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Results of the generalization of studies of wet-steam flows in steam turbine cascades using laser diagnostic systems

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Abstract. The description of experimental investigations of wet steam flows in turbine flow path elements (blade cascades) using laser diagnostics system is presented. This technique is used to obtain velocity fields of discrete phase using photos of illuminated tracers moving in the steam flow. PIV and PTV methods are used for this propose. The studies are performed on experimental rig WSC (Wet Steam Circuit) situated at Moscow Power Engineering Institute. Different ways of laser diagnostics systems application are presented. Example of experimental velocity vector field processing and analyses is presented. The way of increasing PIV/PTV methods quality using neural networks is presented.

1 Introduction

The wet steam flows in last stages of most steam turbines working at thermal power plants and all steam turbines at nuclear power plants. The existence of two-phase medium in flow paths leads to several negative processes caused by mechanical and thermodynamic interaction of liquid particles with steam flow and surfaces of inter-blade channels [1-3]. The erosion wear of turbine blades is one of these physical phenomena. This process is intensified due to the collision of liquid droplets with surfaces of inter-blade channels. It directly affects the reliability of the turbine. Besides erosion wear, thermodynamic process of nonequilibrium condensation during the steam extension in turbine flow path causes the increase of working body kinetic energy losses which leads to decreasing of turbine stage efficiency [1].

One of the most effective approaches that can provide a large amount of information about the characteristics of liquid phase particles moving in the inter-blade channels is the use of laser flow diagnostic systems [4]. In addition to providing a droplets parameters data, they also provide visual images describing complex droplets streams behavior in specific areas.

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This paper describes experimental rig and laser diagnostics system for obtaining droplets velocity vector fields in a wet steam flow and considers its application with the aim of analyzing liquid particles streams in inter-blade channels. The potential of the laser diagnostic system can be expanded by using post processing with neural network designed to detect images of illuminated drops on the obtained photos. This model and the features of its development are described in this article.

2 Experimental rig and laser diagnostics system

Experimental investigations were performed on experimental rig WSC (Wet Steam Circuit). This installation is located in Moscow Power Engineering Institute. It uses steam from power plant to investigate aerodynamic effects of flow in turbomachinery elements in a broad range of Mach numbers and steam conditions (superheated, saturated, wet).

A schematic flow diagram of WSC is shown in Figure 1. Working body from steam turbine extraction moves into the first wetting stage (1). Here its temperature decreases by injection of feed water which comes from feed water header (6). After this wetting stage, working body goes to the steam header (2). The part of fluid flow from this header goes to the receiver tank (3) passing the second wetting stage (9) which is used to achieve a saturated condition of steam. 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 the studied element of turbine flow path (5). It is mounted in removable working part. After passing studied channel, working body 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).

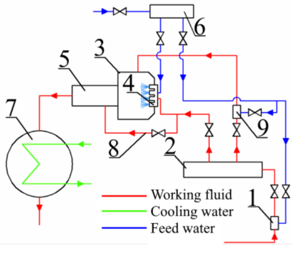
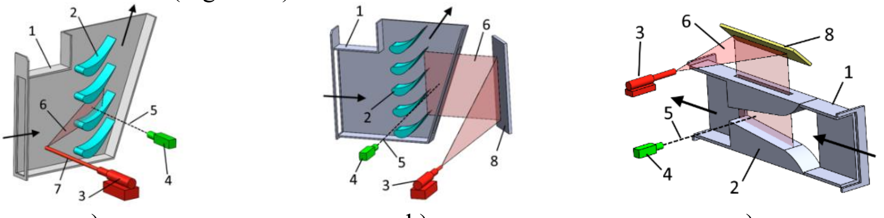


Fig. 1. Schematic diagram of WSC.

