Journal of Applied Fluid Mechanics, Vol. 10, No. 2, pp. 551-567, 2017.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.18869/acadpub.jafm.73.239.26208

Mechanisms of Water Droplets Deposition on Turbine Blade Surfaces and Erosion Wear Effects

G. Ilieva

Centre for Mechanical and Aerospace Science and Technology, Covilhã, 6200-001, Portugal

Email: galinaili@yahoo.com

Received February 13, 2016; accepted November 27, 2016)

ABSTRACT

Failure of turbine blades leads to various exploitation problems, efficiency decrease and economical losses, at all. A detailed research on aerodynamic features, in various exploitation conditions and regimes, and on reasons for failures, is a prerequisite to the obviated technical problems and increased reliability of turbine aggregates. Water droplets erosion is known as a very complex and crucial phenomena. It couples the effects of wet steam expansion, together with condensation (evaporation), presence of second phase with the impact of water droplets over blade surfaces, erosion effects and fatigue mechanisms. The present research deals with a logical sequence for numerical simulations and research on erosion mechanisms in a low pressure stage of K-1000-6 /1500 steam turbine, working at a Nuclear Power Plant. Attention is paid to the impact of droplets' diameter on blade surfaces, their aerodynamic behavior and efficiency of energy conversion through turbine channels. Particular trajectories of water droplets, reasons for occurrence of erosion wear, over certain parts of the streamlined surfaces, are established and discussed. An approach to acquire incidence time to erosion appearance is implemented. Research methodology and obtained results are applicable to determine erosion effects on streamed complex surfaces, to replace expensive measurements campaigns, introduce approaches to decrease wetness in last stages of condensation turbines and prolong the reliability of blades operated in wet steam conditions

Keywords: Droplet diameter; Erosion impact; Turbine blade; Water droplet erosion; Water droplets trajectories; Water hammer pressure.

NOMENCLATURE

Aface	area of cell face at the wall
C(dp)	function of droplet diameter
C_L	sound speed in water
C_S	sound speed in blade material
D	diameter at hub, mid or tip section
E_S	strength for the uncoated blade material
dp	droplet diameter in
Fx	force due to acceleration in x direction
m	wet phase mass
P	water hammer pressure
Re	Reynolds number
u	flow velocity in
up	droplet velocity
U	peripheral velocity of rotor blades
α	impact angle of the droplet with the wall face
$f(\alpha)$	function of the impact angle
μ	molecular viscosity in
ρ	flow density in
ρ_L	density of water droplets in
ρp	droplet density
ρs	density of solid droplets
σe	material's equivalent stress
ν	relative droplets velocity
$b(\upsilon)$	function of relative droplets velocity
Θ	mean impact angle of water droplets over the blade surfaces

1. INTRODUCTION

Modeling of condensation processes in wet steam is very important issue in the design and exploitation of steam turbines and their stages. The presence of second phase causes erosion of turbine blades, leads to disturbed aerodynamics in last stages of low pressure stages and reduced efficiency performance, as mentioned above.

Erosion of turbine blades results in rough surfaces that change steam flow paths. This leads to, as mentioned above, turbine efficiency decrease and limited capacity. Erosion processes in high-pressure turbine are usually caused by solid droplets that present in the steam turbine passages. Erosion in low pressure turbine stages is due to the high rate of expansion and presence of wet steam.

It is important to clarify that the erosion damage is not caused directly by the fine droplets existing in the fluid. These droplets deposit on blade surfaces to form films that are driven by the drag of steam. The rate of deposition depends on the droplets size and on the conditions under which they have formed. The droplets deposited on the moving rotor blades are centrifuged by the blades rotation.

Water droplets after condensation deposit mainly on the trailing edges of the stator blades and then are swept off the trailing edges by the incoming expanding steam flow, see Wang *et al.,* (2007) and Martinez *et al.,* (2011). Relatively large, characterized with low velocity, water droplets hit the leading edge of rotor blades, Azevedo and Sinatora (2009). This impact gives rise to localized surface stress and results in pits, cracks in the surface, or mass loss of the material, as described by Atrens *et al.,* (1983), Azevedo and Sinatora (2009), White (1992), Vishvanathan (1989), Ansari (1986).

Both the erosion and deposition phenomenon change the surface finish; stationary and rotating blade flow areas; alter the shape of leading and trailing edges (Wang *et al.,* (2007) and Azevedo and Sinatora (2009), increase the blade surface roughness (Martinez *et al.,* (2011), A. Campos-Amezcua *et al.*, (2007) and introduce irregularities in the steam path, resulting in eddies generation with losses these eddies produce, see Atrens *et al*., (1983), Azevedo and Sinatora (2009), White (1992), Vishvanathan (1989), Ansari (1986) and Springer (1976).

That is why, to study the mechanism of water droplets erosion, is of great importance, in order to develop approaches to control and reduce its negative impact on the blades. A strong knowledge and a fundamental understanding of various erosion parameters are essential in order to prolong the life of blades operated in the wet steam conditions, also.

Many research works have been conducted to study the condensation, erosion mechanisms and their impact on the turbine blades surfaces and efficiency performance.

Before a detailed discussion on the erosion mechanisms and effects one turbine blade surfaces, one needs to understand the main theory behind the the condensation phenomena.

1.1 Nucleation Processes, Droplets Growth and Droplets Diameter, Thermodynamic and Aerodynamic Effects

During the process of its rapid expansion the steam through turbine stages condensates. The condensation starts shortly after the expansion crosses the saturation line.

The process of condensation appears by creation of nucleating seeds (fog droplets with diameter in the range of 0.01-1.00 microns, (W.E. Nagel *et al.*, 2013), and growth of already existing droplets, which form water film over blades, also.

Nucleation without preferential nucleation sites is called homogeneous nucleation. Homogeneous nucleation occurs spontaneously after a process of vapor supercooling. The creation of a nucleus implies the formation of an interface at the boundaries of a new phase, Brennen (2005). Heterogeneous nucleation starts with the nucleus at a surface and is much more common and faster than homogeneous nucleation, Pruppacher and Klett (1997), Sear and Richard (2014).

Concentration of the vapor phase less than 0.01-0.1%, leads to a lack of effects on the droplets motion of the continuous phase. A solution describing the flow behavior is thus obtained by solving a single phase flow for the continuous phase and inputting the fluid velocities into equations of droplets motion. This approach is known as one-way coupling, Brennen (2005).

When the effect of the second phase (discrete phase) on the continuous phase is taken into account, the solution approach is known as two-way coupling approach; both phases are affected by each other. Equations, describing the aerodynamics of phases, are solved together following an iteration loop, awaiting the solutions to become more or less constant and do not change, Brennen (2005).

The process of rapid expansion of superheated steam into the metastable region causes its supercooling. However, the steam remains dry until a nucleation process starts. The nucleation process is driven by the so called supersaturation ratio or supercooling. The process of phase change and its initiating work is expressed by means of the Gibbs free energy.

The diameter at which the change in free enthalpy attains maximum value is called critical diameter, at that state the system is in unstable equilibrium. Clusters with diameter larger than critical one tend to grow contrary to clusters with radii smaller than critical which tend to decay in fact the system tends to minimize its free energy.

Nucleation rate is the rate at which number of new cores of droplets (nuclei) in unit volume is spontaneously generated from supersaturated vapor steam at the onset of homogeneous condensation.

The internal heat and mass transfer processes are hidden behind the flow changes. The internal heat exchange associated with subsequent return to equilibrium affects the behavior of the parent vapor and is thermodynamically irreversible.

The latent heat of condensing molecules is initially given up to the droplets before returning to the vapor. In addition growth of the liquid causes a slight reduction in the mass flow rate of the vapor. In order to treat the flow it is necessary to estimate the rates of heat and mass transfer between the phases. In addition, the system as a whole must obey the conservation laws of mass momentum and energy. Thus, the equations governing droplet formation and growth are combined with the gas dynamic field conservation equations and the set treated numerically, see Hric and Halama (2005).

The droplets motion may change the turbulence in the continuous phase flow. Also, droplets begin to collide one to another, they change their trajectories and velocities, in function of their mass and diameter. Collisions and random motions may provoke additional turbulent motions in the continuous phase, Brennen (2005).

In Forte *et al.* (1987) is shown that in flows characterized with high relative Reynolds numbers there are several important mechanisms of interactions.

In case of homogeneous nucleation and in the supersonic region, if the flow is heated by the latent heat of the condensation process, its velocity decreases and a condensation shock (due to increased pressure) appears, leading to local losses, Dycas *et al.,* (2013).

The internal heat and mass transfer processes are basic for changes in flow parameters and internal heat exchange. The latent heat of condensing molecules is initially transferred to the water droplets before returning to the vapor. In addition growth of the liquid causes a slight reduction in the mass flow rate of the vapor.

1.2 At the Dawn of the Research on Condensation

One of the first investigators of the phenomena known as thermodynamic condensation was Aitken (1880), who found that any dust or salt droplets present in the expansion of saturated air will act as condensation cores. Wilson (1897) accomplished a detailed study of spontaneous condensation where it was found that in the absence of ions or foreign nuclei during the expansion of saturated air, condensation was delayed, see Hasini *et al.* (2012).

Stodola (1915) published his own results of research on the problems of expansion through nozzles. A detailed discussion of supersaturation effects in nozzles was first given by Callender (1915). Martin in 1918 calculated the limiting supersaturation at other pressures and plotted them on the Mollier chart. This limiting supersaturation line is called Wilson line, see Hasini *et al*. (2012).

