

TURBINE BLADE PROFILE DESIGN USING BEZIER CURVES

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ABSTRACT

The main objective of this research is to create technique of blade profiles design for wet steam turbines. The first results of this study are presented here. In addition to high aerodynamic efficiency, turbine blades working in wet steam conditions should be designed in order to minimize erosion damage caused by discrete liquid phase. Geometry of blade profile plays an important role in the processes of coarse droplets formation in blade passages (droplets separation on blade surfaces, liquid film breakup near trailing edge etc).

In the first part of this paper a parametric method of turbine blade profile design is observed. It uses Bezier curves in order to form profile shape.

Experimental results of coarse droplets movement in blade passage are presented in the second part of this paper. Data is obtained by optical laser method PTV (particle tracking velocimetry). Interaction of droplets with blade leading edge and pressure side surface has been considered. On the basis of experimental data some modifications of original blade have been made in order to control trajectories of coarse droplets, originated near the leading edge of the blade.

KEYWORDS

BLADE, LIQUID PHASE, COARSE DROPLETS, WET STEAM

NOMENCLATURE

t – parametric coordinate of Bezier curve
[0;1]

P – array of Bezier curve control points.

Index “c” – for camber line, “ss” – for suction side, “ps” – for pressure side

m – degree of Bezier curve

ω_1 – leading edge wedge angle

ω_2 – trailing edge wedge angle

R_{max} – maximum radius of circle which can be inscribed in profile

X_{rmax} – coordinate of circle with R_{max}

R_{ut} – radius of circle inscribed in profile at the cascade throat

X_{ut} – coordinate of circle with radius R_{ut}

α_{ut} – angle of unguided turning

α_1 – angle of tangent to camber line at start point

α_2 – angle of tangent to camber line at end point

R_1 –leading edge radius

R_2 –trailing edge radius

X_{max} – location of point of camber line along axis OX with maximum coordinate Y

Y_{max} – maximum value of camber line coordinate Y

$R(t_{camb})$ –function radius distribution of inscribed in profile circles

a_i – the coefficient of the polynomial $R(t_{camb})$

t_{camb} –parametric coordinate of camber line

k – ratio of specific heats

M_{1t} – theoretical Mach number downstream the blade cascade

b – blade chord

t_b – blade spacing

p_0 – total pressure upstream the blade cascade

A_d – cross-sectional area of the droplet
 C_x – aerodynamic drag coefficient of spherical particles
 c_g – velocity of the steam flow

c_d – droplet velocity
 a_d – droplet acceleration
 m_d – droplet mass
 α_d – droplet angle of motion.

INTRODUCTION

The improvement of aerodynamic properties of axial turbine blades is one of the fundamental issues in designing modern turbines. Especially this problem is relevant for wet steam turbines. The presence of discrete phase in the flow has a significant influence on efficiency and reliability of machine. One of negative effects connected with liquid droplets movement in the turbine is an erosion damage of blades.

The problem of blade profile design with desirable aerodynamic characteristics has already been studied in detail. A lot of different methods are presented (Nixing et al., 2007). From the point of view of aerodynamic efficiency, blades that operate in stages of modern turbines have approximately optimized geometry. This is due to the numerous experimental and computational data about the efficiency of blade profiles which are used to optimize the geometry of blade passage (Perret et al., 1998, Cadrecha et al., 2011).

The erosion damage of turbine blades is caused mainly by coarse droplets. Extraction of liquid films from blade surfaces and erosion-resistant materials are used to minimize the negative effects connected with this process. Another important factor which can also increase the reliability of turbine stage is designing blades geometry, taking into account the presence of the liquid phase in the flow (Deitch, 1996). Knowledge about the parameters distribution of coarse droplets in the blade cascades and downstream of them (velocity, exit angle, size) is required.

Previous studies have shown that the structure of the droplets streams in the nozzle blade cascade has a rather complicated form (Deitch, 1996), which is represented in Fig. 1. It should be noted that the formation and movement of the liquid phase particles (except of group I in Fig. 1) is virtually impossible to model, because a lot of factors must be taken into consideration for its mathematical description (Fillipov et al., 2014; Gribin et al., 2015a): the parameters distribution of the main flow, the film flow conditions, wave structure on the film surface, and so on.

