Experimental study of the efficiency of steam injection on wet-steam turbine stator blade cascade

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Abstract. Currently, in order to decrease the negative effects caused by the presence of a discrete phase in the flow path of steam turbines stages operating in wet-steam area, different technical solutions are apply. These methods reduce the number of coarse droplets and wetness of working medium. The implementation of erosion reduction methods requires modifying surfaces of flow path, which can significantly affect the efficiency of the steam turbine. For example application of intrachannel moisture removing and steam injection needs changes of the stator blades surfaces. This article is a part of researches cycle about the efficiency of steam injection on the stator blade surface as the main method of coarse liquid particles diameters reduction in the last stages of high-power steam turbines. The paper presents the results of the analysis and comparison of experimental research unmodified profile to the profile of the stator blade changed by injection slot. The comparison of the profile losses considered blades is present. The analysis of the experimental results showed the feasibility and efficiency of this method of coarse liquid particles diameters reduction in the last stages of high-power steam turbines.

1. Introduction

Today, a promising area for the development of steam turbines is the design of low pressure cylinders (LPC) with increased exhaust area. One of the ways to design such LPC is the height of the blades of last stage being increased. The peculiarity of their operation is largely determined by the presence of a liquid phase in the flow part, which reduces both the efficiency and reliability of the steam turbines. Moisture accumulates on the surfaces of LPC flow parts in the form of a liquid film. As a result of liquid film breaking up from trailing edge, coarse droplets are formed, which leads to erosion damage of rotor blades surfaces. This leads to a change of the rotor blades geometry. And also causes an increase of energy losses associated with deterioration of blades aerodynamic, as well as decreasing reliability of the turbine.

In the literature a lot of publications and papers are dedicated to water film removal from the blade surfaces [1, 2]. But as shown by recent investigations [3, 4] 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 no recoverable losses of turbine power.
The method of heating and steam injecting is not fully described in the literature, although it is quite promising. There are several studies [5, 6], which shows that using this method allows reducing erosion-hazard, but also improving overall turbine efficiency.

Investigation of the efficiency of steam injection was carried out in the laboratory of steam and gas turbine department of Moscow Power Engineering Institute. The results of this study were presented in [7, 8]. It has been shown that the use of the steam injection helps to reduce the average diameter of coarse droplets downstream the nozzle blades, which in turn reduces the erosion damage of the rotor blades. However, the evolution of the efficiency of injection was made on the basis of experimental studies on the modified profile (with a slot on the pressure side). In this paper, we present the results of a comparison of the characteristics of the main flow and the liquid phase for the modified and initial profile of the nozzle blade.

2. The experimental facility and the object of the investigation
The investigations were performed on the experimental facility Wet Steam Circuit (WSC). A schematic flow diagram of WSC is shown in Fig. 2. 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. Schematic diagram of WSC.](image)

The superheated steam from the extraction of the steam turbine goes through two wetting stages (1, 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).

In the paper, there are two linear blade cascades. The first one consists of blades without modification (fig. 2a). The second one consists of blades with injection slot, which was located on pressure side near the trailing edge (fig. 2b). Geometry of linear cascades is the same and listed in table 1.
Cascades were installed into the working part that is shown in Fig. 3. Inlet parameters were controlled by the total pressure probe and temperature probe. The Theoretical Mach number was changed by variation of vacuum in condenser. Static pressure downstream the blade cascade was measured by 10 additional pressure measuring points placed at 0.1b distance downstream the blade trailing edge. The total pressure $P_{inj}$ and the temperature $T_{inj}$ of the injected steam were measured in the injection chamber. The superheat of the injected steam $\Delta T_2$ was determined as:

$$\Delta T_2 = T_2 - T_s(P_{inj})$$  \hspace{1cm} (1)

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:

$$\varepsilon_{inj} = P_{slot} / P_{inj}$$  \hspace{1cm} (2)

$P_{slot}$ 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.

**Table 1.** Geometry of blade cascade.

| h, mm | b, mm | $\Delta_{ss}$, mm | t, mm | $\alpha_1$, deg | $\alpha_s$, deg | $\delta$, mm |
|-------|-------|--------------------|-------|-----------------|-----------------|-------------|
| 46.0  | 76.0  | 0.8                | 53.4  | 13.0            | 36.5            | 0.1         |
|       |       |                    | 0.4   |                 |                 | 0.4         |

**Figure 2.** The studied objects. a) – profile No. 1; b) – profile No. 2.

**Figure 3.** The scheme of working part.
Total pressure losses was determined by traversing along the cascade pitch with a total pressure probe (Fig. 3) at a distance of $z = 0.1b$ (where $b$ is a blade chord) downstream the trailing edge.

The parameters at the test section inlet, outlet and injection are compared in Table 2.

In order to obtain the characteristics of liquid phase downstream the blade cascade, laser diagnostic system “POLIS” was used. In this system the PIV (particle image velocimetry) method has been used. This method allows determining a two-component instantaneous velocity vector field on a regular grid (velocity measuring range: 0.001 – 1000 m/s; error is under 1 %). The methodology of laser diagnostic system adapted to the polydisperse wet-steam flow. This is successfully applied in [9]. 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 [10].