The development of nucleation theory started almost at the same time as the study of condensation but significant results were obtained only after 10 years. Among the earlier investigators on limiting supersaturation were (Yellot (1934); Yellot and Holland (1937); Rettaliata (1938). In their works, attempts were made to define the position of Wilson line more precisely. It was found that the limiting supersaturation was dependent on the nozzle shape and experimental condition and they suggested the replacement of the Wilson line by Wilson zone. Following his work, (Binnie and Woods (1938); Binnie and Green (1943) performed further accurate measurement of axial pressure distribution in nucleating flows in convergent-divergent nozzles. The nucleation theory was first combined with the gas dynamics equations by (Oswatitsch, 1942).

Research of condensation in steam turbines is based on studies and developed knowledge in the area of the nucleation theory, two-phase flows, droplets growth, thermodynamics of two-phase flows, etc.

Condensation and its specific features in steam turbines, was studied in details again by A. Stodola (1922) and published in his book. In next years the investigation of this phenomenon received considerable attention regarding the study of steam turbines (Traupel (1959), Bullock (1960), Kirilov and Yablonick (1962, 1963), Ryley (1961)) and ways to increase their efficiency and reach long-lasting exploitation. A detailed survey related to research of condensation in flows with high speeds is described in Stiver (1963). Also, on the mentioned problems worked and published important outcomes of their works Gyarmathy (1962), Hill (1966), Puzyrewski (1969), Campbell and Bakhtar (1970), Deich *et al*. (1972), Filippov and Povarov (1980). In addition to these investigations, a number of studies aimed at measuring the size of droplets formed by spontaneous nucleation were accomplished, providing further data for comparison with theoretical solutions.

Following new developments and designs of larger steam turbine, the steam velocity could reach much higher values. This led to considerable impact velocities, which brought renewed interest in the area of wetness problems, at the end of 70's and at the beginning of 80's.

1.3 Condensation in Turbine Stages

Performance deterioration in turbomachinery, caused by erosion of the blade surfaces, was studied and described by Tabakoff (1986, 1984) and Tabakoff *et al.* (1976).

In Hutchins *et al.* (1976, 1981) and Alfonso *et al.* (2007), a theoretical analysis and experimental study for predicting erosion damage, caused by solid droplet impact, is introduced. The idea that erosion damage is the gradual removal of materials suffered from repeated deformation and cutting actions is proposed.

In Mann and Vivek (2002) are fulfilled experiments of water jet impingement on solid surfaces were performed, and is reported that the initiation and expansion of crack occur on the surface due to the stress wave and the high-speed lateral jet generated by water drops impact are performed.

Some research works have been performed on the influence of micro-droplets on wet steam erosion, Ahmad *et al.* (2009).

Research works of Grant and Tabakoff (1985), Balan and Tabakoff (1984) provide insights on the increased rate of erosion on both leading and trailing edges of stator blades and proves that the erosion leads to increase in the surfaces roughness. The surface roughness contributes to problems in streaming; a local vortex generation and decrease in stage efficiency are observed.

After a number of experiments, Sugano, Yamaguchi and Taguchi (1982) concluded that the reduction of the profile chord and the removal of material from the concave side of the blade is directly dependent on the droplet size of the secondary phase.

In works of Hamed *et al.* (2004), Kline and Simpson (2004), and Wang *et al.* (2014) is found that degree of erosion is a function of the angle at which the fluid droplets enter in the inter-blade passage, their speed and size.

In research of Fiore and Selig (2014), obtained results indicated that erosion damage over blades depends mainly on *the* first impingement of every solid droplet on the wall after entering into the cascades, and the erosion rate of the first impingement is much larger than the one caused by additional impingements on the wall after droplet rebounding.

Richardson *et al.* (1979) present a relationship between roughness change and size of radial clearance in function of the erosion. A high erosion impact is reported on the concave side of the rotor blades in the vicinity of the trailing edge.

In the research works of Hamed (2005), Tuchinda and Bland (2014) are given results of a comparative study on erosion of turbine blades with and without special coatings.

Specific research on erosion prevention and technologies to new coatings are discussed in Mingazlev *et al.* (2014) and Liu-xi *et al.* (2014).

Erosion of turbine blades in the course of their operation is a result of many factors as trajectory and size of the fluid droplets, geometry of the turbine stage, working conditions and depends on the material they are made. In order to obtain deep knowledge on the erosion impact, one need to clarify the erosion mechanisms and the important parameters causing water droplet erosion of turbine blades.

Parameters such density, wet steam quality, impact velocity, size of the droplet, ultimate tensile strength, hardness of the material, pressure, temperature and viscosity play a significant role in the process of erosion over turbine blades, according to Leyzerovich (1997).

Erosion becomes also more severe as tip speed of the last turbine blades increase.

Water droplets erosion of the turbine blades is affected by impact velocity and angle; droplet size; number of droplets; hardness of the blade's material. Krzyzanowski and Szperngiel (1978) performed detailed study related to the influence of droplet size on turbine blading erosion hazard.

It is empirically found that water droplet erosion rate is proportional to approximately the fifth power of the impact velocity if all other parameters remain constant, (Tsubouchi 1990). The erosion increases with increase of the length of the blade because the peripheral rotational velocity increases.

Stanisa and Ivusic (1995) stated that the craters formed by the impact of droplets are developed parallel to the impact direction of the droplets. In general, the impact angle influences the erosion before craters are formed on the target surface. However, if the incubation period is short enough the effect of impact angle can be neglected.

If the number of impacting droplets is constant, the erosion rate increases with droplet size. It is important to establish the influence of droplet size on the erosion of blades, since water droplets have a broad size distribution, with a diameter from one to hundred microns. Normally, for convenience, mean diameter values are used in the prediction of erosion. Leyzerovich (1997, 2008) supposed that the diameters of droplets at the exit plane of stationary blade are closely related to the trailing edge thickness of the stationary blade that has been used as an erosion parameter by turbine manufacturers.

The final size of droplets is mainly determined by the breakup caused by velocity lag between the continuous medium and droplets. Gelfand (1996) reviewed the fundamental concepts of droplet breakup in flows with velocity lag.

Water droplets erosion damage is strongly related to the radius of curvature of the droplet, at the point of impact, according to Schmitt Jr. (1979). Therefore distorted droplets, having radii larger than their initial diameters, are more erosive.

Normally, a film of water drops is formed on the surfaces of stator blades. The deposition rate depends both on droplets size and velocity.

During the motion of moist vapor through the stator blades, the greatest part of the condensate collects on the concave surface of the nozzle blades. Results of experimental research of Yablonick and Lagerev (1963), visualize specifics of how condensate moves in a turbine stage. The authors established that a condensate flows in the form of a layer along the whole blade. Investigation of its structure showed that the layer is binary: along the blades surface, slowly flows a film of water, and above the film there is a layer with a large number of drops. On the convex surface of the stator profile the film is considerably thinner than the one on the concave surface, where more than 2/3 of the liquid-drop moisture, contained in the flow, collects. From trailing edges of stator blades condensate flows not in a uniform film but in the form of isolated streams atomized by the flow. These streams with respect to the blade's height indicate irregularity of film thickness with respect to the height of blade and non-stationarity of the film flow.

Research on water droplets' impact over leading edge surfaces is discussed in details by Wang *et al.* (2014). Water film formed over the stator blades flows in a direction to the trailing edge, influenced by force, produced due to the steam drag, the impulse of the fog deposition and the pressure drop realized along the turbine blade as discussed by Stanisa Ivisic (1995) and Nishimura (1999). Water, reaching the trailing edge of stator blades collects into large drops and those are sprayed off by steam flow. Some of these drops may be too large in size to be stable. All drops with smaller diameter have same velocity as that of the steam. The others with large diameter (100-200 micron or up to 500 micron) with high relative velocity go straight and hit the moving blade and cause blades erosion.

In the axial clearance occurs acceleration of secondary drops formed when the film of condensate is descending from blades of the rotor splits, and thrusting of drops onto the peripheral surface due to the peripheral component of speed which is imparted to the flow in the stator space.

When liquid impacts on the material surface, it behaves as a compressible fluid, in the early stage, and the so called ''water hammer'' pressure can be generated. This high pressure is responsible for most of damages resulting from the liquid impact, and the high pressure is maintained while the edge of the contact area between the impacting liquid and the solid moves supersonically with respect to the shock speed in the liquid (Xu Wanli *et al.,* 2010).

Contemporary research works are focused on condensation modeling, numerical modeling and analysis of erosion parameters and their impact on blade surfaces, Hamed *et al.*, Fiore and Selig (2014), Nikkhani, Shams, Ziabashrhadh (2009) and Hasril *et al*. Based on erosion rate and droplet models, the erosion characteristics of first row blades, in a supercritical steam turbine, was simulated and analyzed by three-dimension numerical simulation method in the research of Liu-xi *et al.* (2014). The influence of operating conditions, droplets size distribution at the nozzle's inlet and at the axial clearance on the erosion in cascades, nucleation models and many others, are explored and discussed by many researchers - Hamed *et al.*, Liu-xi Cai *et al.* (2014), Nikkhani, Shams and Ziabashrhadh (2009), Hasril *et al.*, and Wroblewski *et al.* (2009).

On the basis of the fulfilled literature survey, is clear that there are not many papers involved in both numerical simulations (to obtain main problematic zones on the blade surfaces) and an approach to calculate those main characteristics that are in a very close relation with the occurrence and rate of erosion.

This work is targeted to research on blades' erosion in a low pressure stage of steam turbine K-1000-6-/1500, working at a power plant. Main objectives of this study are as follows:

- to model, simulate, analyze and evaluate of the impact of the erosion of turbine blades operating in environment of wet steam after implementation of a set of equations included in a code, written by the author, for modeling of droplets distribution through the turbine stage and forces, which impact the blade surfaces;
- to study the specific pathways and deviations of water droplets and reasons for their occurrence;
- to build a sequence and to obtain the incidence time to erosion to appear.