The application of modern experimental approaches, based on the flow laser diagnostics systems, allows to study the features of motion of erosion-hazardous droplets in details (Gribin et al., 2015b; Gavrilov et al., 2014).

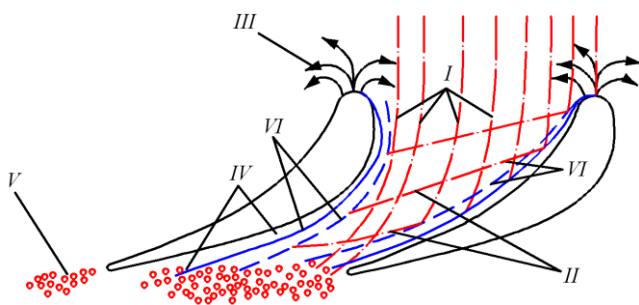


Figure 1: The scheme of droplets movement in the nozzle blade cascade. I – the primary droplets; II – droplets reflected by pressure surface, embossed by primary drops or stripped from the film on the pressure surface by the steam flow; III – droplets, reflected by the leading edge, splashed from the film at the inlet section of the profile; IV – droplets formed from the film on confuser and diffuser sections of suction surface downstream the throat; V – droplets formed due to the film split, running from the trailing edge; VI – wet steam boundary layer over the film.

In this paper, a simple and fast method of turbine profile design based on Bezier curves is given. It takes into account 13 parameters. In the second part of the paper the experimental data

about droplets movement in blade passage is presented. This information has been obtained by using laser diagnostics system with PTV (particle tracking velocimetry) method. The parameters of the mathematical model of coarse droplets movement near the blade leading edge were chosen so as to represent the experimental data. Using this model, initial blade geometry was modified in order to optimize the coarse droplets streams near the leading edge of the blade.

DESCRIPTION OF BLADE PARAMETERIZATION METHOD

The presented method is based on usage of parametric Bezier curves. Its shape is defined by an array of control points (P). A general equation of Bezier of degree m can be written as:

$$S_m(t) = \sum_{i=0}^m B_i^m(t) P_i. \quad (1)$$

B_i^m – Bernstein coefficient, defined as:

$$B_i^m(t) = \frac{m!}{i!(m-i)!} t^i (1-t)^{m-i}. \quad (2)$$

Bezier curves have several advantages that are important for the blade profile design process: they are smooth (their first and second derivatives exist and are continuous); they follow polygonal line formed by control points; these curves are situated in convex hull, formed by control points.

In the presented method Bezier curves are used to represent the geometry of the camber line, suction and pressure sides of blade profile. Thus the main aim is to identify the array of control points for each curve.

The blade profile parameterization method uses 13 parameters. They are presented in Fig. 2. In order to simplify the computational process, the blade profile is oriented and scaled, so the centers of circles of leading and trailing edges are situated at $X = 0$; $Y = 0$ and $X = 1$; $Y = 0$ respectively.

