets deposition on it. 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. At the same time, the average movement characteristics of droplets in the trailing edge wake remain constant. This indicates the absence of the effect of intra-channel moisture removal on the size of the droplets in this area. Nevertheless, the amount of liquid phase particles downstream of the cascade is reduced. Experiments have shown that intra-channel moisture removing reduces the number of erosion-hazardous droplets downstream of the stator blades cascade. Thus, we can talk about the effectiveness of intra-channel liquid film suction as a method of erosion reduction. At the same time, studies have shown the flaws of this method that can be solved by further research.

Acknowledgements
This study was supported by Russian Science Foundation (project No 16-19-10484).

References
[1] Todd K W and Fallon J B 1965 Proc IMechE, Conference Proceedings 180 (15) 50–63
[2] Xinjun W, Tingxiang X and Yanfeng L 2005 Heat Trans. Asian Res 34 (6) 380–5
[3] Gribin V G, Korshunov B A and Tishchenko A A 2010 Thermal Engineering 57 (9) 746–50
[4] Li L, Wu X, Yang J and Feng Z 2018 Proc IMechE Part A: J. Power and Energy 232 (5) 461–72
[5] Hoznedl M, Tajc L and Bednar L 2012 Baumann Centenary Conference BCC-2012-19
[6] Todd W K and Gregory B 1967 Proc IMechE, Conference Proceedings 182 (8) 297–308
[7] Gribin V, Tishchenko A, Gavrilov I, Popov V, Sorokin I, Tishchenko V and Khomyakov S 2016 Power Technology and Engineering 50 180–7
[8] Filippov G, Gribin V, Tishchenko A, Tishchenko V and Gavrilov I 2014 Proc IMechE Part A: J. Power and Energy 228 (2) 168–77
[9] Alekseev R A, Gribin V G, Tishchenko A A, Gavrilov I Yu, Tishchenko V A and Popov V V 2018 Journal of Physics: Conference Series 1128 (1) 012093
[10] Gavrilov I and Popov V 2018 Journal of Physics: Conference Series 1128 (1) 012122
[11] Gribin V, Gavrilov I, Tishchenko A, Tishchenko V, Popov V, Khomyakov S and Alexeiev R 2018 Proc IMechE Part A: J. Power and Energy 232 (5) 452–60
[12] Gribin V G, Tishchenko A A, Tishchenko V A, Gavrilov I Y, Sorokin I Y and Alexeev R A 2017 Power Technology and Engineering 51 (1) 82–8
[13] Alexeev R A, Tishchenko V A, Gribin V G and Gavrilov I Yu 2017 Journal of Physics: Conference Series 891 (1)
[14] Filippov G A, Gribin V G, Tishchenko A A and Lisianskii A S 2012 Izv. Ross. Akad. Nauk, Energetika 6 96–107