This will provide insights on the impact of secondary phase on the aerodynamic behavior and efficiency of energy conversion.

The current study will contribute to understand the mechanisms of the wet steam erosion more completely. Specific approaches to decrease wetness in the last stages of condensation turbines and prolong the reliability of blades operated in wet steam conditions could be introduced as a result of the performed research and obtained results.

2. PROBLEM SET-UP

This section discusses approaches related to the particularities of the numerical procedure for a turbine stage, working in erosive conditions.

2.1 Geometry Formulation

The turbine stage under consideration is the 4th stage, of totally 7 stages, of double-flow low pressure turbine K-1000-6/1500 which works in NPP-Kozlodui-Bulgaria. This turbine is designed for extraction of total power of 1000 MW.

The configuration consists of a stator with affixed 113 turbine blades and rotor with 127 twisted blades. Rotor blades rotate counterclockwise about the x-axis, with 1500 rpm.

Geometry parameters for stator and rotor are as follows:

- stator blade: hub diameter: 3.221 m; tip diameter: 3.761 m; mean diameter: 3.491 m; blade height: 0.270 m; blade chord: 0.14825 m; stagger angle: 53.4deg; mean pitch: 0.097 m;
- rotor blade: diameter at hub: 3.221 m; diameter at tip: 3.821 m; mean diameter: 3.521 m; blade height: 0.300 m; blade chord-hub: 0.0855 m; blade chord-tip: 0.114 m; stagger angle at hub: 21deg; stagger angle at tip: 43.5deg; mean pitch: 0.087 m.

The turbine stage model under consideration is modeled in commercial software GAMBIT. It consists of 8 grid blocks (4 blocks to present the stator blade and its flow domain, 4 blocks to visualize the twisted rotor blade with its flow domain) and 6 sub-volumes. Last mentioned volumes present the flow domain at stage inlet and outlet.

At a close proximity to the leading and trailing edges, to achieve mesh refinement, discretization for each line of the profile contours is carried out, at definite values for the mesh options. Resulting mesh is consistent with both shape and size of elements of the boundary layer. It's highly advisable (Ilieva, 2016) to acquire elements with consistent edge lengths, along the foil section and boundary layer. All this is a prerequisite to overcome the presence of highly skewed elements, when transfer from one to another section along the blade height. Values of "successive ratio" option, when approximating the blade contours, close to the camber line end points, radial direction, are carefully specified, also. Values for options such as "internal count" and "successive ratio", are commensurable, especially those, applied to the leading and trailing edges. Very low values, for both options, lead to creation of negative elements, when Cooper's scheme is applied for volume discretization, Ilieva (2016). Mesh consists of 1 032 561 elements.

For the purposes of the 3D geometry modeling in GAMBIT, Cooper's discretization scheme for stator and rotor blades discretization is applied. Cooper's scheme follows the blade shape in its radial direction in the process of 3D grid generation. This is very important option, which helps to avoid the presence of negative volume elements and elements with bad quality, such as high skewness, etc.

Boundary layer consists of 16 rows of elements. The first row of elements is with height of 0.001 m.

Due to the symmetric geometry of the turbine, the computational domain is created only for one turbine stage.

2.2 Numerical Formulation

Numerical simulations have been performed in Fluent, with implemented user defined code, written by the author. This code includes equations that model distribution of droplets through the stage, interactions among them and forces impact over the blade surfaces.

Working fluid is wet steam, which is turbulent, compressible and viscous. Fluid physical properties are as follows:

- density is varying with the ideal gas law;

- viscosity is *0.0000134 kg/m.s*

- thermal conductivity is *0.02161 W/m.K*

- specific heat capacity is *2.014kJ/kg.K*

The boundary zones that were setup are "pressure inlet", "pressure outlet", "periodic", "wall" and "fluid". The total gauge pressure, static pressure, static temperature, turbulence parameters and flow direction were imposed as "pressure inlet" boundary conditions. Static pressure, static temperature, flow direction and turbulence parameters were implied as outflow boundary conditions. Periodic boundary conditions were imposed along the side boundary zones. No-slip boundary conditions for hub, shroud, blade surfaces were applied. Values of the imposed boundary conditions are as follows:

-inlet boundary zone: total pressure *Ptot =183000 Pa;* static pressure *Pst=180000Pa;* static temperature *Tst = 390 K*; turbulence intensity *Tu= 5%;* hydraulic diameter is *0.09 m.*

-outlet boundary zone: static pressure *pst =94616 Pa*; static temperature *Tst=371K*; turbulence intensity *Tu =5%*; hydraulic diameter is *0.08 m.*

Real flow in turbine stage is quite complex, being unsteady, viscous, turbulent, compressible and three-dimensional.

Moving rotor blades and the interaction effects between stator and rotor are modeled by "mixing plane" model. In this approach, each fluid zone is treated as a steady-state problem. Flow field data, such as pressure, velocity, temperature and turbulence parameters, from adjacent zones, are transferred as boundary conditions after each iteration. All mentioned parameters are spatially averaged at the mixing plane interface zone. This mixing removes any kind of unsteadiness that can arise due to the circumferential variations in the passage-to-passage flow field such as wakes, separated flows and others.

A turbulence model, appropriately chosen, has a great significance for the correct modeling of droplet trajectories and therefore for the droplets deposition over streamed surfaces. In our research, Realizable k-ε closure model is applied. This model calculates pressure distribution effects in the flow domain better than Renormalized Group model (RNG) and Standard k-ε models. This is very important because correct pressure distribution in the core flow, droplet trajectories distribution and droplet impact on blade surfaces, have to be predicted. Also, the Realizable k-ε model gives a new formulation for turbulent viscosity and dissipation rate, it is comparatively new from the other k-ε turbulence models and gives a new formulation for the turbulent viscosity and dissipation ratio, as is discussed by Roy and Saha (2012). Modeling with Realizable k-ε turbulence model is appropriate due to the fact that the model includes effects of mean rotation in the turbulent viscosity term, as it's discussed by Z. Carija *et al.* (2012). This model predicts boundary layer growth along the trailing edge, from the suction side of the blade, as shown in Ebrahimi and Roozbahani (2011).

2.3 Mathematical Model and Specific Parameters that Must be Determined and Included in the Numerical Procedure

The nucleation model presented in this study is with included second phase - water droplets.

Droplets are defined with constant diameter and regularly distributed at the turbine stage inlet. Processes of condensation and evaporation are not subject of modeling. Coupling between phases is based on influence via drag, velocity and turbulence.

Discrete two-phase model is applied for numerical modeling of erosion over turbine blades. The model can predict the trajectory of a discrete phase by integrating the force balance acting on droplets, written in Lagrangian reference frame. This force balance equates the droplet inertia and is presented by Eq. (1) (written for x direction in Cartesian coordinates):

$$dup/dt=Fd(u-up)+gx(\rho p-\rho)/\rho p + Fx \quad (1)$$

Drag force *Fd* can be calculated after application of Eq. (2):

$$Fd=18.\mu.Cd.Re/(24.\rho p.dp^2) \quad (2)$$

Drag coefficient Cd can be taken from Eq. (3)

$$Cd = a_1 + a_2/Re + a_3/Re^2 \quad (3)$$

In Eq. (1), term *Fd(u-up)* gives drag force per unit droplet mass. In "*Fx"* term are also included forces that arise due to the rotation of the reference frame.

Initial inputs for discrete phase calculations are velocity, trajectory and temperature of water droplets; mass flow rate; model of interaction between saturated steam and water droplets, etc. These initial parameters give needed starting values for all of the dependent discrete phase variables that describe the instantaneous states of every droplet. Boundary zone of type "pressure-inlet" is defined as a zone for surface injections, i.e. from where droplets are being injected into the flow. The discrete phase is uniformly distributed in the flow domain.

The erosion rate is defined in Eq. (4) as a product of the mass flux and specified functions for the droplet diameter, impact angle, and velocity exponent as is in Eq. (4):

$$R_{erosion} = \sum_{p=1}^{Ndroplets} [m.C(dp).f(\alpha).v/(A_{face})] \quad (4)$$

Water droplets were set of type "inert". An "inert" droplet is a discrete phase droplet that obeys Eq. (1) and is subject to heating or cooling via the thermodynamic law.

Droplets are with spherical shape and their diameter distribution is of type "uniform". Droplets deformation, growth and rupture were not considered. Deposition, but not rebound has been encountered when droplets encounter a wall in the blade passages.

2.3.1. Droplet Parameters

For numerical simulation of wet steam flow, the general assumptions are as follows: ignore the speed slipping between droplets and steam; interaction forces among water droplets are equal to zero; the quantity of condensation phase is maximum 10–12%; the volume of liquid phase is not considered.

In wet steam flow, the number of the so called "secondary water droplets"-formed after the water film break in the wake of the stotor blades, is small while mass of a single droplet is heavy. The dynamic impact of secondary droplets on the moving blades is the main reason for moving blades' water erosion.

The fluid phase influences particulate phase mainly via drag and turbulence. Particulate phase has no influence on the gas phase.

The droplets are set of type "inert" - "water-liquid". An "inert" droplet is a discrete phase element (droplet, droplet, or bubble) that obeys the force balance (1) and is subject to heating or cooling via Law 1, described on the ANSYS site (www.ansys.com).

Droplets are with spherical shape and their diameter distribution is of type "uniform. Droplets' deformation, growth and rupture was not under consideration. Deposition, but not rebound, was encountered when droplets encounter a wall in the blade passages.