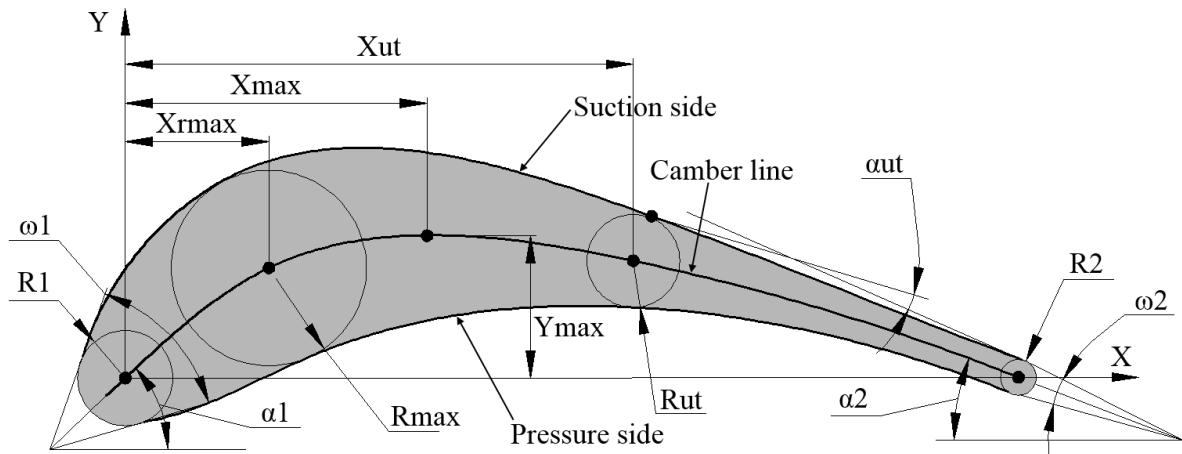


Figure 2: Blade parameters

Chosen parameters are directly connected with gas-dynamic and mechanical properties of the turbine blade cascade. R_{max} , X_{rmax} have a sufficient influence on the moment of inertia and the moment of resistance of the profile; R_{ut} , X_{ut} , α_{ut} define the throat and spacing of blade cascade; α_1 , α_2 define the inlet and exit angle of flow correspondingly as well as their combination define the stagger angle; ω_1 defines sensitivity of profile operation at non-design inlet angles of the flow. Parameters X_{max} , Y_{max} are included in this method on the basis of analyzing different geometries of known turbine blades. They have significant influence on static pressure distribution along the blade sides and location of boundary layer transition from laminar to turbulent conditions on the suction side of the blade profile. At current stage of method development any correlations between chosen

profile parameters and optimal characteristics of the blade cascade (spacing, angle of installation etc.) are not presented.

The process of turbine profile calculation is divided into several stages.

1. Calculation of the profile camber line. Its shape is presented as a Bezier curve of degree $m=4$. The array of control points for this curve (P_c) is calculated by solving the system of non-linear equations using the modified Newton method (Atluri et al., 2009). The general behavior can be presented as:

$$P_c = f_1(\alpha_1, \alpha_2, R_1, R_2, X_{max}, Y_{max}). \quad (3)$$

2. Calculation of radius distribution of inscribed in profile circles. This function $R(t_{camb})$ corresponds polynomial with degree 7 and can be written as:

$$R(t_{camb}) = \sum_{i=0}^7 a_i t^i = f_2(t, \omega_1, \omega_2, R_1, R_2, R_{max}, X_{rmax}, R_{ut}, X_{ut}, \alpha_{ut}). \quad (4)$$

Thus, as a result of first two stages we have a camber line with circles distribution along it (see Fig. 3a). Pressure and suction sides of profile, as was mentioned above, have to be tangent to these circles.

3. Calculation of pressure and suction sides arrays of control points P_{ss}, P_{ps} . General relations for P_{ss}, P_{ps} are presented as:

$$P_{ss} = f_3(R_1, R_2, \omega_1, \omega_2, R_{max}, X_{max}, R_{ut}, X_{ut}, R(t_{camb})). \quad (5)$$

$$P_{ps} = f_4(R_1, R_2, \omega_1, \omega_2, R_{max}, X_{max}, R_{ut}, X_{ut}, R(t_{camb})). \quad (6)$$

In order to fit pressure and suction sides to parameters described in (5) and (6) a multidimensional minimization method is used. This process is not a standard optimization method in the sense that location parameters (t_i) and control points have to be estimated separately. In order to increase calculation speed the L-DFGS method was used (Wenny et al., 2012). It allows solving simultaneously t_i and the control points array.

The advantage of the current profile design method is the possibility of using Bezier curves in a broad range of degree (m). It is important for blade profiles with complex geometry (profiles with high deflection, convergent-divergent blade passages, dolphin-shaped blades etc). The approbation of the developed method has shown degrees of Bezier curves for pressure side $m = 6$ and for suction side $m = 8$. It allows one to design common blade profiles in a broad range of geometry. In Fig. 3b the example of generated profile geometry together with the polygonal lines of curves control points is shown.