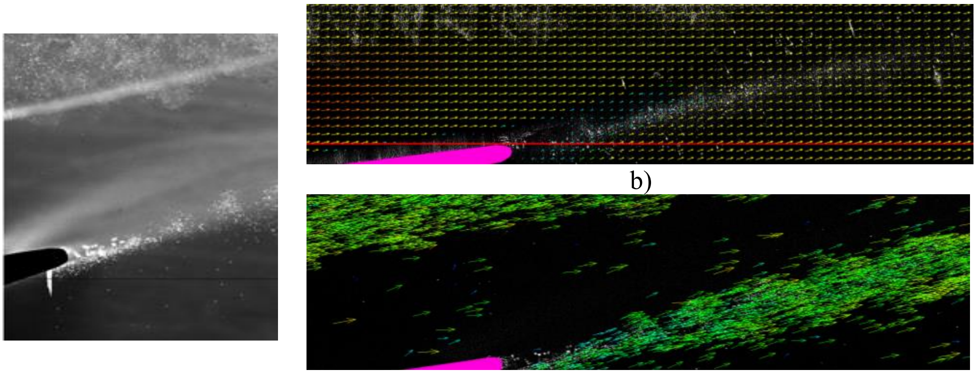
Experimental rig uses laser diagnostics system to study the droplets movement in wet steam medium flowing in studied objects [4, 5]. The examples of its application are presented in Figure 2. In the removable working part (1) the studied object (2) is installed. Coupled laser (3) makes impulse and lights up droplets moving in the steam flow. High speed PIV camera (4) makes photo of them. It’s axis (5) is oriented in perpendicular to flat laser knife plane (6). Laser beam is guided into the flow by endoscope (7) or mirror (8). Figure 2 represents different types of laser system applications – to study droplets movement inside inter-blade channel (Figure 2a), downstream the blade cascade (Figure 2b) or inside channel (Figure 2c).



a) b) c)

Fig. 2. Schemes of laser diagnostic system application to study wet steam flows: in inter-blade channel (a), downstream a blade cascade (b), inside channels (c).

Current laser diagnostics system utilizes two algorithms: PIV (Particle Image Velocimetry) and PTV (Particle Tracking Velocity), which are used to estimate droplets velocity vector fields. Typical photo of illuminated droplets is presented in Figure 3a, while results of PIV and PTV algorithms are shown in Figure 3b and Figure 3c respectively.



a) b) c)

Fig. 3. Typical photo, obtained by laser diagnostics system (a), velocity vector fields obtained by PIV (b) and PTV (c).

PIV method calculates droplets velocity vectors on regular grid, estimating average value in a cell, while PTV algorithm determines velocity vector of each separate detected droplet. There are two main features of laser diagnostics system used to study wet steam flows:

a) The contactless approach in determining droplets velocity allowing perform investigation with minimal aerodynamic disturbance.

b) It provides photo of droplets structure moving inside elements of turbine flow paths allowing visual analyses of liquid particles streams (it's behavior, location of its source and direction of propagation).

So, it is a very powerful tool in studying wet steam flow behavior in turbine flow paths elements.

During the experimental session for certain wet steam flow regime in a studied channel, laser diagnostics system takes about 1000 – 5000 pairs of illuminated droplets photos. They are used by PIV and PTV algorithms to calculate vector fields and make statistical analyses of obtained data. During the use of laser diagnostics system on the WSC experimental rig, more than 20 turbine blade stages have been studied, for each of them more then 20 flow conditions were performed. Generalization of obtained experimental results allowed to formulate the features of droplets generation, movement and their interaction with surfaces of inter-blade channels.