Numerical simulations were performed with water drops diameters of 1, 5, 15, 25 microns, see Danmei Xie *et al.*, (2010) and W.E. Nagel *et al.,* (2013). Experimentally, droplets' maximum diameter for the conditions and velocities under consideration is 15–25 microns, as is stated in Danmei Xie *et al.*, (2010) and Nagel *et al.,* (2013). Droplets of size 150–200 microns could be only found in a very small area in the vortex immediately after the trailing edge where a fragmentation of the wet film is observed, (Danmei Xie *et al.*, (2010) and W.E. Nagel *et al.,* (2013). In order to attain better insights into the problems of surface deterioration and erosion, a research with implemented diameter of 150 microns has been performed, Schmelzer (2005).

The droplets' temperature is set to 320 K. Velocity of the wet phase (secondary phase) depends on droplets' size and mass and is variable.

The "Total Flow Rate of all droplets released from the "inlet"surface has to be set-up. The total mass flow rate of wet steam for the turbine stage, according to the exploitation documentation, is 2.97 kg/s. The total mass flow of the secondary phase is 0.133 kg/s, a value equal to 4.4% wetness. This value is responding to the real wetness measured in the turbine stage in exploitation.

Boundary conditions, concerning the secondary phase must be determined. In current case of research -"Discrete Phase Boundary Condition" is activated.

The Navier-Stokes equations set was solved via density based solver. The solution approach uses Advection Upstream Splitting Method (ASUM) scheme, fully implicit approach, as in Bagheri-Esfe *et al.* (2016).

Second Order Upwind discretization scheme is applied to achieve equations set discretization and physically correct results.

It is well-known that after the iteration values, obtained for the unknown variables, should become closer and closer together and thus converge. Due to strong non-linear equations, unsteady solution, separation and other aerodynamic effects, the solution is unstable; that is why a set of relaxation factors is used to remove the steep oscillations. For all under-relaxation factors, calculations were performed with initial values that were equal to the default values included in FLUENT. After a gradual decrease, the final value for each under-relaxation factor was 0.5.

Convergence is obtained when the scaled residuals are in the range of 10^{-4} for all the unknown

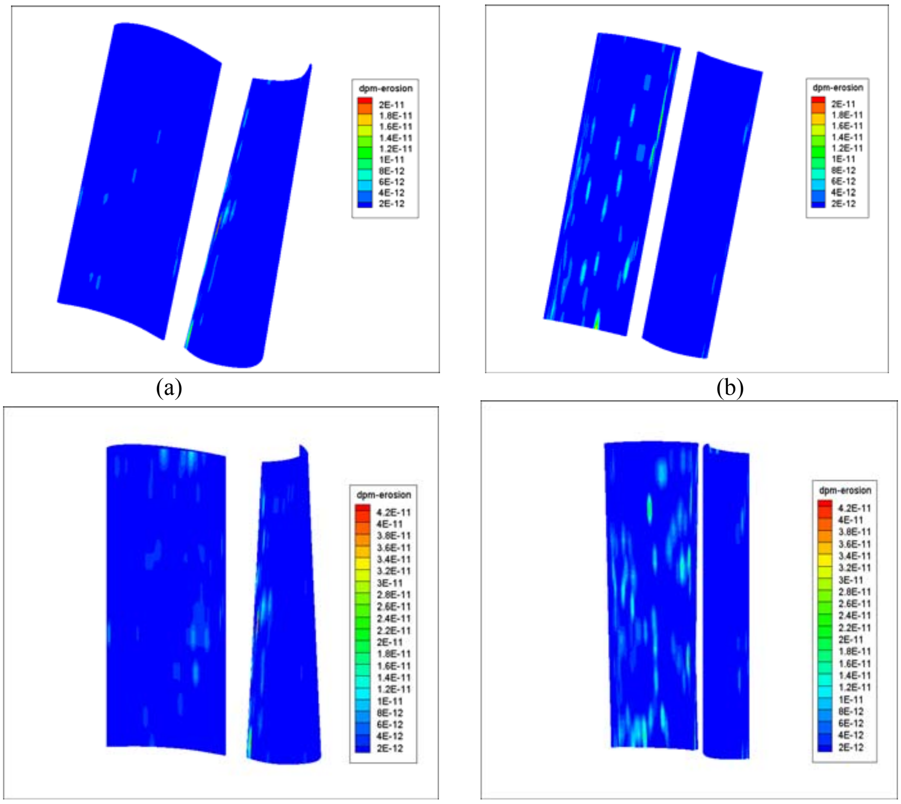


Fig. 1 (a, b, c, d). Erosion on blades surfaces - water droplets with diameter 1 micron and wet phase mass flow rate 0.133kg/s – concave surface of stator blade and leading edge of the rotor blade (a), leading edge of the stator blade surface and concave surface of the rotor blade (b); for water droplets with 1 micron diameter and wet phase mass flow rate 0.266kg/s – concave surface of stator blade and leading edge of the rotor blade (c), leading edge of the stator blade surface and concave surface of the rotor blade (d) .

parameters; exceptions are energy and turbulence parameters, they are set to 10^{-6}.

All obtained results are discussed in the following chapter.

3. RESULTS

Results in erosion values are shown in Fig. 1(a, b)–4(a, b).

The primary droplets, with diameter in the range of (1–5) microns, small mass and velocities as those of steam droplets, are following the main flow, from the stator to the rotor, also into the next stage. Only a small amount of them deposits on the leading edges (stator and rotor blades) and trailing edges of the rotor blades, Fig. 1(a, b).

Droplets with diameter from 15 microns to 25 microns (secondary droplets) increase the rate of deposition on the blade surfaces, Fig. 2 (a,b), Fig. 3 (a, b), Fig. 4 (a, b). Those droplets are characterized with bigger mass and poor following behavior, their tracks rise superior to the steam flow. All secondary droplets deposit mainly over the stator blades pressure side and over the rotor blades pressure side in close proximity of the trailing edge. Also, water droplets are collected mainly along the leading rotor edge, on the convex side, and along the trailing edge, on the concave side. The amount of deposition in the convex surface is greater than that on the concave surface. Most droplets deposits after the turning point on the concave surface.

Also, it is visible that increase of wet phase mass fraction leads to increase in erosion impact over surfaces under consideration.

It's reasonable to set suction slots onto places where droplets are collected. This approach will decrease significantly the wetness and rate of erosion. Another possibility is the application of cover materials, as discussed by Mingazhev (2014) and Liu-Xi Cai *et al.*, (2014). This will prevent blade surfaces from erosion; future fatigue failure; worse aerodynamic performance and will decrease energy losses due to the secondary phase.

For the purposes of explanation of erosion effects over turbine surfaces, scaled velocity triangles, showing steam and water droplets velocity vectors, were constructed, Figs. 6-8. By the velocity triangles, Figs. 5-8, it is easy to verify that the larger the peripheral velocity U and the angle of incidence, the bigger at other equal conditions is the normal component of drop velocity Wdr, i.e., the greater the impact force of a drop on the blade.

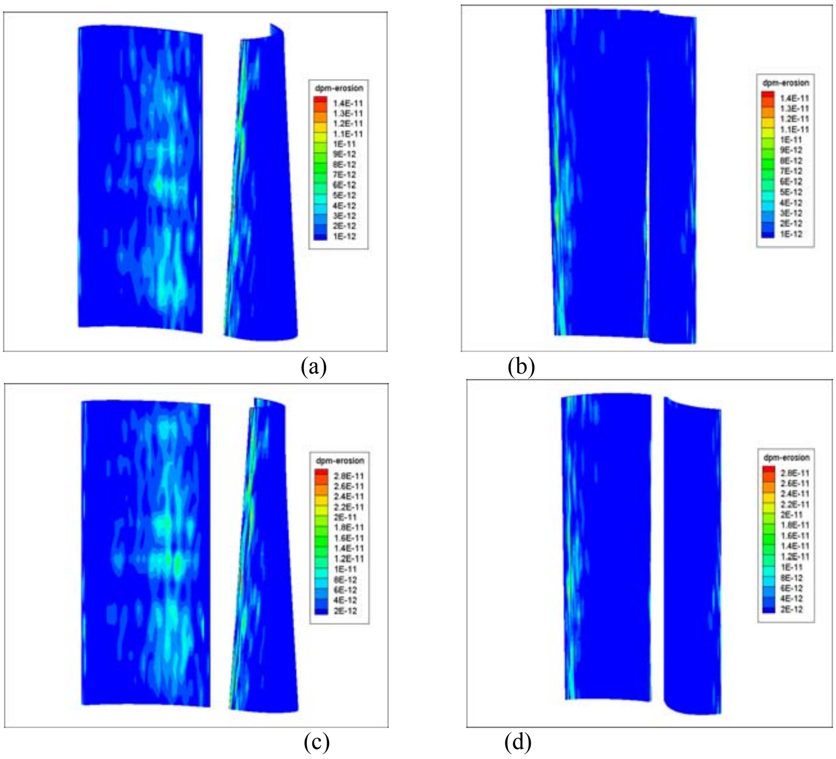


Fig. 2 (a, b, c, d). Erosion on blades surfaces in case of water droplets with 5 micron diameter and wet phase mass flow rate 0.133kg/s – concave surface of stator blade and leading edge of the rotor blade (a), leading edge of the stator blade surface and concave surface of the rotor blade (b); in case of water droplets with 1 micron diameter and wet phase mass flow rate 0.266kg/s – concave surface of stator blade and leading edge of the rotor blade (c), leading edge of the stator blade surface and concave surface of the rotor blade (d) .

