Influence of the temperature of the heating steam on the characteristics of the liquid phase downstream the stator blades of steam turbine

I Gavrilov, V Popov
National Research University "Moscow Power Engineering Institute",
Krasnokazarmennaya 14, Moscow, 111250 Russia

E-mail: gavriloviy@mpei.ru

Abstract. The paper presents the results of an experimental study of the efficiency of heating with the injection of steam on the surface of the stator blades of the last stages of steam turbines operating in the wet steam flow conditions. The major task of the research was to determine the main mechanisms of the heating temperature influence on the kinematic characteristics of the polydisperse flow of a liquid phase downstream an isolated nozzle blade cascade. Measurement of the characteristics of the liquid phase particles was carried out using a laser flow diagnostic system implemented on the basis of the "PIV-IT" complex and processing the obtained images using the PTV method (particle tracking velocimetry). It is established that heating leads to evaporation of the liquid film formed as a result of the deposition of liquid phase on the surfaces of the nozzle blades, as well as to the increase in the velocities of droplets, and as a consequence, a decrease in diameters and wetness.

1. Introduction
A feature of the steam expansion process taking place in a steam turbine is the presence of the phase transition in a low-pressure cylinder. A presence of a liquid phase leads to a decrease in the efficiency of the steam turbine and the occurrence of the rotor blade erosion hazard. The most dangerous is the coarse droplets which are formed in consequence of the liquid film separation from a blade surface.

One of the main problems in the design of the turbine elements operating in conditions of polydisperse wet-steam flow is reducing the erosion wear of rotor blades. For this, passive and active protection methods are used. Passive methods aim at improving the erosion resistance of the blade material. One of the most common active methods is the intracanal separation of the moisture from the surfaces of the stator blade. As the practice of operating steam turbines shows, these methods do not fully solve the problem of erosion wear of rotor blades. Slots on the airfoil surface at intracanal separation lead to increased kinetic energy losses. As shown in [1], this method allows reducing the wetness downstream the stator blade, but the droplet size does not change.

There are a number of promising methods that have not received wide dissemination. They can be more effective than intracanal separation [2-3]. One of such methods is heating the surface of the nozzle blades with the injection of steam to the surface profile.
As shown in [4], injection of heating steam allows bringing the loss of kinetic energy in the wet steam at the level corresponding to the plain profile, despite the presence of the slit on the surface. It was shown in [5] that the droplet sizes are decreasing downstream the nozzle blade cascade; therefore the erosion wear of the working blades is reduced. At the same time, in this work, the PIV method was used to study the effect of temperature on the characteristics of the liquid phase. In the study of the polydisperse flow of wet steam this gives only a certain averaged flow pattern.

In this paper, for a more detailed study, the PTV method was used. As a result, droplet velocity distributions were obtained from their number. This allowed us to better estimate the effect of the heating steam temperature on the characteristics of the liquid phase.

2. The experimental facility and target of research
The studies were carried out using the test bench WSC-2 (Wet Steam Circuit-2, see Fig. 1) at Moscow Power Engineering Institute. This test bench allows for studying the flow of superheated, saturated and wet steam in the flow path elements of turbo machines. Fig. 2 shows the basic heat flow diagram of the facility. The saturated steam of the steam turbine bleed is subjected to the first humidification stage (1), which is used to decrease steam temperature to the value required for injection, by injection of feed water (coming from the header (6)) into the flow. Having passed the first humidification stage steam enters the header (2). A part of the working medium comes to the test bench receiver tank (3) from the header (2). In this pipeline branch, the second humidification stage (9) is located which provides steam temperature decrease to the saturated state. The third humidification stage (4) is a steam jet block to which feed water is supplied also from the header (6). The jet block (4) is used to produce polydisperse droplets medium ahead of tested object (5). The working medium passes the studied channel mounted in the removable working part (5) and comes to the condenser (7), after that condensate returns into the power plant cycle. Supply of heating steam injected into the inter-blade channel (8) is realized due to its extraction from the header (2).

