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APPLICATION OF NEURAL NETWORKS TO ANALYZE THE BEHAVIOR OF LIQUID PHASE PARTICLES IN THE ELEMENTS OF FLOW PATHS OF TURBOMACHINES

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Abstract The article discusses the issue of using neural networks to analyze the nature of the movement of droplets in the interblade channels of turbomachines. An experimentally verified computational model was used to analyze the parameters affecting the process under study. A set of 23 independent parameters was identified. They included both regime parameters and geometric ones. The presented set of parameters uniquely determines the behavior of a liquid particle moving through the channels of turbomachine cascades. The applicability of neural networks to analyze the behavior of droplets in the interblade channels of turbomachines is considered. For this purpose, a neural network was created that predicts the proportion of secondary droplets formed during the interaction of primary moisture with the surface of a turbine blade.

Key words: wetsteam, steam turbine, turbine blade, droplets, neural network.

AMS Mathematics Subject Classification: 76-04, 76-05, 76-10, 76T10, 76N99.

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1 Introduction

An important feature of the last stages of steam turbines is the presence of a liquid phase in the steam flow. Processes caused by the presence of a liquid phase negatively affect the aerodynamic characteristics and reliability of the flow path in low-pressure cylinders (LPC) of steam turbine units. Large droplets generated in the flow path are involved in the processes of erosive wear of the surfaces of the working blades. While fine submicron moisture primarily participates in thermodynamic interaction with a continuous medium. To combat these phenomena, a number of measures are implemented in the turbine design, for example, organizing the removal of moisture from the flow path through separation slits located on the elements of the LPC casing or hollow nozzle blades [1]. The efficiency of such solutions is determined by many factors. Which depend both on the design implementation and on the parameters of the wet-steam flow [2].

By now, a huge amount of experience has been accumulated in the design and operation of condensing steam turbines. However, issues related to the formation and movement of the liquid phase remain relevant at the moment. This is due to the complexity of studying the processes occurring in wet-steam flows under such conditions. This task represents is a complex problem [3]. Existing calculation methods do not allow modeling the movement of wet steam flows with sufficient accuracy. Therefore, an experiment plays a significant role in such studies.

At present, modern methods of laser diagnostics have been successfully applied to study a wet steam flows [4]. This has allowed us to significantly expand our knowledge and understanding of the movement of the liquid phase in the channels of turbomachine cascades [3]. However, in order to use these data for designing the flow paths of steam turbines, they must be generalized and unified. This must be done in a wide range of geometric and operating parameters of the aerodynamic system. This task is quite difficult due to the complex shape of the interblade channels and a significant number of factors associated with the properties of the medium and operating conditions. This paper considers an approach using neural networks to solve the problem of the movement of the liquid phase in the interblade channels of steam turbines.

2 Model of liquid phase movement in interblade channels of steam turbine grates

To analyze the processes of wet steam flow in the interblade channels of turbomachine cascades, a model of the motion and formation of the liquid phase was developed. The method is based on the calculation of the motion of a discrete medium in the field of parameters of a continuous medium.

The continuous medium is steam in a saturated state. The calculation of the continuous medium motion is performed in the CFD package Ansys Fluent. The integration of additional software modules into the CFD code made it possible to ensure accurate calculation of wet steam parameters. This was confirmed by comparing the obtained data with the experimental results [5].

To calculate motion and formation of a liquid phase, a combination of several models is used. The calculation of the motion of droplets in a steam flow is based on the aerodynamic resistance force. According to the results of experimental studies [6], this force determines the nature of the droplet movement in the flow. The aerodynamic force acting on droplets in a polydisperse flow of wet steam is described based on [7, 8, 9]. In general, this force can be represented as a parametric dependence:

$$\overrightarrow{F_{df}} = f(d_d, \overrightarrow{c_d}, \rho_d, \overrightarrow{c_{st}}, M_{st}, \rho_{st}, \mu_{st}), \quad (1)$$

where d_d is the droplet diameter, $\overrightarrow{c_d}$ is the droplet velocity vector, ρ_d is the water density in the droplet, $\overrightarrow{c_{st}}$ is the steam velocity vector, M_{st} is the steam Mach number, ρ_{st} is the steam density, μ_{st} is the dynamic viscosity of steam.