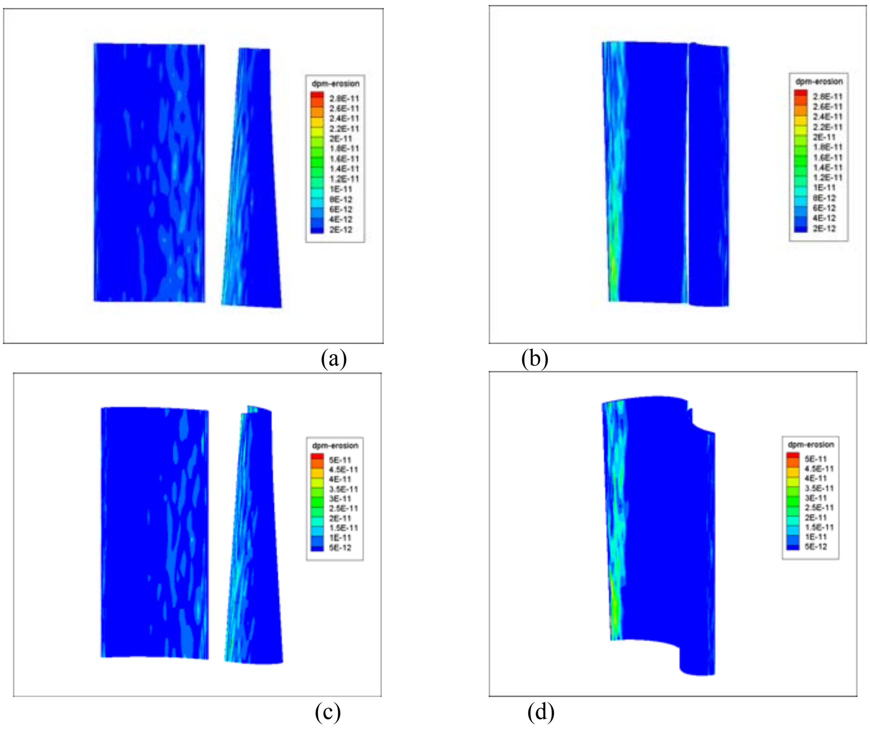


Fig. 3 (a, b, c, d). Erosion on blades surfaces in case of water droplets with 15 micron diameter and wet phase mass flow rate 0.133kg/s – concave surface of stator blade and leading edge of the rotor blade (a), leading edge of the stator blade surface and concave surface of the rotor blade (b); in case of water droplets with 1 micron diameter and wet phase mass flow rate 0.266kg/s – concave surface of stator blade and leading edge of the rotor blade (c), leading edge of the stator blade surface and concave surface of the rotor blade (d) .

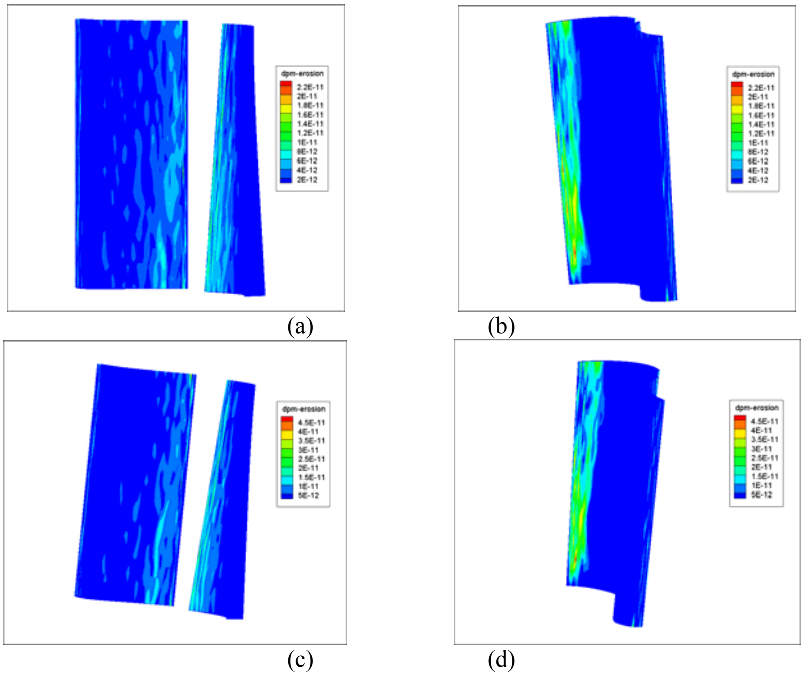


Fig. 4 (a, b, c, d). Erosion on blades surfaces in case of water droplets with 1 micron diameter and wet phase mass flow rate 0.133kg/s – concave surface of stator blade and leading edge of the rotor blade (a), leading edge of the stator blade surface and concave surface of the rotor blade (b); in case of water droplets with 25 micron diameter and wet phase mass flow rate 0.266kg/s – concave surface of stator blade and leading edge of the rotor blade (c), leading edge of the stator blade surface and concave surface of the rotor blade (d).

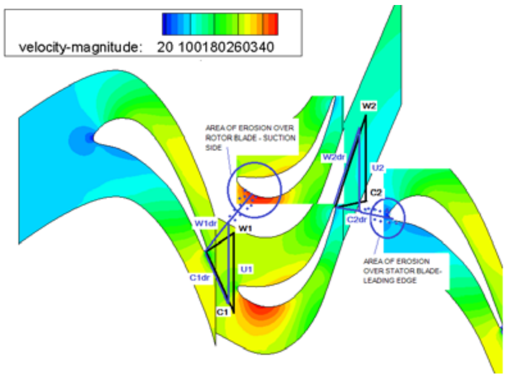


Fig. 5. Velocity triangles of steam flow and water droplets with diameter 1 micron - tip section.

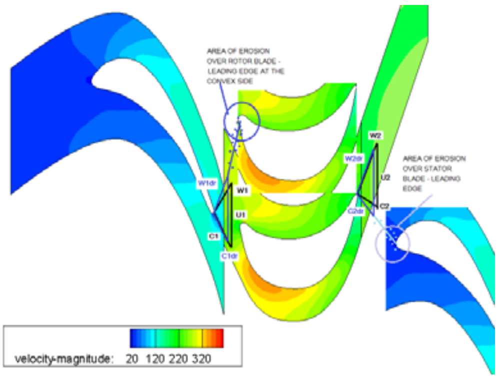


Fig. 6. Velocity triangles of steam flow and water droplets with diameter 1 micron - hub section.

For water droplets with diameter - 15 microns and 25 microns, absolute velocity C1dr is less, their relative velocity W1dr and its normal component of W1dr are bigger than for small drops, Fig. 7 and 8. Consequently, force of the impact of a separate drop with increase of its dimension will grow faster than the mass of a drop. The quantity of W1dr is a function of peripheral velocity of rotation of rotor U, flow angle into rotor blades, absolute velocity of vapor, its density and magnitude of clearance between stator and rotor blades.

In Fig. 6 and 8 are shown changes in velocity triangles in function of varying drop diameters and their velocities at the hub section. Relative component of velocity Wdr changes and water droplets are entering into the inter-blade rotor channels at increasing impact angle. Last mentioned fact and the twistness ratio (hub - active profile, tip – reactive profile) leads to an increase in the erosion pattern.

The rate of change of twistness and drops' diameter provoke increase of erosion on the convex side of the rotor blades, in direction from hub to shroud Fig. 1(a, b)–4(a, b).

In Fig. 5 and 7 are shown changes in velocity triangles in function of varying drop diameters and their velocities at the shroud section. Water drops absolute velocity changes, water droplets are entering into the stator's inter-blade channels at increasing impact angle. This provokes increase in erosion at the leading edge of the stator blades.

Increase of vapor axial component of speed and its density, magnitude of axial clearance between stator and rotor blades leads to the fact that a drop in the clearance accelerates more strongly, i.e., absolute velocity Cdr is increased and force of impact of drop against blade decreases together with decrease of normal component of speed of the water drop. It is clear that with increase of ratio (U/C1normal) conditions for appearance of erosion become more favorable.

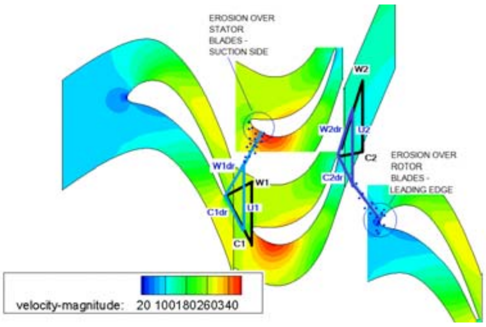


Fig. 7. Velocity triangles of steam flow and water droplets with diameter 25 micron - tip section.

The question of the actual diameter of droplets causing the erosion of blades of steam turbines is very important. In the current turbine stage the axial clearance between stator and rotor blades is not small, disintegration of drops is not completed and drops reaching blades of rotor have a diameter exceeding the one corresponding to the critical diameter value. Examining turbines, working with water vapor, one talk about that region of conditions in which growth of velocity of a drop in absolute motion leads to deceleration of drop with respect to blade.

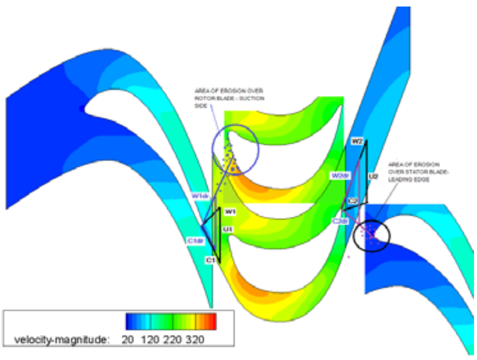


Fig. 8. Velocity triangles of steam flow and water droplets with diameter 25 micron - hub section.

In Fig. 11(a, b, c) are visualized main flow streamlines and moving traces of water drops at hub and shroud sections. Some drops impact the blade, others move through the blade channel. Mainly, water drops deviate due to their less velocities and larger mass, tend to impact on the blade and induce water drop erosion in the area of leading, trailing edges and sidewalls of convex and concave surfaces. In this case of research other reasons to path digression are: changes in rotor blade sections from hub to tip; secondary vortices formed along the pressure sides that contribute to streamlines diversion Fig. 11(a,b,c); centrifugal forces that deviates droplets to the tip sections; pressure differences in radial direction and secondary flows; change in axial gap size in radial direction; inertial forces acting on the droplets, etc (Fig. 12 a, b).