The PIV-IT laser flow diagnostic system implements the PTV (particle tracking velocimetry) method. It allows obtaining instantaneous velocity vectors for each droplet detected by the method in studied flow domain. The flow downstream the blade cascade is illuminated by a plane laser knife formed by a dual pulsed laser. It is directed through the endoscope into working part. A twin impulse laser at 400 ns intervals illuminates droplets moving downstream the blade cascade, and high-speed PIV camera takes their photos. The obtained droplet flow photos are used as initial data for the PTV
method. This technique obtains irregular vector field for each pair of photos. To process the velocity fields, an algorithm was used to exclude erroneous vectors and identify the sources of droplets, which is presented in the paper and is based on the data clustering algorithm.

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. 2). Data about cascade geometry are listed in Table 1. The cascade was installed into the working part that is shown in Fig. 2. The test conditions are 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 within the range of $\Delta T_2$ from 0 to 60 K. The superheat of the injected steam $\Delta T_2$ was determined as:

$$\Delta T_2 = T_2 - T_{s}(P_{inj})$$

(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:

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

(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.

![Figure 2](image)

**Figure 2.** The studied object (a); scheme of working part (b)

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

**Table 1.** Geometry of blade cascade

| $p_0$, kPa | $y_0$, % | $Re_v$ | $M_{tr}$ | $\varepsilon_{inj}$ | $\bar{g}$ | $\bar{c}$ |
|------------|----------|--------|----------|----------------------|----------|----------|
| 40         | 1 - 4    | $5 \cdot 10^5$ | 0.7      | 0.8          | 0.03     | 1.74     |

**Table 2.** Considered condition.
3. Results and discussion
The PTV method gives much more information than the PIV method, especially in the polydisperse flow of wet steam. As shown in the studies [5], the use of heating with steam injection on the pressure side of the profile allows reducing the average diameters in the droplet trailing edge wake downstream the blade cascade, where erosion-hazardous coarse droplets are concentrated. At the same time, it was shown that the increase in temperature practically does not affect the change in the velocity distribution (determined by the PIV method) along the pitch of blade cascade, and hence also the average droplet diameters (determined by PIV vector field and calculated main flow field [5]). In order to analyze in more detail the effect of temperature on the kinematic characteristics of the liquid phase, these same photographs were processed by the PTV method. For the same comparison, as was done in previous studies, droplet velocity distributions were determined at a distance of 0.1b downstream the blade cascade. For this purpose, a line was selected on the vector fields and divided into 1 x 1 mm cells. In each cell a probability density function is constructed and the maximum value is determined. As a result, the distribution of the droplet velocities having the maximum concentration along the pitch of the blade cascade \( \bar{t} \) (\( \bar{t} = \frac{t}{b} \), where \( t \) is the pitch of the blade cascade, mm, \( b \) is the chord of the blade, mm) is obtained, shown in Fig 3.

From the presented distributions and analysis of previous works [4-5], it is possible to isolate the area of the droplet trailing edge wake \( \bar{t} = 0.2 - 0.85 \). When the heating is turned on, the velocities increase noticeably in the range \( \bar{t} = 0.25 - 0.65 \). The distribution structure takes the shape of two peaks. An increase in temperature leads to an increase in the velocities, up to the values of fine droplets in the flow core (\( \bar{t} = 0.4 - 0.55 \)). This happens due to several reasons:

1) Crushing of a liquid film formed on a pressure side by the injected steam;
2) Heating of the blade wall and, consequently, the evaporation of the liquid film;
3) The evaporation of droplets moving near the blade wall.

It is worthwhile to distinguish separately the area \( \bar{t} = 0.65 - 0.9 \), where the velocities are lower than those in the core and the temperature of the heating steam does not affect them at all. As shown in [6], the vapor-drop boundary layer can occupy 25% of the cascade throat and heating does not affect some of these droplets.