**Table 2. Considered condition.**

| $p_{0b}$, kPa | $y_{0b}$, % | Re$_b$ | $M_{1t}$ | $\varepsilon_{inj}$ |
|---------------|-------------|--------|----------|-------------------|
| 40            | 1 - 4       | 5 · 10$^5$ | 0.7 – 0.9 | 0.65 – 1          |

### 3. Influence of the steam injection on the main flow characteristics

This section represents the results of the study of influence of the heating steam injection into profile losses in the blade cascade. Comparison between blades No. 1 and No. 2 is considered.

The value of profile losses for the blade No. 1 was determined by the equation:

$$
\varepsilon_p = \frac{2}{k-1} \frac{1}{M_{1t}} \left( \varepsilon_0 \frac{k-1}{k} - 1 \right)
$$

(3)

where $M_{1t}$ is the theoretical Match number downstream the blade cascade.

$$
\varepsilon_0 = \frac{p_0}{p_{01}}
$$

(4)

where $p_0$ is a total pressure upstream the studied cascades, $p_{01}$ is a total pressure at the distance of $z = 0.1b$ downstream the blade cascades.

The average integral losses were determined from the formula

$$
\bar{\varepsilon}_L = \frac{1}{L} \int_0^L \varepsilon_p \, dx
$$

(5)

As shown in [11] when steam injection is switched on ($\varepsilon_{inj}=0.8$), the main changes of liquid phase and steam characteristics take place in the trailing edge wake area. Accordingly, in this area one should take into account the supply of additional energy from the steam injection, while in the core of the flow the losses of kinetic energy is determined on the basis of the total energy upstream the studied blade. Thus, average integral losses were determined by the formula (3). The value of $\varepsilon_p$ at each point along the pitch is determined from formula (1). The value of $\varepsilon_0$ that is included into the formula (1) is calculated on the basis of formula (2), where the total pressure $p_0$ is determined by the equation:

$$
\begin{align*}
    p_0 &= \begin{cases}
        p_0, & \tilde{\tau} \neq 0.25 - 0.70; \\
        p_{0mi}, & \tilde{\tau} = 0.25 - 0.70
    \end{cases}
\end{align*}
$$

(6)

Figure 4 shows the changes of the profile energy losses as a function of the relative injection pressure $\varepsilon_{inj}$ for the theoretical Mach number $M_{1t}=0.9$. Two conditions with initial wetness $y_0=4\%$ and $y_0=8\%$ are considered. The injected steam at all cases was saturated.

As one can see from the presented figure, with the increase of injected steam pressure, the value of the profile losses decreases. When the a minimum value of $\varepsilon_{inj}$ is reached, the increase of profile losses for blade No. 2 relative to the blade No.1 is minimal. However, according to the technical and economic considerations described in [6], the mass flow rate of the injected steam should not exceed 0.03$G_0$. Therefore, in order to determine the efficiency of the blade No.2 in comparison with the blade No.1, they will be given at the value of the relative steam injection pressure $\varepsilon_{inj}=0.8$. 

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4. Analysis of the liquid phase characteristics

Liquid film separating from trailing edge is broken up into coarse droplets. These droplets are accelerated by the main flow. Consequently, the main parameters determining the erosion wear of rotor blades are the velocity and size of coarse droplets downstream the nozzle blade.

Fig. 5 shows the distributions of slip coefficients \( \nu = c_d / c_s \) along the pitch \( \bar{\xi} = x / t \) at the distance of \( z = 0,1 \xi \) downstream of the blades cascade for theoretical Mach number \( M_1t = 0.7 \) and two initial wetness \( y_0 = 1 \%; y_0 = 4 \% \).

It can be seen that the slip coefficient in the area \( \bar{\xi} = 0.2 – 0.8 \) for the profile No. 2 without steam injection is lower than for the profile No. 1. This may be due to the fact that part of the liquid film formed on pressure side is separated from the area of injection slot, and other part is separated from the trailing edge.

When the steam injection is enabled \( (\varepsilon_{inj}=0.8 \text{ m } \Delta T_2=73 \text{ K}) \), the slip coefficients significantly increase in comparison with the profile No. 1. The increase of the slip coefficient is due to the liquid film is broken up by the injection steam on the pressure side. This process occurs upstream the liquid film is broken from the trailing edge into the trailing edge wake, where the steam velocities and density are substantially lower than area of injection slot. Hence the drag force acting on the droplets is not sufficient for their destruction.

Increasing of the slip coefficient ratio shows that the velocity of droplets significantly increases in the trailing edge wake. Steam injection influences to the velocity of liquid phase while the steam velocity is practically not changed. As was shown in [11] this accure to decreasing of the average diameters of coarse droplets.
Figure 6 shows similar distributions of slip coefficients for $M_{1t} = 0.9$. The flow pattern of the liquid phase qualitatively coincides with the flow pattern at $M_{1t} = 0.7$.

![Graph showing slip coefficients](image)

**Figure 6.** The distributions of slip coefficients along the pitch downstream blades cascade at $M_{1t} = 0.9$; a – $y_0 = 1\%$; b – $y_0 = 4\%$

### 5. Conclusions
1. Application of steam injection on the pressure side leads to the destruction and fragmentation of the liquid film downstream the blade.
2. The distribution of the slip coefficients along the pitch of blade cascade shows that the average droplet size decreases when the steam injection is enabled.
3. The kinetic energy losses of the main flow for blade No. 2 with the injection of steam $\epsilon_{inj} = 0.65-0.8$ was increased on 15-20%.
4. Though increase of kinetic energy losses, the presence of steam injection significantly affects the characteristics of the liquid phase downstream the trailing edge. This is due to the average diameters of liquid phase is decreased downstream the blade cascade.

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