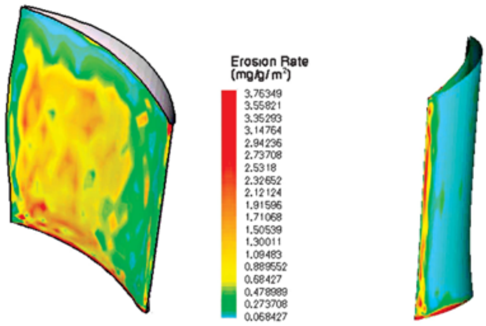
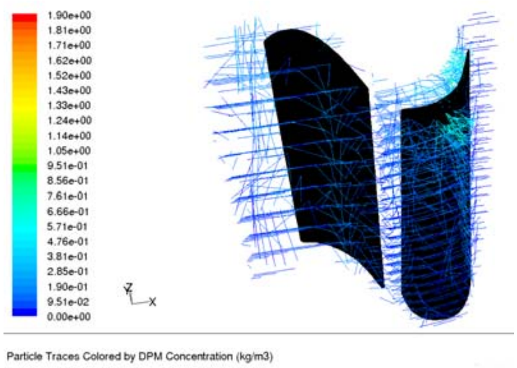
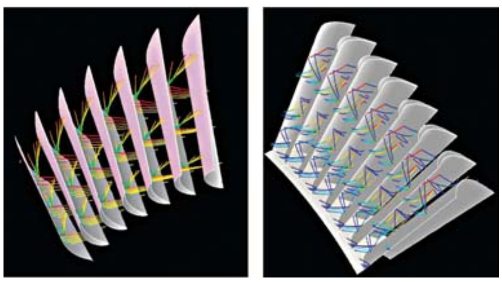


Fig.9. Erosion over turbine blades after Hamed *et al.* (2005).

Results present that water droplet erosion damage is strongly related to the radius of curvature of the droplet at the point of impact Fig. 12 (a, b). Therefore distorted droplets, having radii larger than their initial diameters, are more erosive.



(a)

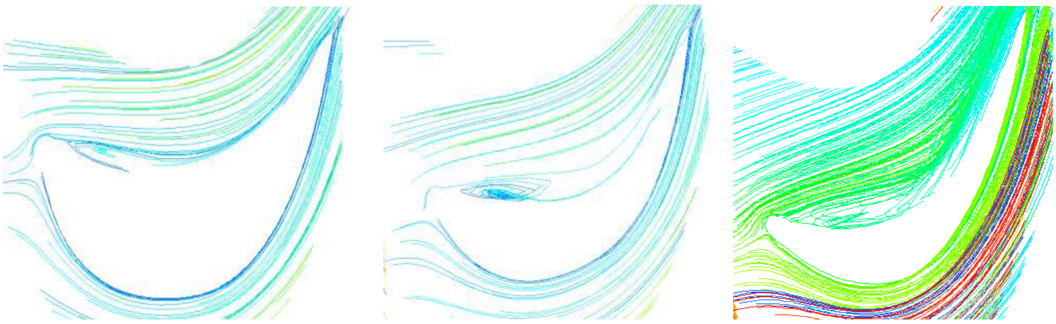


(b)

Fig. 10 (a, b). Liquid droplet traces, coloured by DPM concentration in (kg/m^3) (a); liquid droplet traces in research of Hamed *et al*. (b) (2005).

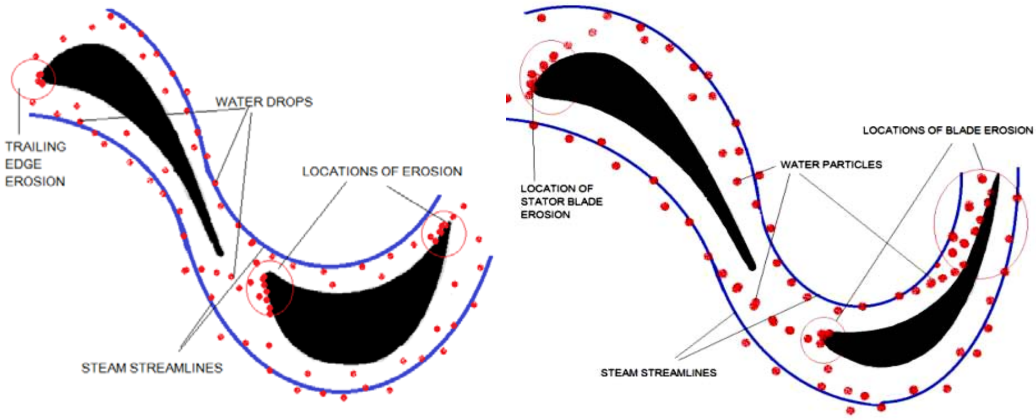
Observed negative consequences, due to the water droplet impacts, are:

- degradation of surface finish and increase of profile loss due to surface roughness;



(a) (b) (c)

Fig. 11(a, b, c). Control sections in hub (a), mid (b) and tip (b) area of turbine stage showing streaming features, vortex structures at pressure side and flow droplets streamlines deviation. Colouring is in function of number of droplets concentrated along and around the streamed surfaces.



(a) (b)

Fig. 12(a, b). Steam traces and water droplets paths along blade channels – hub section (a), shroud section (b).

- increase of the discharge area and decrease of momentum of steam entering into the rotor inter-blade channels;
- increase of seal area - decrease of main steam flow;
- different flow angle – changes in aerodynamics, efficiency of energy conversion;
- changes in geometry of leading and trailing edges; intensive separation and wakes increase;
- efficiency decrease, etc.

Efficiency decreases with increase of wet portion in the flow past turbine stage. In Fig. 13 change in efficiency value for mass flow rate of the wet phase of 0%, 4.478% and 8.956% is demonstrated. It is proven that efficiency decrease is in a direct ratio to the wet part of the flow. In our case of research efficiency changes from 67.15% to 59.69%.

Numerical simulations show that in reactive stages the angle of this change will be less than in active, considering the change of direction relative to velocity of drops upon change of peripheral velocity.

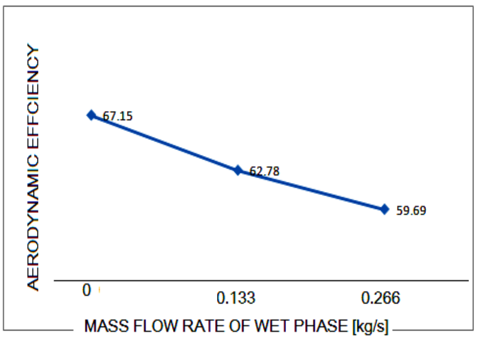


Fig. 13. Efficiency of turbine stage in case of 0%, 4.4% and 8.8% wetness.

Efficiency decreases with increase of wet portion in the flow past turbine stage. In Fig. 13 change in efficiency value for mass flow rate of the wet phase of 0%, 4.478% and 8.956% is demonstrated. It is proven that efficiency decrease is in a direct ratio to the wet part of the flow. In our case of research

efficiency changes from 67.15% to 59.69%.

Numerical simulations show that in reactive stages the angle of this change will be less than in active, considering the change of direction relative to velocity of drops upon change of peripheral velocity.

Consequently impacts of droplets in reactive stages will be distributed over a smaller area than In active stages, i.e., the impact influence of water per 1 cm□2 of blade surface in reactive stages will be greater than in active stages.

In Figs. 9 and 10 results verification is shown. In Fig. 10(a) are visualized liquid droplets' traces and their concentration on the blade surfaces in the current research and verification of the results, after Hamed *et al.* (2013), is observed in Fig. 10(b).

The blade fails by varying stress during impact, and the liquid-solid impact problem must be solved so as to evaluate the blade lifetime in a more reliable manner.

When a spherical water drop impacts on a solid plane, a shock wave forms inside the water drop due to the compressibility of liquid, see the book of Schmeltzer (2005). The water drop thus imposes a pressure distribution (water hammer pressure) on the surface of solid which varies with time and space, inducing stress waves which transmit through the solid, with possible formation and propagation of micro cracks. The shock waves and imposed pressure over the surfaces are dependent on the droplet velocities, flow parameters, water drops diameter and mass.

Once we have numerical results for erosion rate on blade surfaces and all flow and water droplets' parameters in the regions of high erosion, we can perform computations regarding the erosion resistance of blade materials or materials that must be applied to decrease erosion effects over turbine blades.

The equation, applied for "water hammer pressure" calculation is, (Soni and Pandy, (2011):

$$P=(C_S.\rho_S.V.\cos\theta)/[(C_S.\rho_S/C_L.\rho_L)+1] \quad (5)$$

Density of water droplets is equal to known as $\rho_L=1000\ kg/m^3$; density of solid blade material, in this case martensitic stainless steel *1Cr13,* is $\rho_S=7700\ kg/m^3$, see(www.steel-grades.com and Q. Zhou *et al.* (2008).

Sound speed in water medium is $C_L=1465\ m/s$, a value taken from the database on *www.hyperphysics.phyastr.gsu.edu*. Sound speed in the chosen blade material is $C_S=(Es/\rho_S)0.5=(200.10^9/7700)0.5=5096\ m/s$, (refer to www.hyperphysics.phyastr.gsu.edu and Q. Zhou *et al*. (2008).

Peripheral velocity of rotor blade is $U=\pi.D.n/60\ m/s$. Calculated values for 3 control sections – hub, mid and tip are $Uhub=252.85\ m/s$, $Umid=276.40\ m/s$ and $Utip=299.95 m/s$.

