PERFORMANCE OF A WET-STEAM TURBINE STATOR BLADE WITH HEATING STEAM INJECTION


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ABSTRACT

The results of the experimental studies of wet-steam flow with injection of hot steam from the slot downstream of the turbine flat stator blade cascade have been considered. In the studied profile there is one injection slot on the pressure side surface near the trailing edge. The investigations have been carried out at different initial wetness of the main flow and different injected steam temperatures at the constant pressure of injection. Laser diagnostic system “POLIS” which includes PIV method has been used to analyze the influence of heating steam injection on the characteristics of the liquid phase downstream of the blade trailing edge.

It is shown a heating steam injection has an effect on the vector fields of coarse droplets downstream of the blade cascade. At the same time kinetic characteristics of coarse droplets downstream of the stator blades cascade are independent of the temperature of the injected steam. Exit angles of coarse droplets obtained at the different distance from the trailing edge are presented.

KEYWORDS

STEAM INJECTION, STEAM TURBINE LAST STAGES, WET-STEAM, PIV

NOMENCLATURE

- $b$: chord of the blade
- $h$: height of blade
- $\alpha_1$: deviation angle
- $\alpha_s$: stagger angle
- $\Delta_{tr}$: trailing edge thickness
- $\overline{\Delta_{tr}}$: trailing edge thickness to throat ratio
- $\delta$: height of injection slot
- $c_d$: velocity of the liquid particles
- $c_s$: velocity of the steam
- $M_{lt}$: theoretical exit Mach number
- $P_0$: total pressure upstream studied object
- $P_{inj}$: total pressure of the injected steam in the injection chamber
- $P_{slot}$: static steam pressure in the interblade channel in a section of the injection slot
- $t$: pitch of the cascade
- $\bar{t}$: pitch ratio
- $T_0$: total temperature upstream the studied object
- $T_2$: total temperature of the injecting steam upstream the injection chamber
- $T_{inj}$: total temperature of the injected steam in the injection chamber
- $T_s(P_{inj})$: saturation temperature at the pressure of the injected steam
- $x$: coordinate along pitchwise direction
- $y_0$: steam initial wetness (upstream studied object)
- $z$: axis (coordinate) perpendicular to front of the blades cascade
- $\alpha_{dT}$: exit angle of liquid phase particles
- $\alpha_{Set}$: blade stagger angle
- $\alpha_{st}$: exit angle of steam phase
- $\Delta T_2$: deference between total temperature upstream the injection chamber and saturation temperature at the pressure of the injected steam in the injection chamber (superheat)
- $\Delta \alpha_d$: angular misalignment between steam and liquid phases
\( e_{\text{inj}} \) relative pressure of the injected steam  
\( v \) slip coefficient  
\( Re_{b} \) Reynolds number by chord  
\( \dot{g} \) mass flow rate in the slot to mass flow rate in the channel ratio  
\( \bar{c} \) velocity in the slot to the flow velocity ratio  
\( h_{\text{inj}} \) enthalpy of the injected steam in the injection chamber  
\( h_{2} \) enthalpy of the injecting steam upstream the injection chamber  
\( \dot{G}_{\text{inj}} \) mass flow of injected steam  
\( F_{s} \) heated surface

**INTRODUCTION**

At the moment the problem of erosion of turbine blades which operate in wet-steam area is quite nowadays. This problem is still unsolved and is one of the main issues which manufacturers of wet steam turbines face. The presence of erosion-hazard due to coarse droplets leads to damage of rotor and stator blades surfaces. It reduces the efficiency and reliability of steam turbines.

The processes of erosion determine the value of maximum wetness downstream of the last stage of steam turbine according to Filippov and Korobkov (1973). The main source of the erosion-hazard droplets in the flow paths of steam turbine is the process of water film breakup from the surfaces of inter-blade channels which formed by deposition of liquid particles. This process takes place in low pressure cylinders of steam turbines according to Filippov and Povarov (1980). The process of deposition of water droplets on the blade surface depends on their diameter and density of working fluid (Filippov et al. (2012)).