3 Example of laser diagnostics system application for studying wet steam flows

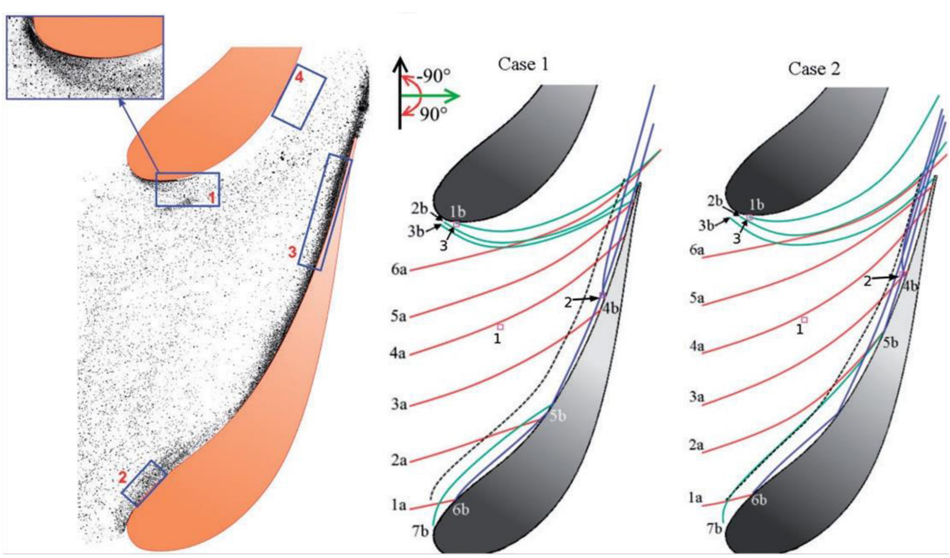
The example of droplet's stream's structure is shown in Figure 4a [6, 7]. This photo represents illuminated by laser beam liquid phase droplets (black dots) in the inter-blade channel. Basic features of droplets distribution common for most cases of flow regimes are observed. There are two types of particles in the flow - primary and secondary. Droplets at blade cascade inlet are primary (generated by sprayers in receiver tank of experimental rig). Secondary particles are produced during the interaction between primary droplets and inter-blade walls (or liquid films on blade surfaces). One can see several zones common for all wet steam flows regimes in blade cascades (see Figure 4a). There is a ‘‘fountain’’ of secondary liquid particles (zones 1 and 2) at the leading edge of the blade. These droplets are formed due to the collision of primary droplets with this surface and its subsequent breakup. Droplets generated in ‘‘fountain’’ near the blade pressure side (zone 2) move along this surface while particles near the suction side (zone 1) move into the flow core and cross the inter-blade channel. As one can see from the visual data presented in Figure 4a, the maximum concentration of liquid particles is observed near the blade pressure side (zone 3). Streams of these droplets together with steam flow and liquid fllm form two-phase boundary layer. The aerodynamic shadow for the droplets – not achievable for liquid particles zone is observed near the blade suction side (zone 4). The concentration of liquid particles is minimal for this area.

Observed distribution of liquid droplets streams is common for all studied blade cascades and steam flow regimes. Experimental studies performed on different geometries and for different working body flow conditions allowed to identify the influence of different parameters on liquid particles streams behavior and droplets characteristics in different zones. As an example, Figure 4b represents trajectories of droplets streams originated at different points of inter-blade channels. These results are obtained by processing data PTV calculated droplets vector fields [7]. Two cases are shown: $\bar{\rho} = 3685$ and $\bar{\rho} = 2585$. Here $\bar{\rho}$ – density ratio:

$$\bar{\rho} = \frac{\rho_l}{\rho_s},$$

where ρ_l – liquid phase density at inlet, ρ_s – steam phase density at inlet.

Red color of lines corresponds the primary droplets, while green – secondary particles. As one can see, primary and secondary droplets have different behavior of droplets streams trajectories which is connected with average diameters, areas of its origin and zones of movement. Secondary droplets originated from blade leading edge (trajectories 1b, 2b, 3b) have considerably curved trajectories.



a) b)

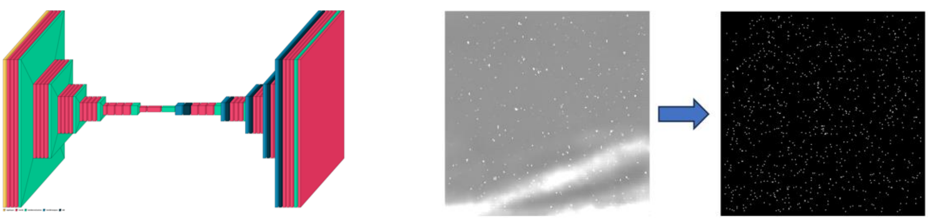
Fig. 4. The structure of liquid flow in inter-blade channel (a) and trajectories of primary and secondary droplets (b): case 1 $\bar{\rho} = 3685$; case 2 $\bar{\rho} = 2585$.

With parameter $\bar{\rho}$ decrease (the transition from Case 1 to Case 2), these trajectories move closer to the blade surface. This can be explained by increase of aerodynamic impact on droplets from the steam flow, because density of gas phase increases.