![Figure 3](image)

**Figure 3.** The distribution of the droplet velocities along the pitch of the blade cascade.

So, based on the velocity values, we can say that a change in the temperature of the heating steam leads to a decrease in the diameters of the droplets that have the maximum concentration in the flow. In order to determine how the redistribution of droplet velocities occurs within a region \( \bar{t} = 0.25 - \), probability density functions were constructed. For correct construction of the data distribution and removal of erroneous vectors, the clustering algorithm was used that is presented in [6]. The obtained probability density functions are shown in Fig. 4.
The obtained distribution confirms that the increase in temperature of the heating steam causes a redistribution of the velocities. The maximum concentration of droplets in the absence of heating corresponds to the droplet velocities, which differ substantially from the velocity of the main flow. This indicates that coarse droplets are concentrated in this area. The inclusion of heating leads to the formation of two peak structures of these distributions. So, for $\Delta T = 6 \, K$, there is still a region in the flow corresponding to the coarse droplets without heating and the formation of a new region with an increased velocity. An increase in temperature leads to a further decrease in the concentration of coarse droplets and a transition to velocities corresponding to small droplets, as in the flow core.

In this work, the pressure ratio on the slot was kept constant. Consequently, the flow rate through the slit also did not change. That is, the process of crushing moisture due to the blowing of the steam jet was the same for all regimes. This means that the main mechanism for increasing the velocity in this case is the evaporation of the liquid and the decrease of droplets diameter.

In addition to reducing the droplet diameter, heating can reduce the concentration of droplets. Figure 5 shows the temperature of the heated steam as a function of the number of droplets defined on one frame for the areas shown in figure 4. Here $\overline{n} = n_d$ is the number of droplets in one frame, $n_d$ is the number droplets in whole PTV field, $n_f$ is the number of frames. Heating leads to a decrease in the number of droplets detected by the PTV method by approximately 10%. At the same time, the increase in temperature does not affect the number of drops.
Apparently, the minimum value of the heating steam temperature is sufficient to evaporate practically the entire liquid film moving along the blade surface. A further increase in temperature leads, apparently, only to a partial evaporation of the drop. This is due to the transfer of heat from the blade to the droplets moving near the wall. As a result, heating reduces the droplet diameters, and also evaporates part of the liquid.

1. Conclusions
The following conclusions can be made:
1. The temperature of the heating steam has a significant effect on the velocity characteristics of the liquid phase.
2. In consequence of the analysis of the obtained velocity distributions, it is established that:
   2.1 Heating leads to evaporation of the liquid film;
   2.2 Increasing the temperature of the heating steam leads to an increase in the velocity in the region of motion of coarse droplets, which may indicate a decrease in their diameter;
   2.3 Heating reduces the number of droplets downstream the blade cascade.
3. Preliminary analysis showed the promise of using the active method like blades heating to reduce the erosion wear of rotor blades.

Acknowledgements
This study was supported by the Russian Science Foundation (project No. 17-79-10181).

References
[1] Gribin V, Tishchenko A, Gavrilo V, Popov V, Sorokin I, Tishchenko V, Khomyakov S 2016 Power Technology and Engineering 50 180-187
[2] Deitch ME 1996 Gasdynamics of turbine cascades (Moscow: Energoatomizdat)
[3] Averkin N, Kachuriner Yu, Orlik V, Suharev F, Filaretov M 2004 Power plant 2 24-28
[4] Khomyakov S, Alexeev R, Gavrilov I, et. al. 2017 Journal of Physics: Conference Series 891 conf. 1. 012256
[5] Gribin V, Tishchenko A, Gavrilo V, Tishchenko V, Sorokin I, Alexeev R, Popov V, Khomyakov S 2017 Proc. 12th Conf. Turbomachinery Fluid dynamics and Thermodynamics (Stockholm) paper ID: ETC2017-312
[6] Gribin V, Gavrilov I, Tishchenko A, Tishchenko V, Popov V, Khomyakov S, Alexeev R 2017 Proc IMechE Part A. J. Power and Energy Prepublished 13 sep