A semi-empirical approach was formulated to calculate the interaction of droplets with an interblade walls [10] and the formation of secondary droplets [11, 12, 13]. This approach allowed us to present the parameters of the forming secondary moisture particles in the form of a parametric dependence:

$$(\overrightarrow{c_{d_i}}, d_{d_i}) = f(t_w, d_{d0}, \overrightarrow{c_{d0}}, \overrightarrow{c_{n0}}, t_{d0}, A, B, C, D, E, F), \quad (2)$$

where $\overrightarrow{c_{d_i}}$ is the velocity vector of the secondary droplet, d_{d_i} is the diameter of the secondary droplet, t_w is the surface temperature, d_{d0} is the diameter of the primary droplet, $\overrightarrow{c_{d0}}$ is the velocity vector of the primary droplet, $\overrightarrow{c_{n0}}$ is the vector of normal component of the velocity of the droplet relative to the wall, t_{d0} is the temperature of the primary droplet, A, B, C, D, E, F are empirical coefficients wich were selected based on the results of experimental studies [14].

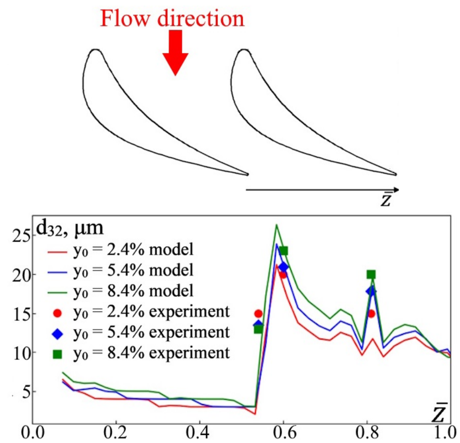

Figure 1: Comparison of droplet diameters behind turbine blade cascade obtained by simulation and experiment.

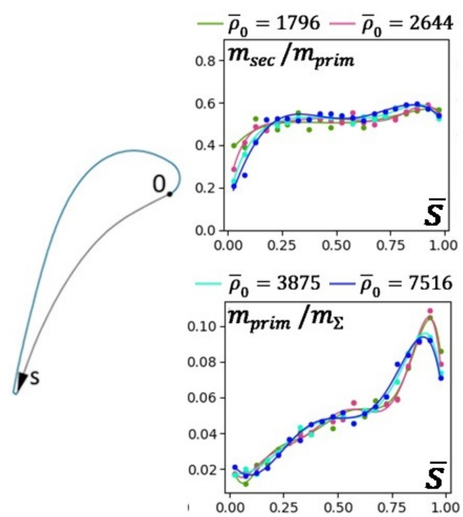

Figure 2: Distributions of interaction parameters of primary drops along the concave surface of a blade at different vapor densities.

The developed model was supplemented with equations describing the nature of the formation, movement and destruction of the liquid film on the surfaces of the interblade channels [15, 16, 17, 18]. In general, the velocity vector $\overrightarrow{c_f}$ and thickness h_f of the film can be represented as a parametric dependence:

$$(\overrightarrow{c_f}, h_f) = f(y_0, t_w, d_{d0}, \overrightarrow{c_{d0}}, \overrightarrow{c_{n0}}, P_{st}, t_f, \bar{l}, A, B), \quad (3)$$

where y_0 is the initial steam wetness, P_{st} is the pressure of the main flow, t_f is the film temperature, $\bar{l}$ is the vector characterizing the surface curvature.

The final model was formed as a set of the models described above. The model allowed us to calculate the parameters of the droplet flow behindthe turbine blades cascade [19]. The reliability of the data obtained using the model was confirmed experimentally. The Sauter droplet diameter was chosen as a criterion for assessing the accuracy of the modeling:

$$d_{32} = \sum_{i=1}^{\infty}(n_i \cdot d_i^3) / \sum_{i=1}^{\infty}(n_i \cdot d_i^2), \tag{4}$$

where n_i is the number of droplets with diameter d_i.

Fig. 1 shows the calculated distributions of the value of d_{32} downstream the turbine blades cascade along the pitch. In the region of large droplet motion, the data are in good agreement with the experimental values.

For a detailed analysis of the influence of operating factors on the movement of moisture in the interblade channel, modeling was carried out in a wide range of relative density of the medium $\overline{\rho}_0 = \rho_0/\rho_s t$. Fig. 2 shows the obtained ratio of the mass of secondary droplets formed m_{sec} to the mass of primary droplets m_{prim} and the ratio of the mass of settled primary moisture to the total mass of primary droplets that collided with the entire surface m_{Σ}.