Results, obtained for water hammer pressure "*P",* are presented in Table 1 and must be compared with material's equivalent stress, which is $\sigma e=468\ [MPa]$,(Q. Zhou *et al.* (2008)) and is a measure of the multi-axial stress field at a material point. In Table 1, value "θ" is the mean angle at which droplets impact blade surfaces, at hub, mid and tip sections of the stage under consideration.

Calculations were performed for case of water droplets with diameter of 25 microns and mass flow rate of 0.266 kg/s, this is the case with observed maximum rate of erosion over blade surfaces.

Table 1 Results for three control sections

	Parametere				
	D [m]	U [m/s]	θ [deg]	P [MPa]	T 10^6 [s]
Hub	3.22	252.85	65	150.715	0.764
Mid	3.52	276.40	60	194.914	0.815
Tip	3.82	299.95	55	242.653	0.926

In the current research, as an impact velocity, we can assume the one, at which, the section under consideration hits with water droplets. It was clarified before that water steam water drops, depending on their size and mass, are travelling at speed equal or less of the steam flow speed. All results are described in Table 1. Water hammer pressure effect increases in radial direction because sections from hub to tip meet water droplets with gradually increasing peripheral velocity.

Next step is to calculate important parameters as number of water droplets affecting the blade surfaces, number of impacts over blades and incubation time to erosion, (Soni and Pandey, 2011):

- number of water droplets per unit volume of steam

$$n_{droplets}=6.(m/\rho_L).10^9/(3,14.dp^3) \quad (6)$$

- number of impacts over one square meter of surfaces under consideration

$$N_{impacts}=(8,9/dp^2).(\sigma_e/P_{imp})^{5.7} \quad (7)$$

- incubation time to erosion processes to appear is

$$T_s=N_{impacts}/(n_{droplets}.U.\cos\theta) \quad (8)$$

Loss of material is given with equation (9):

$$m_{loss}=73,3.10^{-6}.Es.dp^3.(Pimp/E_S)^4\ kg/m^2 \quad (9)$$

For the assessment of the erosion resistance of a material for blade coatings is necessary to verify the dependence on the peripheral velocity and droplet size. The choice for the cover material and its thickness over the substrate may vary depending on the impact velocity, droplets' diameter and rate of erosion over surfaces.

Under a wide range of conditions the mass loss of a material will vary with time. For a definite time period - initial incubation time, the weight loss is negligible. For a definite period- after the initial incubation time, the rate of weight of lost material is nearly constant and the weight loss changes with time in linear manner.

The research shows that erosion and decrease in efficiency depend on water droplets diameter, their velocity, impact angles, mass flow rate; aerodynamic features as vortices around the blades; blade shape and profile shape change in radial direction.

4. CONCLUSIONS

Research on prerequisites to erosion and its effects on long turbine blades of complex shape, is accomplished and a study on droplet trajectories and reasons for their deviations is performed. A set of equations, included in a code written by the author, is implemented, for the purposes of modeling of droplets distribution through the turbine stage and forces, which impact blade surfaces.

During the research campaign was proved that erosion rate over blade surfaces is in a function of the wetness percentage, flow angle, droplets velocity components and change in blades shape from hub to shroud. Where exactly will appear erosion wear it depends on the specific blade shape and its change in radial direction. Last mentioned together with wet droplets deviations, induced by their mass changes, velocities, forces action on them, lead to very specific wear on blade surfaces.

It is found that the strongest erosive influence is produced by large drops of condensate, since they are more difficult to accelerate by vapor flow and increases with rate of wetness. Effects due to the presence of water drops in steam are erosion of blades due to impact of water drops at high relative speeds, worse aerodynamic behavior and efficiency decrease. An approach to obtain incidence time to erosion effects appearance is implemented. Research methodology and obtained results are applicable to determine specifics of erosion effects over streamed complex surfaces and replace expensive measurements campaigns. In addition, the outcome of the research work highlights the opportunities for future development of the knowledge on erosion mechanisms, approaches to decrease wetness in the last stages of condensation turbines and to prolong the life cycle of blades operated in wet steam conditions.

REFERENCES

Ahmad, M., M. Casey and N. Suken (2009). Experimental assessment of droplet impact erosion resistance of steam turbine blade materials. *Wear* 267, 1605–1618.

Aitken, J. (1881). 'XII.—On Dust, Fogs, and Clouds', *Transactions of the Royal Society of Edinburgh* 30(1), 337–368.

Alfonso, C. A., G. M. Armando, C. A. Romero, M. C. Zdzislaw and C. A. Rafael (2007). Numerical investigation of the solid particle erosion rate in a steam turbine nozzle. *Appl. Therm. Eng.* 27, 2394–2403.

Ansari, A. R (1986). Blade erosion problem in steam turbine, *Journal of Institution of Engineers* (India)–Mech.Eng. 67,1-3

Atrens, A., H. Meyer, G. Faber and K. Schneider (1983). *Corrosion in Power Generating Equipment*. Plenum Press.

Awatef, A. H., W. Tabakoff, R. B. Rivir, Kaushik Das and Puneet Arora (2005). Turbine Blade Surface Deterioration by Erosion, *Journal of Turbomachinery* 127(3), 445-452.

Azevedo, C. R. F. and A. Sinatora (2009). Erosion-fatigue of steam turbine blades, *Eng. Fail. Anal.* 16 (7), 2290–2303.

Bagheri Esfe, H., M. J. Kermani and M. Saffar Avval (2016) Effects of non-equilibrium condensation on deviation angle and performance losses in wet steam turbines, *Journal of Applied Fluid Mechanics (JAFM)*, 9 (4), 1627-1639.

Bagheri Esfe, H., M. J. Kermani and M. Saffar-Avval (2016). Numerical simulation of compressible two-phase condensing flows, *Journal of Applied Fluid Mechanics (JAFM*), 9(3), 867-876.

Balan, C. and W. Tabakoff (June, 1984). *Axial Compressor Performance Deterioration*, AIAA Paper 84-1208.

Binnie, A. M. and J. R. Green (1943). An Electrical Detertor of Condensation in High-Velocity Steam. *Proc. Royal Society (London)*, A, 181, 134-154.

Binnie, A. M. and M. W. Wood (1938). The Pressure Distribution in a Convergent-Divergent Steam Nozzle. Proc. *Instn. Mech. Engrs* 138, 229-226.

Bullock, R. O. *Vapor turbine for space power*. A. R. S. Paper. 1327-60.

Callender, H. L. (1915). On the Steady Flow of Steam Through a Nozzle or Throttle, Proc. Instn. Mech. Engrs. 53-77.

Campbell, B. A. and F. Bakhtar (1970). Condensation Phenomena in High Speed Flow of Steam. *Proc. Instn. Mech. Engrs.* 185, 395-404.

Campos Amezcua, A., Z. Mazur, A. Gallegos Munoz, R.C. Alejandro, J. Manuel Riesco Avila and J. M. Medina Flores (2007). Numerical study of erosion due to solid particles in steam turbine blades, numerical heat transfer, Part A: Applications: *An International Journal of Computation and Methodology* 53(6), 667–684.

Carija, Z., L. Cranjcevic, V. Banic and M. Cavrac (2012). Numerical analysis of Wells turbine for wave power conversion, *Engineering Review* 32(3), 141-146.

Christopher, E. B. (2005). *Fundamentals of Multiphase Flow*, Cambridge University Press.

Danmei, X., X. Yu, W. Li, Y. Hou, Y. Shi and S.

Cai (2010). Numerical Simulation of Water Droplets Deposition on the Last-Stage Stationary Blade of Steam Turbine, *Energy and Power Engineering* 2, 248-253.

Deich, M. E., G. V. Tsiklauri, V. K. Shanin and V. S. Danilin (1972). Investigation of Flows of Wet Steam in Nozzles. *Teplofizika Vysokikh Temperatur* 1(1), 122-129.

Filippov, G. A. and O. A. Povarov (1980). *Moisture Separation in the Turbines of Nuclear Power Station*. Energy, Moscow.

Fiore, G. and M. Selig (2014). *A simulation of Operational Damage for Wind turbine Blades*, 32nd AIAA Applied Aerodynamics Conference, AIAA Aviation, 16-20.

Forte, A. F., D. Joseph, D. Lundgren and T. S. (1987). Nonlinear mechanics of fluidization of beds of spherical particles. *J. Fluid Mech*., 177, 469-483.

Galina, I. (2015). *Numerical Modeling and Research of 3D Turbine Stage*, Engineering Applications of Computational Fluid Dynamics, Springer, Advanced Structured Materials series 44, 103-126.

Galina, I. (2016). Geometry modeling of 3D turbine stages – how to obtain high quality grid and overcome discretization problems, *International Journal of Research – Granthaalayah*, 4(2), 197-205.

Gelfand, B. E. (1996). Droplet breakup phenomena in flows with velocity lag, *Progress in Energy and Combustion Science*, 22(3), 201-265.

George, F. S. (1979). *Liquid and solid particle impact erosion, Coatings and Thermal Protection Materials*, Branch Nonmetallic Materials Division, Technical Report AFML-TR-79-4122.

Grant, G. and W. Tabakoff (1985). Erosion Prediction in Turbomachinery Resulting from Environmental Particles, *Journal of Aircraft*, 12 (5), 471–478.

Gyarmathy, G. (1962). Theoretical Principles of Condensation turbine. Dissertation ETH, Zurich, Juris-Verlag (English Translation: CEGB (London) Rept T-781 (1963))

Hamed A., W. Tabakoff, R. Swar, D. Shin, N. Woggen and R. Miller (2013). *Combined Experimental and numerical simulations of thermal barrier coated turbine blades erosion*, NASA/TM-2013-217857.