In the literature a lot of publications and papers are dedicated to water film removal from the blade surfaces (Gribin et al. (2010), Sakamoto et al. (1992), Tanuma and Sakamoto (1991)). But as shown by recent investigations (Gribin et al. (2016) and Hoznedl et al. (2012)) the number of removed water is strongly dependent on the operational parameters of turbine. Even small changes in turbine stage operational conditions reduce the efficiency of this method. It should be noted that together with removed moisture a portion of steam is removed too. However, this leads to nonrecoverable losses of turbine power.

In the previous part of this study (Gribin et al. (2014)), it was shown how the injected steam pressure influences on the characteristics of liquid phase. This paper presents the results of an experimental study of the effect of the temperature of injected steam on the main characteristics of the erosion-hazard droplets in the isolated flat stator blades cascade.

**THE EXPERIMENTAL FACILITY AND THE OBJECT OF THE INVESTIGATION**

The investigations were performed on the experimental facility Wet Steam Circuit (WSC) (see Fig. 1) in the turbine laboratory of the Moscow Power Engineering Institute (MPEI). This experimental facility is used to study the flows of superheated, saturated and wet steam in the different elements of flow parts of steam turbines.

![Figure 1: The experimental facility Wet Steam Circuit (WSC)](image-url)
A schematic flow diagram of WSC is shown in Fig. 2. The saturated steam form the extraction of the steam turbine goes to the first wetting stage (1), which is used to decrease the steam temperature by injection of feed water (coming from the feed water header (6)) into the flow. After the first wetting stage working fluid enters the steam header (2). A part of the steam comes to the receiver tank (3) from the header (2). In this steam pipeline is located the second wetting stage (9) which is used to reduce steam temperature to the saturated state. The third wetting stage (4) is a block of the feed water jets. These jets (4) are used to produce polydisperse two-phase medium upstream of the studied object (5). The working medium passes the studied object mounted in the removable working part (5) and comes to the condenser (7). Then condensate returns into the power plant cycle. Supply of injected steam (8) is realized by the extraction from the header (2).

![Schematic diagram of WSC](image)

**Figure 2: Schematic diagram of WSC**

To investigate the influence of the injection steam temperature on the dynamics of the liquid phase downstream of the isolated stator blades cascade, the POLIS laser diagnostic system was used. In this system the PIV (particle image velocity) method has been used. This method allows to determine a two-component instantaneous velocity vector fields on a regular grid (velocity measuring range: 0.001 – 1000 m/s; error of no more than 1 %). The methodology of laser diagnostic system adapted to the polydisperse wet-steam flow. This is successfully applied in Gavrilov et al. (2014), Sorokin et al. (2016), Filippov et al. (2014), Gribin et al. (2016) and Gribin et al. (2014). The steam velocity \( c_s \) was determined by a simulation using the Ansys Fluent 14 incorporating wet-steam model. The results of this model are compared with experimental data in Filippov et al. (2014).

In this paper, the averaged characteristics of droplet’s streams downstream of the blade cascade were determined (the example of the velocity vector field is given in Fig. 3). They were obtained by means of statistic processing of instantaneous velocity vector fields set. In Fig. 3 the coordinate axes \( (z, x) \) are marked. The liquid phase parameters have been obtained along the lines downstream of the blade cascade shown in the Fig. 3.
The studied object is a flat cascade of hollow stator blades with a slot for steam injection at the pressure surface of the blade (see Fig. 4). Data about cascade geometry are listed in table 1. The cascade was installed into the working part that is shown in Fig. 4. The investigation condition was described in table 2. Pressure was measured by vacuum gauge ($\pm 0.15$ full scale output). Temperature was measured by PT100 platinum resistance thermometer. The total pressure $P_{inj}$ and the temperature $T_{inj}$ of the injected steam were measured in the injection chamber. The WSC facility includes a surface heat exchanger (3) in order to change the temperature of the injected steam. In this way, it is possible to vary the injected steam temperature upstream of injection chamber in the range of $\Delta T_2 = 0 – 100$ K. The superheat of the injected steam $\Delta T_2$ was determined as:

$$\Delta T_2 = T_2 - T_s(P_{inj}).$$

The relative pressure of the injected steam at all conditions remains constant and corresponds to $\varepsilon_{inj} = 0.8$. The relative pressure of the injected steam $\varepsilon_{inj}$ was determined as:

$$\varepsilon_{inj} = P_{slot} / P_{inj}.$$  

$P_{slot}$ was measured in the injection chamber when steam wasn’t injected ($\varepsilon_{inj} = 1$). The mass flow rate of the injected steam was controlled by a mass flow meter 4.