4 Using neural network to increase efficiency of laser diagnostics system

Presented example of laser diagnostics system application for wet steam flows investigations is a part of results, which can be obtained during the study. PIV/PTV methods may be used in development of blade profile geometry or liquid film evacuation systems for last stages of steam turbines. Laser diagnostics system application for wet steam flows is accompanied with negative optical effects connected with the appearance of liquid phase presence – appearance of liquid films on optical glasses, overexposure of obtained photos, interference of laser knife. These features cause the low quality of obtained photos and as result PIV/PTV data for different flow regimes (especially at high initial wetness). First of all, PIV/PTV methods cannot correctly detect droplets (and pairs of droplets) on low quality photos of illuminated particles. While the human eye clearly sees the image of liquid particle. As a result, in order to increase the efficiency of these techniques one can apply neural network model to detect liquid particles on photos, by “cleaning” described negative effects.

The prepared neural network presents the combination of encoder-decoder architectures with skip connections. The structure of developed model is presented in Figure 5a and consists of groups of convolution layers. This neural network gets the photo obtained by the laser diagnostics system (for example, as shown in Figure 3a) and “cleans” it leaving only images of droplets. Figure 5b represents the input photo of liquid phase droplet’s structure and the result of neural network application.



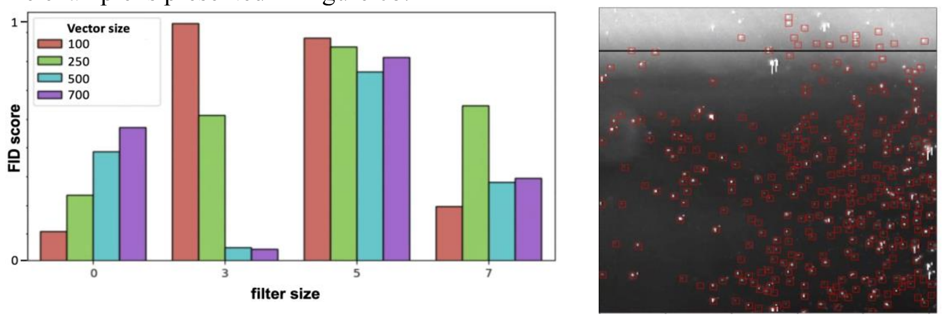
a) b)

Fig. 5. Architecture of neural network (a), postprocessing procedure of neural network (b).

The ability to prepare and train such neural model is due to accumulation of amount of experimental data obtained for years by laser diagnostics system application. Preparation of training and validation datasets requires the knowledge about position of every droplet on the photo. Each picture of liquid particles streams structure in steam flow contains up to several hundred thousand images and it’s impossible to mark out them manually. For this reason, training and validation datasets were prepared by combing photos of different backgrounds (relevant to obtained by laser diagnostic system photos) generated by DCGAN neural model and samples of drops images located on them in an arbitrary place. These particle images were taken from manually prepared library containing over 50000 elements of different droplets structures.

DCGAN neural model was trained on real photos obtained by laser diagnostics system. Synthetic images generated by this network are supplemented with image of droplets position (see Figure 5b). The complex behavior of illuminated droplets structures requires fine tuning of DCGAN model to generate realistic photos. Different variants of neural network hyperparameters were studied to obtain the most realistic images. Influence of the latent vector size and post averaging filter size were studied. The Frechet Inception Distance (FID) [8] was used to examine the quality of the trained model. The comparison of FID score normalized value of different variants is presented in Figure 6a. The lowest value of FID is achieved for DCGAN model with latent vector size 700 and averaging filter size 3.

As a result, neural network for detecting droplets images on photos obtained by laser diagnostics system (see Figure 5a) provides the post process of experimental data in a such a way that PIV/PTV algorithms correctly detect droplet's positions for low quality photos. The example is presented in Figure 6b.



a) b)

Fig. 6. Comparison of FID score for DCGAN model (a), example of detected droplets using developed neural network (b).

5 Conclusions

The results of using laser diagnostic systems to study wet steam flows created a theoretical and practical basis for implementing various solutions aimed at increasing the efficiency and reliability of the last stages of steam turbines. The features of the distribution of droplet flows in different flow zones in the elements of the flow paths of turbomachines were studied. Reliable information was obtained on the processes occurring in the interblade channel and determining the nature of the formation of droplet flows behind the turbine cascade.

With the development of computing capabilities, the approaches used in laser flow diagnostics systems to determine droplet parameters from photographs can be significantly expanded using neural networks. A general approach to their application in this area has been formulated. The existing accumulated set of information allows creating a high-quality training dataset that is critical for training neural networks.

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