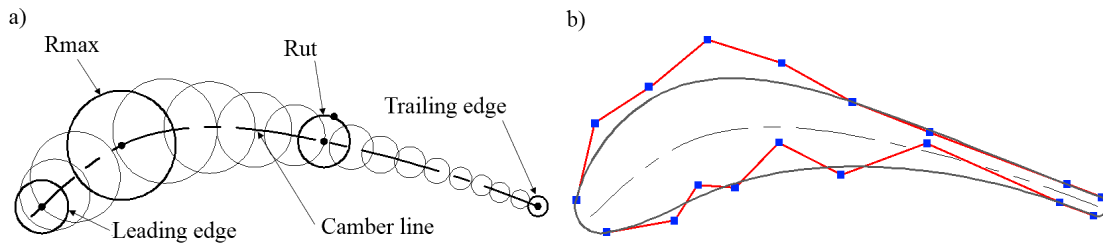


Figure 3: Distribution of inscribed in profile circles (a) and generated profile with polylines of curves control points (b)

MODIFICATION OF TURBINE BLADE PROFILE WITH KNOWN GEOMETRY

In this section opportunities of the developed method are shown. The developed method allows creating effective technique describing the known geometry of blade profile using selected

parameters. All 13 parameters can be determined on the basis of a list of points forming pressure and suction sides. An algorithm of this method is presented in Fig. 4.

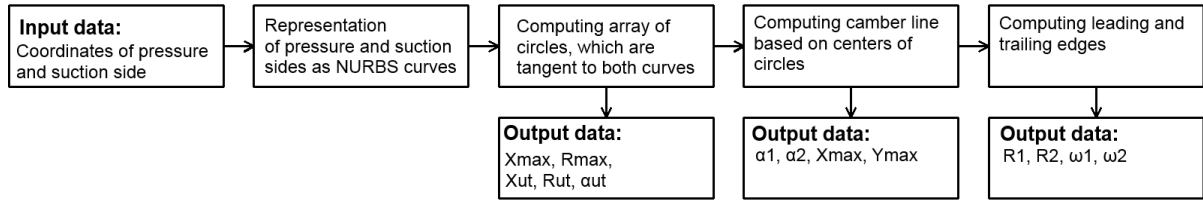


Figure 4: Algorithm of representation of blade profile

Pressure and suction sides are represented as NURBS curves. This process is implemented by the method described in (Becker et al., 2011). Presentation in the form of rational B-splines allows defining a tangent and curvature of the curve at any point. Based on NURBS curves the array of circles which touch both pressure and suction sides is calculated. It leads to the definition of parameters R_{max} , X_{max} , R_{ut} , X_{ut} , α_{ut} . The geometric loci of circles centers form a camber line, so it will be possible to calculate α_1 , α_2 , X_{max} , Y_{max} . Parameters R_1 , R_2 , ω_1 , ω_2 are calculated on the basis of tangents of NURBS curves in endpoints. Accuracy of reproduction of profile geometry essentially depends on the order of NURBS curves and the number of circles that have been used to describe the camber line. Achievable absolute inaccuracy is less than 0.005 mm.

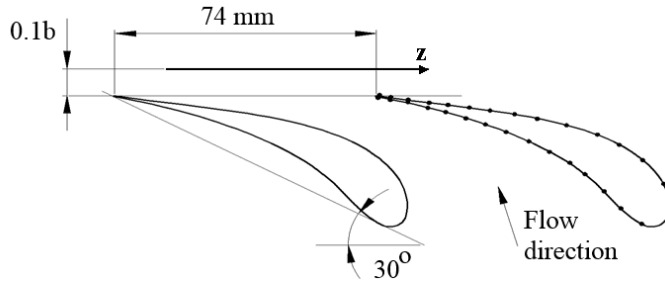


Figure 5: Studied nozzle blade cascade

The origin nozzle blade profile generated using described technique is shown in Fig. 5 (initial points are shown as markers). The blade chord $b = 92.5$ mm; flow inlet angle 105° . This geometry will be used in the next section in order to study the coarse droplets movement. The examples of the origin blade modification using the developed technique are shown in Fig. 6. The following parameters have been changed: R_{max} , ω_1 , Y_{max} (while other remained constant).