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**Figure 3:** Averaged velocity vector field of liquid phase downstream the blade cascade

**Figure 4:** The studied object (a) scheme of working part (b)
\[ h, \text{ mm} \quad b, \text{ mm} \quad \Delta_{tr}, \text{ mm} \quad t, \text{ mm} \quad \alpha_{f}, \text{ deg} \quad \alpha_{s}, \text{ deg} \quad \Delta_{tr} \quad \delta, \text{ mm} \]

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<th>b, mm</th>
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<th>t, mm</th>
<th>\alpha_{f}, deg</th>
<th>\alpha_{s}, deg</th>
<th>\Delta_{tr}</th>
<th>\delta, mm</th>
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<td>76.0</td>
<td>0.8</td>
<td>53.4</td>
<td>13.0</td>
<td>36.5</td>
<td>0.1</td>
<td>0.4</td>
</tr>
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</table>

Table 1: Geometry of blade cascade

\[
p_0, \text{kPa} \quad y_0, \% \quad \text{Re}_b \quad M_{it} \quad \epsilon_{inj} \quad \bar{g} \quad \bar{c}
\]

<table>
<thead>
<tr>
<th>p_0, kPa</th>
<th>y_0, %</th>
<th>\text{Re}_b</th>
<th>M_{it}</th>
<th>\epsilon_{inj}</th>
<th>\bar{g}</th>
<th>\bar{c}</th>
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<td>40</td>
<td>1 - 4</td>
<td>(5 \cdot 10^5)</td>
<td>0.7</td>
<td>0.8</td>
<td>0.03</td>
<td>1.74</td>
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Table 2: Considered condition

**EFFECT OF THE INJECTED STEAM TEMPERATURE ON THE VELOCITY CHARACTERISTICS OF LIQUID PHASE DOWNSTREAM OF THE BLADES CASCADE**

In this section the results of the investigation of injected steam temperature influence on the characteristics of the liquid phase downstream of the stator blades cascade are presented. All obtained data was compared with the conditions without steam injection, which hereafter will be designated as \(\epsilon_{inj} = 1\). Fig. 5 shows the distributions of slip coefficients \(v\) along the pitch at the distance of \(z = 0.1b\) downstream of the blades cascade. Slip coefficient \(v\) and relative coordinate along the pitch of the cascade (pitch ratio) were determined as:

\[ v = c_d / c_s, \quad (3) \]
\[ \bar{c} = x / t. \quad (4) \]

![Figure 5: The distributions of slip coefficients along the pitch downstream blades cascade at \(M_{it} = 0.7\); a – \(y_0 = 1\%\); b – \(y_0 = 4\%\)](image)

From these distributions it can be clearly seen that the trailing edge droplets wake occupies large part of the pitch. The width of this wake is almost independent of the presence of steam injection. When the steam injection is enabled the distributions have a two-peak structure. It should be noted that even when the value of \(\Delta T_2\) is minimum the slip coefficients in the trailing edge droplets wake increases. Especially it can be observed in the area near the suction side of the blade. This is due to 2 reasons:

a) The breakup of the liquid film formed on the pressure surface of the blade;

b) Evaporation of the water film on the surface of the blade, heated by injected steam.

One should pay attention to the condition with the same basic initial parameters, but with a value of initial wetness \(y_0 = 4\%\) (see Fig. 5 (b)) it is clearly seen that the width of the trailing edge droplets wake increases. When the steam injection is enabled the flow of the droplets is redistributed, and the minimum of the slip coefficients shifts in the direction of increased relative coordinate. Furthermore, two-peak structure of the trailing edge droplets wake disappears at \(y_0 = 4\%\). However, the tendency remains the same: with increasing the injected steam temperature the velocity of the droplets in the wake slightly increases. This occurs as a result of breakup of the
liquid film which separates from the pressure surface of the blade, and its evaporating mostly from the suction surface of the blade.

For illustrative purposes and clarification of the slip coefficients change, the distributions of droplets and steam velocities are shown as an example in Fig. 6, with heated steam injection and without it. As it can be seen from this figure there are significant changes in the velocity of liquid phase particles due to the influence of the steam injection.