3 Parameters that uniquely determine the behavior of droplets movement in the interblade channel of turbine cascade

In [20] a parameterized approach to the description of turbomachine blade profiles is proposed. Combining developed model with this approach makes it appropriate to use neural networks for modeling. To do this, it is necessary to select a set of parameters that uniquely determine the behavior of a droplet in the interblade channel. These parameters can be divided into regime and geometric ones.

The list of regime parameters can be determined by analyzing and comparing the parametric dependencies (1-3). First of all, it is necessary to take into account that in most cases the steam and liquid in the channel are in the saturation state. This allows us to reduce the parameters of the medium properties:

$$(y_0, P_{st}, M_{st}, \rho_{st}, \mu_{st}, \overrightarrow{c_{st}}, t_d, t_f, \rho_d) = f(y_0, P_0, P_z), \tag{5}$$

where P_0 is the inlet total pressure of the main flow, P_z is the static pressure downstream the cascade.

The kinematic parameters of the droplet should characterize its movement relative to the steam flow. They can be presented as the slip coefficient of the droplet $\nu = |\overrightarrow{c_d}|/|\overrightarrow{c_{st}}|$ and the misalignment angle $\Delta\alpha = \widehat{\overrightarrow{c_d}\overrightarrow{c_{st}}}$. In general, the set of regime parameters that uniquely determine the trajectory of any droplet in the interblade channel can be represented as:

$$\overline{P_d} = f(y_0, P_0, P_z, d_d, \nu, \Delta\alpha). \tag{6}$$

If there is intensive heat exchange from the surface of the blade, it is necessary to enter the wall temperature parameter t_w.

The nature of the interaction of the droplet with the surfaces of the interblade channel is determined by the geometry parameters. The blade profile itself has a complex shape and can be monosemanticaly determined using 13 parameters (Fig. 3(a)) [20].

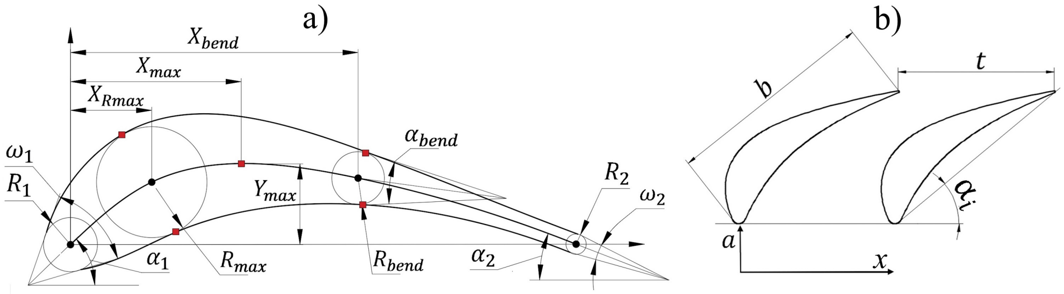

Figure 3: Parametric representation of turbine blade profile (a) and particle position in turbine blade cascade (b).

The shape of the interblade channels of the turbine cascade will be additionally determined by the profile installation angle α_i and the relative cascade pitch $\bar{t} = t/b$ (where t is the cascade pitch, b is the profile chord). The monosemantic position of the droplet will be determined by its relative distance to the cascade front $\overline{a} = a/b$ along the turbine axis and the relative distance from the center of the circle describing the leading edge along the cascade pitch $\overline{x} = x/t$ (Fig. 3(b)).

Thus, the influence of geometric factors on the behavior of a droplet moving through the channels of turbomachine grates can be uniquely determined using 17 independent parameters:

$$\overline{L_b} = f(\alpha_1, \alpha_2, X_{max}, Y_{max}, R_1, R_2, \omega_1, \omega_2, X_{Rmax}, R_{max}, X_{bend}, R_{bend}, \alpha_b end, \bar{t}, \alpha_i, \overline{a}, \overline{x})$$

Based on the analysis, 23 independent parameters can be identified that uniquely determine the behavior of a droplet when moving in the interscapular channel. These parameters will be transmitted as input data to the neural network.

