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Issues to improve the safety of 18K370 steam turbine operation

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Abstract. The paper presents the process of improving the safety and reliability of operation the 18K370 steam turbines Opole Power Plant since the first failure in 2010 [1], up to install the on-line monitoring system [2]. It shows how the units work and how to analyse the contol stage as a critical node in designing the turbine. Selected results of the analysis of the strength of CSD (Computational Solid Dynamic) and the nature of the flow in different operating regimes - thanks to CFD (Computational Fluid Dynamic) analysis have been included. We have also briefly discussed the way of lifecycle management of individual elements [2,3]. The presented actions could be considered satisfactory, and improve the safety of operating steam turbines of type 18K370.

1 Introductions

Both due to the emerging failures as well as variable movement conditions, it is necessary to conduct research in improving the safety of power units. After analysing the load status of individual devices of the cycle, it should be noted that particularly vulnerable to variable parameters of steam are boilers [4-9], then valves [10] and finally the first stages of the turbine [11-15]. To face these threats, it is necessary to increase the safety of operation of energy cycles including steam turbine type 18K370 [1-3]. The work regimes for load of control stage are different, so we have to rely upon more accurate calculation tools [3,16] including predicting further safe operation of steam turbine rotors after the calculated working time [14] as well as the increased expenditure and even entry into resonance resulting from the non-stationary operating conditions [17,18]. Another aspect is the interaction of fatigue and creep [12,13].
The new computational tools such FSI (Fluid Solid Interaction) allow determining the fluid - solid interactions [3,6,16,18]. Of particular importance is the transfer of information on the interface (with working medium - construction) which represents the connection, and at the same time the boundary condition, between the CSD (Computational Solid Dynamic) and CFD (Computational Fluid Dynamic). Thus, the analysis of the strength of CSD derive data from CFD and could, as a result of movements, at the same time affecting on nature of the flow.

The aim of this article is to present results of analysis of failures of two casing internal parts of the HP turbines, type of 18K370 and the presentation of the activities (including numerical calculation) taken to improve the safety of operating parameters of turbines in power plant PGE GiEK SA Branch in Opole.

1.1 Main motives

The main motivations for seeking areas of safe operation of the turbine 18K370 were two failures that took place respectively: 13 May 2010 and 26 October 2010. The scope of the devastation are shown in Fig.1 and Fig.2.

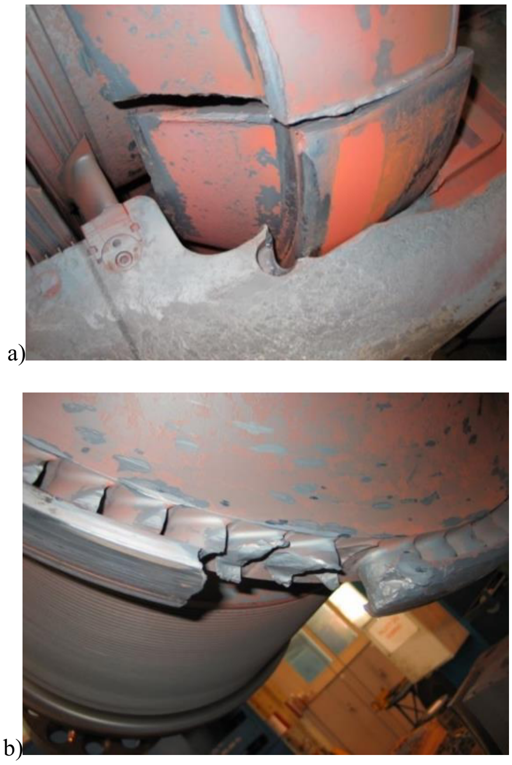

Fig. 1. Damages of control stage chamber after the first failure: a) the casing protection ring, b) the rotating wheel of control stage – two blades with shroud are completely destroy.

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While research it was found that breakthroughs fragments of detached blades on control stage are fatigue. It could suggest that the primary cause of the failure was a rupture of the blades on the degree of control and its propagation leading to a break of the rotating element. The time, when entire process took place in, is difficult to determine. The broken off part of the blade came between the rotating wheel of control stage and the control ring (the casing protection ring), causing a damage of the catch pawl of this ring, which consequently has been destroyed (Fig. 1).