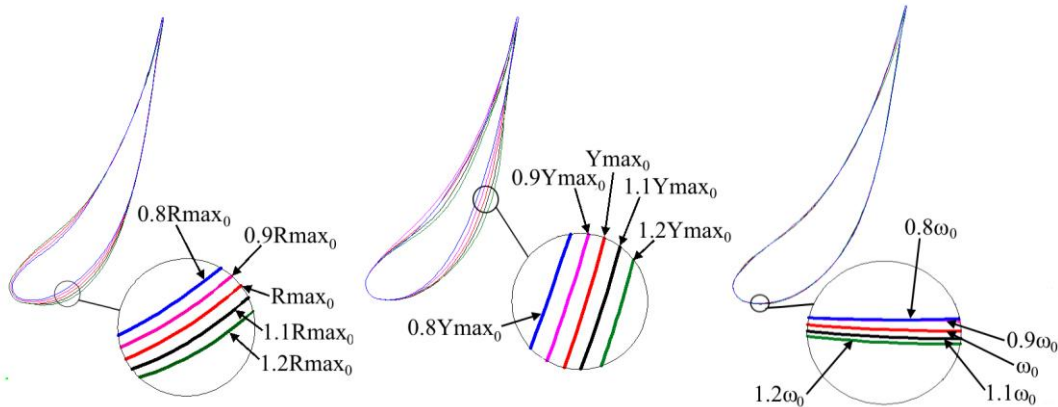


Figure 6: Examples of modified blade profiles

MODIFICATION OF BLADE PROFILE IN ORDER TO CONTROL COARSE DROPLETS STREAMS

The first results regarding to control of coarse droplets movement in blade passage using blade profile geometry modification are presented. Also some results of experimental study of liquid phase movement in inter-blade channel of the nozzle blade cascade are presented.

As was mentioned before, the processes of interaction between droplets and blades surfaces are very complicated and it is difficult to calculate them using mathematical models. Especially it relates to the problem of droplets interaction with the wall and liquid films. So, the fundamental principles of axial blades design from the point of view of presence of liquid phase in the flow should be stated on the basis of experimental studies. However some streams of coarse droplets (besides primary particles trajectories I in Fig.1) can be computed by means of mathematical model fitted to experimental results. In this paper we attempted to simulate formation of the “fountain” of secondary droplets (see Fig.1 stream III), which is situated near the blade leading edge. Using this approach, the geometry of turbine blade profile has been modified in order to optimize parameters of coarse droplets formed in “fountain”.

Modeling of wet steam flow in the nozzle blade cascade has been performed by the CFD code Ansys Fluent 14. The modified wet steam model was used (see MoPo model in Starzmann et al., 2016) in order to simulate gas phase of multiphase flow. Coarse droplets trajectories were computed by DPM (discrete phase model) incorporated in Ansys Fluent. This model is based on the solution of motion equation of inert spherical particle:

$$\frac{1}{2}A_d C_x \rho_g |\vec{c}_g - \vec{c}_d| (\vec{c}_g - \vec{c}_d) = \vec{a}_d m_d. \quad (7)$$

Distributions of coarse droplets diameters and velocities at the inlet of computational domain correspond to parameters of experimental facility used in this work. In order to calculate the interaction of primary droplets with the blade leading edge Fluent uses the mathematical approach of droplets splashing process based on the work (Mundo et al., 1995). This model has one free parameter – possible number of formed parcels of secondary droplets after the splashing on the surface. This quantity was determined by comparing the parameters distributions of splashed droplets obtained by the experiment and the mathematical simulation. It is important to note that using such splashing model in wet steam flow conditions is rough approximation. But this can help to estimate some optimal profile geometries which should be studied on experimental facility.