4 Application of neural network to analyze the behavior of liquid phase particles

To test the hypothesis about the applicability of neural networks for analyzing the behavior of droplets in the interblade channels of turbomachines, the problem of interaction of droplets with the surface of a turbine blade is considered. A fully connected neural network is built that predicts the appearance of secondary droplets and their mass fraction of primary moisture.

The input parameters: the Mach number M_{1t}, the relative coordinate of the primary droplet $\overline{s}$, the diameter of the primary droplet d_0, and the components of the primary droplet velocity vector c_x and c_y. The output parameter is the mass fraction of secondary droplets δm. When constructing the neural network, four architecture options were considered (Fig. 4(a)). The ReLU activation function is used for all hidden layers and Tanh for output layer. The models were compiled using the Adam optimizer and the Mean Squared Error (MSE) loss function. The metric for assessing the quality of training is Mean Absolute Error (MAE). The dataset consisted of 116 150 rows. The training sample was 80%. The final validation MSE $= 0.043$.

To predict the behavior of liquid particles in the channels of turbomachine cascades, it is proposed to use a set of three neural networks (Fig. 5). The first neural network predicts main steam flow parameters along the walls of interblade channels (1 in Fig. 5). The second predicts droplet deposition on the inter-blade channel wall (2 in Fig. 5).

a)

	Model 1	Model 2	Model 3	Model 4
Hidden layers number	3	5	4	7
Neurons number in hidden layers	12, 24, 12	14, 28, 56, 28, 14	14, 28, 28, 14	14, 28, 28, 56, 28, 28, 14
MSE	0,061	0,054	0,06	0,043

b)

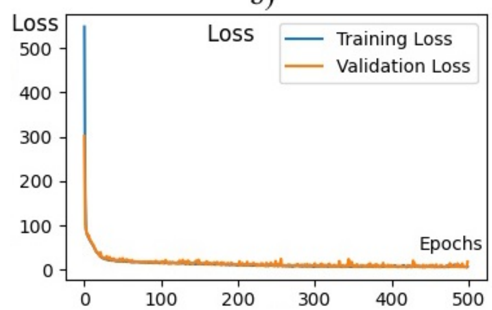

Figure 4: Architecture options of considered neural network (a) and training process of the best one (b).

The third predicts the process of secondary droplets generation (3 in Fig. 5). In turn, the output data from the third neural network is supplied to the input of the second to predict the behavior of secondary moisture in the flow.

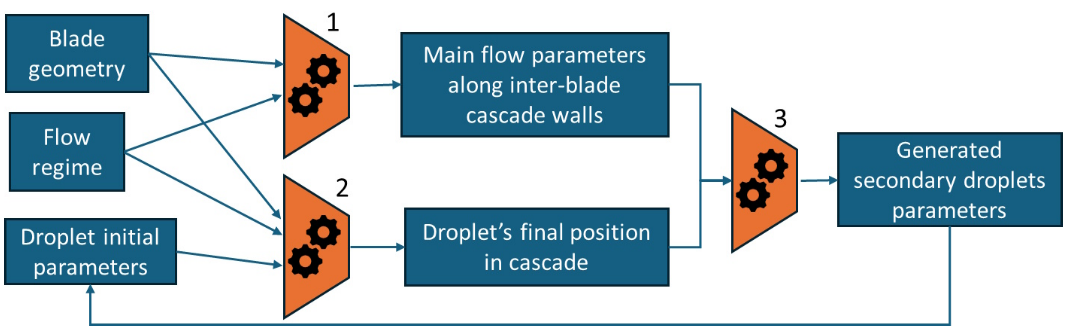

Figure 5: Droplets parameters predicition pipeline.

5 Conclusions

The use of an experimentally verified model of droplet motion made it possible to identify a set of parameters that uniquely characterize the behavior of a droplet in the channels of turbomachine cascades. The set contains 23 parameters. The regime parameters characterize the physical properties of the medium, the kinematics of the droplet, and its interaction with the main flow. The geometric parameters characterize the shape of the interblade channel of the turbine cascade and the position of the droplet in this channel.

To predict the mass fraction of secondary droplets, a fully connected neural network of 10 layers was trained. The number of neurons in the layers varied from 6 to 96. The final validation error MSE was 2.8. This confirms the prospects for using neural networks to model complex processes of liquid phase motion in turbomachine cascades channels.

A concept of using neural networks to predict droplet behavior has been developed. The algorithm involves the combined use of three neural networks to predict the parameters of the main flow, droplet deposition and secondary moisture formation.

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