![Figure 6: The distributions of steam and droplets velocities along the pitch downstream blades cascade at $M_{t} = 0.7, y_{0} = 1 \%$](image)

With increasing $\Delta T_{2}$, the slip coefficients in the trailing edge droplets wake increase. These results may indicate that the water film located on the surface of the blade is partially evaporated. It should be noted that a decrease of the liquid film thickness on the surface of the blade reduces the number of coarse droplets formed by breaking away from the waves on the surface of the water film according to Filippov and Povarov (1980). Also in the trailing edge wake the slip coefficients increase because the liquid film was disrupted and evaporated by steam injection on the blade surface. With increasing $\Delta T_{2}$, there is a consistent insignificant increase in the values of the slip coefficients along the pitch.

Overall, the pattern of the influence of the steam injection on the kinematic characteristics of the discrete phase downstream the stator blades cascade is the same for all represented conditions.

**EFFECT OF THE INJECTED STEAM TEMPERATURE ON THE COARSE DROPLETS AREA DOWNSTREAM OF STATOR BLADES CASCADE**

As it was previously noted, the data about the distribution of slip coefficients downstream the stator blades cascade allows making conclusion about the presence of coarse droplets in the stream. Because of their inert behavior, the slip coefficients of such liquid phase particles should be significantly less than 0.8 (Filippov et al. (2012)).

To identify the areas of coarse droplets presence downstream of the blades cascade instantaneous vector fields obtained by the PIV method have been filtered by the value of slip coefficient. The obtained velocity vector fields were filtered in order to find droplets with $\nu < 0.6$. Based on this data the areas of coarse droplets presence downstream of the investigated cascade have been detected for different injected steam temperature (see. Fig. 7).
Figure 7: Areas of coarse droplets presence at $M_{It} = 0.7$, $y_0 = 4 \%$; 1 – without injection; 2 – $\varepsilon_{inj} = 0.8$, $\Delta T_2 = 6$ K; 3 – $\varepsilon_{inj} = 0.8$, $\Delta T_2 = 73$ K

The Fig. 7 shows the reduction and redistribution of coarse droplets presence area downstream of cascade under the influence of injected steam with different values of $\Delta T_2$. On the suction surface of the blade the liquid film is completely evaporated due to its small thickness Deich et al. (1991). There is a slight shift of the coarse droplets area in the direction of the core of the flow (It could be clearly seen on the distribution of the angular misalignment shown at next section of the paper). This process can be explained by the influence of the injected steam to the liquid film that breaks up from the pressure surface of the blade. Also with the growth of the injected steam temperature the coarse droplets area is narrowed.

Boiling heat transfer on blade surfaces was described by the dependence of the heat flux $q$ from the superheat of the injected steam $\Delta T_2$ (see fig. 8). The heat flux $q$ was determined as:

$$ q = \frac{G_{inj}(h_2 - h_{inj})}{F_s} $$

In figure 8 curve agrees with the Nukiyama curve (Nukiyama (1934)).

Figure 8: Boiling heat transfer on blade surface at $M_{It} = 0.7$, $y_0 = 4 \%$

The obtained results have a good correlation with visual data of the structure of droplet streams downstream the cascade. For visual analyses of the flow structure a snapshots of illuminated liquid phase particles obtained by the laser diagnostic system "POLIS" were used. Fig. 9 (a) shows typical pictures of condition without steam injection ($\varepsilon_{inj} = 1$), and with enabled steam injection with the maximum value of $\Delta T_2$ (Fig. 9 (b)). In the first series of images (Fig. 9 (a)) the process of the liquid film breakup from the trailing edge of the blade is clearly observed. Digit (1) denotes the "tongue" of liquid that breaks down from the trailing edge of the blade. Then it is collapsed into clusters of coarse droplets (2), visible across the whole width of the trailing edge wake. In the second series of images in Fig. 8 (b) "tongue" is not observed at all. However, the several clusters (2) and individual coarse droplets (3) appear mainly from the pressure side of the blade. This confirms the previous assumption about the evaporation of liquid film from the suction surface and the breakup of the
water film from the pressure surface of the blade. This confirms the effectiveness of the steam injection from the point of view of reduction of the average size of coarse droplets.