In order to obtain behavior of droplets motion in the nozzle blade cascade, the experimental studies were performed. The investigations were carried out in the experimental facility Wet Steam Circuit (WSC) in the turbine laboratory of the Moscow Power Engineering Institute (MPEI). This experimental plant is used to study the flow of superheated, saturated and wet steam in stationary channels. The object of the study was the flat nozzle blade cascade which consists of 5 blades (see Fig. 5).

The laser flow diagnostic system “POLIS” was used. It uses the PTV (particle tracking velocimetry) method which allows obtaining instantaneous velocity vectors for each droplet detected by the method in studied flow domain. The information about the experimental facility and data processing algorithms are considered in (Gribin et al., 2016) in more detail. The optical scheme of laser diagnostic system is shown in Fig. 7. The flow in blade passage is illuminated by a plane laser knife formed by a dual pulsed laser. It is directed through the endoscope into working part where the flat nozzle blade cascade is installed. A twin impulse laser at 800 ns intervals illuminates droplets moving in the blade passage and high-speed PIV camera takes photos of them. The obtained droplet photos are used as the initial data for the PTV method. This technique obtains irregular vector field for each pair of photos. To increase statistical significance of results, 1000 pairs of photos have been made for the studied condition. This allows detecting the total amount of droplets approximately equal $20e6$.



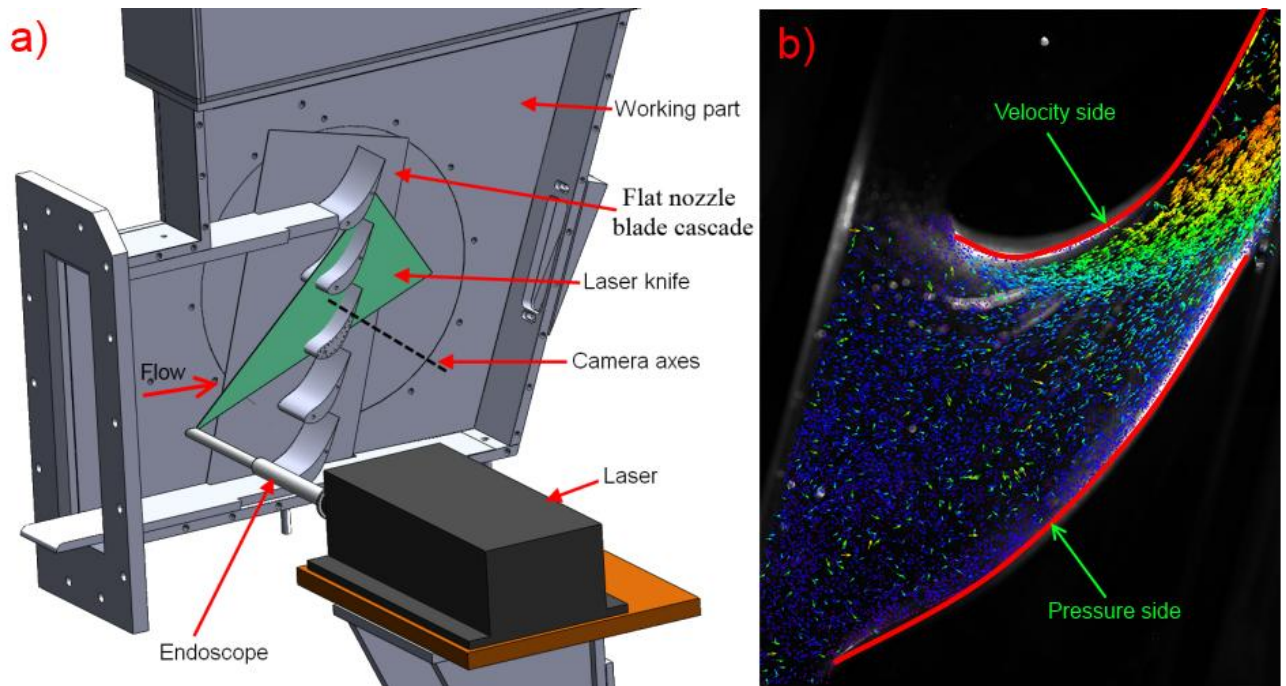


Figure 7: Optical scheme of the laser diagnostic system (a), example of obtained by PTV instantaneous vector field (b)