On the other hand, analysing the second failure it is clear that the microstructure of the shaft was not fatigue or weak because of operating. In places of microsections, the material had a homogeneous fine-grained structure and hardness. Based on the issued metrics, there was not observed any curvature of the shaft.

a) 

b) 

Fig. 2. Damages of control stage chamber after the second failure: a) the casing protection ring – huge crash and displacement, b) the rotating wheel of control stage.

Based on the survey of the manufacturer (producer), it has been stated that the shaft has to be repaired and then is suitable for further use. Because of the scope of damage all of the rotor blades have to replace by new ones (Fig.2). During the researches, it found out an impossibility of get off the blades from 4th to 8th rotor stages. Because, in order to allow to further operating of the shaft, we have to check the state of notches blade, the only way to dismantling those blades was their bore. During the failure 1-3 rotor degrees were completely destroyed, so there was not any way to their reconstruction. The damage of 9-19 degrees were also significant.

Also on the basis of the manufacturer research, it has been stated that repair of the damaged catch pawl in the casing for the directing segment does not guarantee the safe operation of the turbine. It was recommended to construct a new casings.

On the other hand, on the basis of Institute Fluid-Flow Machinery Polish Academy of Sciences (IFFM PAS) investigation, traditional experiment tools and classical computational tools indicated that none of the known mechanisms of failure appeared. Additionally, it was shown that classical mechanisms of degradation such as: cyclic plasticity, low-cyclic thermal fatigue, low-cyclic creep fatigue, high-cyclic fatigue induced by flow pulsations, excessive resonant forced vibration do not appear in the chamber of control stage.

Therefore, it was necessary to put forward a hypothesis as to the possible mechanisms of destruction and look for secondary and indirect causes. For example, one of the hypothetical mechanisms of degree destruction can be an introduction a small piece of metal to the sealing area. This could become due to human causes during the shut-down. It could also be metal shavings or corroded part of the boiler detached by an accidental blow of the hammer.

At the time of the failure, the wheel structures, for inputs of turbines for units 3 and 2, were different. Because of destruction of the whole ring of the input from unit 2, it was virtually impossible to determine the causes of failure. But due to differences in rotating wheel design is excluded this element as a focus failure, so the causes and course failure were different for the two blocks. Despite the fact that the existence of two such large failure at one time on machines with a relatively short period of operation, in combination with long-term operation of twin machines, makes us seek common denominator for these events. This may be the design of wheel ring or operating regime. It was decided to introduce structural changes and introduce additional measurement raising the safety of operating.

1.2 Constructive improvements

The main constructive change was to complete the measuring system with a new element to measure the temperature around the control stage chamber (Fig. 3).

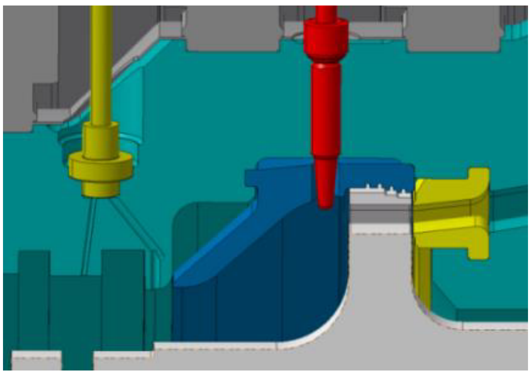

Fig. 3. Location of the thermowell to measurement of temperature in the control stage chamber.

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In order to renew the control stage chamber and increase the supply of its security, the material of control ring (the casing protection ring) was modified.

The power plant complemented the measuring system and made amendments to the diagnostic system by using the "dual diagnosis": first the classical and the other based on "reference state calculation" turbine, designed for engineering supervision and performed in "forecasting repairs" to monitor the expenditure and degradation operating.

In order to improve the safety of operating and equip the turbines in numerical model of control stage working parameters, the IFFM PAS conducted following numerical simulations:

1. Geometry and numerical models to analysis of the vitality of control stage.
2. Three-dimensional (3D) flow analysis of control stage with taking into account full geometry of the nozzle boxes and inlets in order to determine parameters behind the nozzle boxes.
3. Three-dimensional (3D) flow analysis of warming up the disc of control stage with a shaft part basing on boundary conditions enumerated in the analysis above.
4. The analysis of thermal stress distribution accuring in the disc of control stage, the casing protection ring and in the part of rotor shaft.
5. The algorithm for the vitality loss of control stage lifetime in particular stages of unsteady turbine work.