Hamed, A., W. Tabakoff, R. B. Rivir Das and K. Arora, P. (2004). *Turbine Blade Surface Deterioration by Erosion*, ASME-IGTI 54328.

Hasini, H., M. Zamri Yusoff and N. A. Malek (2012). *Numerical Modelling of Wet Steam Flow in steam Turbine Channel*, Mechanical Engineering, Dr. Murat Gokcek (Ed.)

Hill, P. G. (1966). Condensation of Water Vapour During Supersonic Expansion in Nozzles. *J. Fluid Mech*. 25(3), 593-620

Hric, V. and J. Halama (2015). *Numerical solution of Transonic Wet Steam Flow in Blade-to-Blade cascade with Non-equilibrium Condensation and Real Thermodynamics*, EPJ Web of conferences 92, 02025

Hutchings, I. M., N. H. Macmillan and D. R. Rickerby (1981). Further studies of the oblique impact of a hard sphere against a ductile solid. *Int. J. Mech. Sci*. 23, 639–646.

Hutchings, I. M., R. E. Winter and J. E. Field (1976). Solid particle erosion of metals: the removal of surface material by spherical projectiles. *Proc. R. Soc. Lond. Ser. A* 348, 379.

Karuna, T and B. Sasithon (2014). Computational Study and Wear Prediction of Steam Turbine Blade with Titanium-Nitride Coating Deposited by Physical Vapor Deposition Method, *International Scholarly and Scientific Research and Innovation* 8(7).

Kirillov, I. I. and R. M. Yablonik (1962). Enhancement of turbine stages working in wet steam conditions (original in Russian), Teploenergetika, 10: 41-47

Kirillov, I. I. and R. M. Yablonik (1963). *Kinetics of condensation processes of steam in turbine stages* 4, 4–8.

Kline, M. and G. Simpson (2004). The Development of Innovative Methods for Erosion Testing a Russian Coating on GE T64 Gas Turbine Engine Compressor Blades, *ASME Paper GT2004-54336*.

Krzyzanowski, J. and Z. Szperngiel, (1978). The influence of droplet size on turbine blading erosion hazard, ASME *Journal of Engineering for Power*, 100, 561-565.

Leyzerovich, A. (1997). *Large Power Steam Turbines: Design and Operation*, Penn Well Books.

Leyzerovich, A. S. (2008). *Steam turbines for modern fossil fuel power plant*, The Fairmont Press Inc., Georgia, USA.

Liu xi, C., S. Wang, J. Di, J. Mao, Z. Feng, J. Zhang and Y. Xu (2014). *Study of Erosion Characteristics of Solid Particles in the First Reheat Stage Blades of a Supercritical Steam Turbine*, GT2014-26674 V01BT27A040; 13.

Mahmood, E. and M. H. Roozbahani (2011). Comparative Investigation in a Turbine Blade Passage Flows with Several Different Turbulence Models, *Int J Advanced Design and Manufacturing Technology* 4(4), 39-45.

Mann, B. S. and A. Vivek (2002). An experimental study to correlate water jet impingement erosion resistance and properties of metallic materials and coatings. *Wear* 253, 650–661.

Martin, H. M. (1918). A New Theory of the Steam

Turbine, *Engineering*, 106: 1-3, 53- 55, 107-108, 161-162, 189-191, 245-246

Martinez, F. R., M. T. Velazquez, F. S. Silva, A. A. R. Martinez, S. A. Montes and O. M. H. Chavez (2011). Theoretical and numerical analysis of the mechanical erosion in steam turbine blades, In: Part I, *Energy and Power Engineering* 3,227– 237.

Mingazhev, A. D., A. V. Novikov, N. K. Krioni and R. R. Bekishev (2014). Protective Coating for Steam Turbine Blades, *Electronic scientific journal "Oil and Gas Business* 4, 257-278.

Nagel, W. E. and *et al.* (eds) (2013). *High Performance Computing in Science and Engineering*'12 Springer-Verlag, Berlin Heidelberg.

Nikkhani, B., M. Shams and M. Ziabasharhagh (2009). A numerical investigation of two phase steam flow around a 2D turbine's rotor tip, *Int. Comm. Heat and Mass Transfer* 36, 632-639

Nishimura, M. (1999). Estimate erosion damage under any conditions, *Japan Society of Corrosion Engineering*, 48(6), 355-361.

Oswatitcsh, K. L. (1942). Condensation Phenomena in Supersonic Nozzle. *Z. Angew. Math. Mech*. 22(1), 1-14.

Pruppacher, H. R. and J. D. Klett (1997). *Microphysics of Clouds and Precipitation*, Kluwer.

Puzyrewski, R. (1969). Condensation of Water Vapour in a Laval Nozzle. *Instn. Fluid Flow Machinery*, Gdansk (Poland).

Rettaliata, J. T. (1938). Undercooling in Steam Nozzle, *Transaction of ASME* 58, 599-605.

Richardson, J. H., Sallee, G. P. and Smakula, F. K. (1979). *Causes of High Pressure Compressor Deterioration in Service*, AIAA 79-1234.

Ryley, P. J. (1961). Phase equilibrium in low-pressure steam turbines*, Internat. J. Mech. Sc* 5(1-2), 28-46.

Sandeep, S. and J. D. Pandey (2011). Erosion behavior of steam turbine blades of glass-epoxy 2, 110-117.

Schmelzer, J. W. P. (2005). *Nucleation Theory and Application*, Wiley, Hoboken, 2005.

Sear, R. P. (2014). Quantitative Studies of Crystal Nucleation at Constant Supersaturation: Experimental Data and Models. *Cryst Eng Comm.* 16(29), 506.

Shunsen, W., L. Cai, J. Mao, J. Zhang and Y. Xu (2013). Mechanisms of steam turbine blade particle erosion and crucial parameters for minimizing blade erosion, *Journal of Power and Energy,* 227(5), 546-556.

Sławomir, D., M. Majkut, K. Smołka and M. Strozik (2013). Research on steam condensing flows in nozzles with shock wave, *Open Access Journal Journal of Power Technologies* 93 (5), 288–294.

Springer, G. S. (1976). *Erosion by liquid impact*, John Wiley and Sons, New York, USA.

Stanisa, B. and V. Ivusic (1995). Erosion Be haviour and Mechanisms for Steam Turbine Rotor Blades, *Wear* 186-187, 395 - 400.

Stiver (1963). *Condensation phenomena in high speed flows (original in Russian). Collection: Gas dynamics principles, Edited by G. Emmons, Foreign literature Press*, edited by G. Emmons, Izd-vo Inostrannoy literatury.

Stodola, A. (1922) *Dampf- und Gasturbinen*. Springer -Verlag. Berlin.

Sugano, H., N. Yamaguchi and S. Taguchi (1982). *A Study on the Ash Erosion of Axial Induced Draft Fans of Coal-Fired Boilers*, TR, Vol. 19, Mitsubishi Heavy Industries, Tokyo, Japan.

Sukanta, R. and U. K. Saha (2012). *Comparative analysis of turbulence models for flow simulation around a vertical axis wind turbine*, Indo-Danish International Conference on Wind Energy: Materials, Engineering and Policies (WEMEP 2012) 22nd – 23rd November, 2012 Hyderabad, India.

Tabakoff, W. (1984). Review - Turbomachinery Performance Deterioration Exposed to Solid Particulates Environment, Transactions of ASME, *Journal of Fluids Engineering*, 106, 125-134.

Tabakoff, W. (1986). Study of Single Stage Axial Flow Compressor Performance Deterioration, *American Society of Mechanical Engineers, Fluids Engineering Division* (Publication) FED, 37, 95-100.

Tabakoff, W., W. Hosny and A. Hamed (1976). Effect of Solid Particles on Turbine Performance, Transactions of ASME, *Journal of Engineering for Power* 47-52.

Traupel, W. (1959). *Zur Theorie der Nassdampfturbine*, Schweiz. Bauzeitung. 77(20), 324-328.

Tsubouchi, K., N. Yasugahira and S. Yoshida (1990). *An Evaluation of Water Droplet Erosion for Advanced Large Steam Turbine*, PWR-Vol 10, Advances in Steam Turbine Technology for Power Generation, Book No. G00518, 245-251.

Viswanathan, R. (1989). *Damage mechanisms and life assessment of high temperature components*. Metals Park: ASME International.

Wang, W. Z., F. Z. Xuan, K. L. Zhu and T. Shan Tung (2007). Failure analysis of the final stage blade in steam, *Eng. Fail. Anal.* 14(4), 632–641.

White L. C. (1992). *Modern Power Station Practice*. London: British Electricity International, Pergamon Press.

Wilson, W. T. R. (1897). Condensation of Water Vapour in the Presence of Dust-free Air and

Other Gases. *Phil. Trans. Royal Society* (London) A, 189, 265-307

Wroblewski W., S. Dykas and A. Gepert (2009). Steam Condensing Flow Modelling in turbine channels*, Int. J Multiphase Flows*, 35, 498-506.

Xu W., W. Jiadao, Q. Li, C. Haosheng and C. Darong (2010). Investigation of Erosion Damages Induced by Wet Steam Containing Micro-Particles, *Tribol Lett,* .

Yablonik, R. M. and V. V. Lagerev (1963). Research on wet steam flows in stator blades of steam turbines, Teploenergetika Press, *Teploenergetika*, 1963(11), 55-60.

Yellot, J. L and C. K. Holland (1937). The Condensation of Flowing Steam, Part 1 – Condensation in Diverging Nozzles. *Transaction of ASME*, 59, 171-183

Yellot, J. L. (1934). Supersaturated Steam. *Transaction of ASME*, 56, 411-430

Zhou, Q. and *et al.* (2008). Water drop erosion on turbine blades: numerical framework and applications, *Materials Transactions*, 49(7), 1606 – 1615.