Here we present a brief analysis of experimental data. Trajectories of typical streams of coarse droplets obtained by the experimental study are shown in Fig. 8a. Wet steam flow conditions correspond to following parameters: $p_0=40000$ Pa, $M_{It} = 0.8$, $y_0=3\%$.

There are two types of liquid phase particles in the flow: primary (with a prefix) and secondary (with b prefix). Sprayers in the receiver tank of the experimental facility produce primary droplets. Secondary particles appear as a result of interaction between primary droplets and wall of blade passage or liquid film surface. There is a “fountain” of secondary particles of liquid phase at the inlet of the nozzle blade cascade. These droplets are formed as a result of reflection with subsequent breakup of primary droplets, which contact with the leading edge of the blade. Droplets of this “fountain” from the pressure side of the blade (5b) move along the surface and deposit on the blade surface or liquid film. Particles from the suction side (trajectories 1b and 2b) move into the flow core and cross the inter-blade channel. They have considerably curved trajectories and leave the blade passage without any interaction with walls of nozzle blade. It is remarkable that some droplets (1b) have very high exit angles and they cross the trailing wake downstream of the blade. This confirms previous results about droplets streams distribution downstream the turbine blades (Fillipov et al., 2014; Gribin et al., 2015b). The estimation of droplets diameters in 1b and 2b streams was made in (Gribin et al., 2016). Their average sizes are about 10-12 μm .

Trajectories of secondary droplets 3b and 4b follow along the blade pressure side. They are situated in a two-phase boundary layer. These droplets are formed as a result of interaction between primary particles of liquid phase and liquid film (Deitch et al., 1970).

The free parameter of the droplets splashing model was fitted based on the series of experimentally studied flow conditions. As an example, comparisons between experimental and calculated results are presented in Fig. 8b and Fig. 8c. Here one can see the distributions of flow angles and velocities of polydisperse liquid phase in the area which is marked as a square in Fig. 8a.

The experimental data shows that the secondary droplets, originated from point 1b and 2b leave the blade passage without any mechanical interaction with blade surfaces. So the liquid phase particles moving along these trajectories cannot be extracted from turbine flow path through the separation slits. The main aim of blade profile modification is to decrease the diameters of these particles in order to minimize an erosion effect on rotor blades. It can be achieved by decreasing the normal component of droplets velocity vector (relative to the blade surface). Because of this the

impact kinetic energy of primary droplets decreases. As shown in (Rosa et al., 2006) it leads to the deposition of droplets on the blade surface without splashing and formation of secondary droplets. So the modification of the original blade profile was done by increasing the angle between the normal to the surface and the angle of attack of the primary droplets.

In Fig.9a geometry of the original and modified profiles are shown. The following parameters were changed: Y_{max} , R_1 , ω_1 . In Fig 9b distributions of average secondary droplets diameters along the nozzle blade cascade pitch (see line in Fig. 5) are shown. For the case of modified profile, decreasing of droplets diameters is observed. It is due to the fact that primary liquid particles with big sizes were deposited on the blade surface and they are not involved in the process of secondary droplets formation.