**Figure 9:** Visual structure of the wet steam flow downstream the cascade at $M_{1t} = 0.7$, $y_0 = 4\%$; a – $\varepsilon_{inj} = 1$; b – $\varepsilon_{inj} = 0.8$, $\Delta T_2 = 73$ K

**EFFECT OF THE INJECTED STEAM TEMPERATURE ON THE EXIT ANGLE OF THE LIQUID PHASE**

The liquid phase inlet angle of the rotor blades is an important factor affecting the process of erosion wear of the steam turbine last stages operated in wet-steam area. The fine droplets move along the streamlines of the main flow. But the coarse droplets move with angular misalignment $\Delta \alpha$ determined by the formula:

$$\Delta \alpha = \alpha_d - \alpha_{st}. \quad (5)$$

The distribution of angular misalignment can be used as an indirect criterion to determine the effectiveness of the investigated method on minimization of rotor blades erosion damage. Fig. 10 shows this distribution for one studied condition ($M_{1t} = 0.7$, $y_0 = 1\%$), obtained at a distance of 0.1$b$ downstream of the stator blades cascade.

As it can be seen, the value of $\Delta \alpha$ practically does not depend on the value of $\Delta T_2$. The data obtained with other initial parameters of the flow will be presented by the typical conditions ($\varepsilon_{inj} = 1$ and $\varepsilon_{inj} = 0.8$ with the maximum value of $\Delta T_2$).
The highest values of $\Delta\alpha$ were observed in the trailing edge wake due to the maximum concentration of coarse droplets in this area. By enabling the steam injection ($e_{\text{inj}} = 0.8$) $\Delta\alpha$ reduces from the velocity side of the blade, and also in the center of the trailing edge wake due to evaporation and liquid film breakup processes. But from the pressure side of the blade there is a small growth in $\Delta\alpha$, due to the restructuring of the flow at the place of injection slot and destruction of the liquid film by the steam injection. Fig. 10 (b) shows the angular misalignment distributions obtained at a distance of 0.15$b$.

As it can be seen, the value of $\Delta\alpha$ from the pressure side ($\bar{t}= 0.8 – 1$) decreases, and the center of trailing edge wake ($\bar{t}= 0.3 – 0.8$) remains the same as at a distance of 0.1$b$. The steam injection affects on the droplets in the trailing edge wake by the following way:

1) In the area near the suction side of the blade ($\bar{t}= 0.2 – 0.4$) $\Delta\alpha$ reduces due to the liquid film evaporation.

2) In the center of the trailing edge wake $\Delta\alpha$ reduces due to disruption of liquid film by steam injection.

3) In the area from the pressure side of the blade $\Delta\alpha$ increases due to the effect of steam injection on the width of the trailing edge wake.

The steam injection leads to decrease of coarse droplets diameters, but trailing edge wake near front of the cascade (0.1$b$) becomes wider. But in the downstream direction (0.15$b$) value of $\Delta\alpha$ becomes similar to the condition without steam injection due to the reduction of droplets diameters.

The distributions are obtained with the same basic initial parameters at initial wetness of $y_0 = 4\%$, which approximately corresponds to previously obtained data (see Fig. 11).
CONCLUSIONS
1. The steam injection increases the slip coefficients in a trailing edge wake of the stator blade. This process indicates the reduction of coarse droplet diameters. The increase of the injected steam temperature provides insignificant increase in slip coefficients.
2. The steam injection has a significant influence on the kinematic characteristics of the liquid phase. The influence of the steam injection on the kinematic characteristics of the steam phase is negligible.
3. Enabling of steam injection leads to significant reduction of coarse droplets area. The increase of the injected steam temperature provides to insignificant reduction of this area.
4. Visual analysis of the flow structure shows the liquid film was disrupted by the steam injection on the blade.
5. Analysis of angular misalignment distributions shows insignificant increase in the trailing edge wake width. But the values of angular misalignment decrease.

The overall results of experimental data show that the steam injection leads to reduction of the liquid droplets diameters in the trailing edge wake area. Besides the increase of the injected steam temperature does not have a significant influence on the efficiency of this method. So this method of minimization of the rotor blades erosion damage can be used as the main system of erosion wear reduction.

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REFERENCES