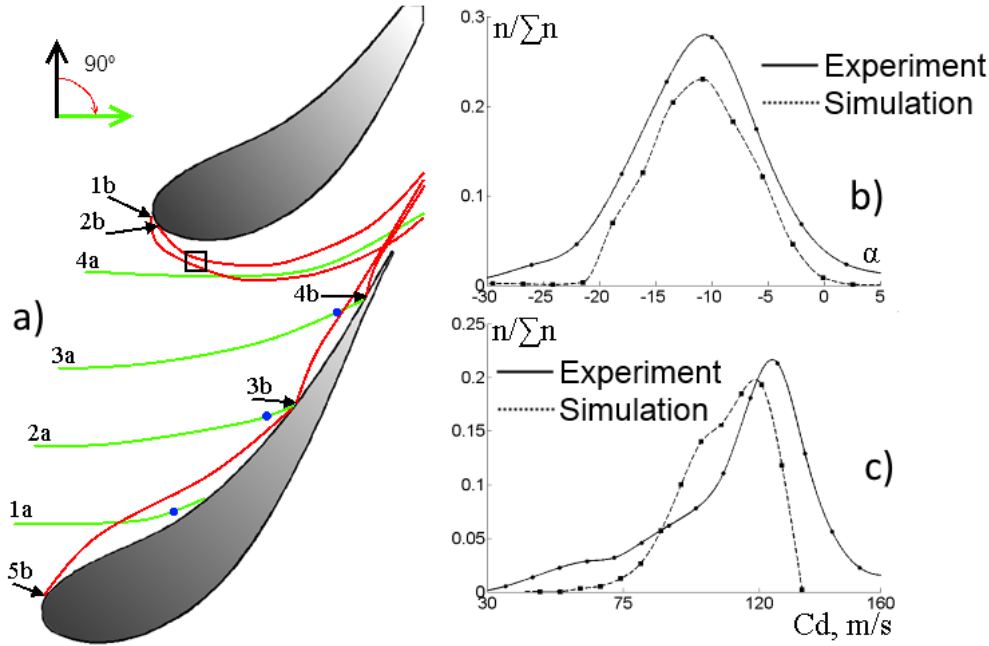


Figure 8: Trajectories of coarse droplets in blade passage (a), distribution of droplets angles (b), distribution of droplets velocities (c)

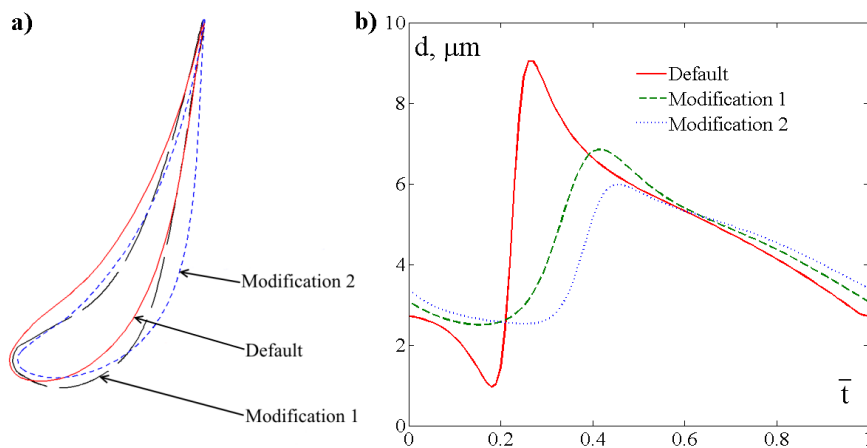


Figure 9: Modified profile geometry (a) and secondary droplets diameters distribution in pitch wise direction (b)

The proposed modification is not yet complete. It should be noted that the variation of the profile parameters leads to change of aerodynamic properties of the blade. So in order to finish the

modification it is necessary to use correlations between blade parameters which present the blade profile geometry and optimal cascade characteristics. It will be done in future work.

CONCLUSIONS

1. The fast and simple parameterization method of blade profile design was presented. The developed method allows creating effective technique describing the known geometry of blade profile using 13 parameters/

2. First results of experimental study of coarse droplets movement in blade passage are presented.

3. The possibility of controlling the streams of secondary coarse droplets by varying the profile geometry is shown. In order to minimize diameters of secondary droplets the angle between velocity vector of primary droplet and normal vector of surface has to be increased.

4. Recommendation about geometry of inlet area of nozzle blade is suggested. The variation of the profile parameters Y_{max} , R_1 , ω_1 leads to changing of shape of inlet area of the blade. This approach can be used to control droplets streams formed in the “fountain” near the leading edge.

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