Taking into account the imposed tasks and aims, the FSI scheme of calculations was adopted, which are presented in next part of this paper.

1.3 The governing equations

An important tool in the analysis of the entire considered issue (deformation, stress and temperature field) is the combination of CFD + CSD, often called FSI - Fluid Solid Interaction or Fluid Structure Interaction. On the basis of FSI (Fluid Solid Interaction) system of equations both for liquid and solid the three dimensional geometry have been calculated. The part below is taken from the methodology of Energy Conversion Department IFFM PAS [5,6,11] for describing fluid behaviour using the CFD equations. The starting point for CFD computation is formulation of universal set of mass, momentum and energy balance equations for the fluid, supplemented with equations for turbulence evolution k-ε in the form of:

$$\frac{\partial}{\partial t}\begin{Bmatrix} \rho \\ \rho\mathbf{v} \\ \rho e \\ \rho k \\ \rho\varepsilon \end{Bmatrix} + \mathrm{div}\begin{Bmatrix} \rho\mathbf{v} \\ (\rho\mathbf{v}\otimes\mathbf{v}) + p\mathbf{I} \\ (\rho e + p)\mathbf{v} \\ \rho\mathbf{v}k \\ \rho\mathbf{v}\varepsilon \end{Bmatrix} =$$

$$= \mathrm{div}\begin{Bmatrix} 0 \\ \mathbf{t}^{res} \\ \mathbf{t}^{res}\,\mathbf{v} + \mathbf{q}^{c} \\ \mathbf{J}_k \\ \mathbf{J}_\varepsilon \end{Bmatrix} + \begin{Bmatrix} 0 \\ \rho\mathbf{b} \\ \rho S_e \\ \rho S_k \\ \rho S_\varepsilon \end{Bmatrix} \tag{1}$$

where: : $\rho = \rho(\mathbf{x}, t)$ - density depends, in general, on time t and location $\mathbf{x}$, $\mathbf{v} = v_i\mathbf{e}_i$ - velocity, $\mathbf{e}_i$ - direction vector, p - thermodynamic pressure, $\mathbf{I} = \delta_{ij}\,\mathbf{e}_i \otimes \mathbf{e}_j$ - unit tensor, δ_{ij} - Kronecker's delta, $\mathbf{t}^{res} = \mathbf{t}^{lam} + \mathbf{t}^{tur}$ - flux components of viscous stress – (laminar and turbulent, respectively), $\mathbf{b}$ - mass force of gravity, $e = u + \frac{1}{2}\mathbf{v}^2$ - sum of internal and kinetic energy , $\mathbf{q}^c$ - total heat flux, $\mathbf{J}_k$, $\mathbf{J}_\varepsilon$ - diffusive flux k and diffusive flux ε and sources S_k, S_ε . Then, using the CSD equations, we obtain following system:

$$\frac{\partial}{\partial t}\begin{Bmatrix} 1 \\ \rho\mathbf{v} \\ \rho e \\ \rho\mathbf{e}^{pl} \\ \rho\boldsymbol{\alpha} \\ \rho r \end{Bmatrix} + \mathrm{div}\begin{Bmatrix} 0 \\ \rho\mathbf{v}\otimes\mathbf{v} \\ \rho e\mathbf{v} \\ \rho\mathbf{e}^{pl}\otimes\mathbf{v} \\ \rho\boldsymbol{\alpha}\otimes\mathbf{v} \\ \rho r\mathbf{v} \end{Bmatrix} =$$

$$= \mathrm{div}\begin{Bmatrix} 0 \\ \boldsymbol{\sigma} \\ \boldsymbol{\sigma}\,\mathbf{v} + \mathbf{q}^{c} \\ 0 \\ 0 \\ \mathbf{J}_r \end{Bmatrix} + \begin{Bmatrix} 0 \\ \rho\mathbf{b} \\ \rho S_e \\ \rho S_{pl} \\ \rho S_\alpha \\ \rho S_r \end{Bmatrix} \tag{2}$$

where: $\boldsymbol{\sigma}$ - tensor of solid stresses; $\mathbf{e}^{pl}$ - tensor of plastic strain; $\boldsymbol{\alpha}$ - kinematic hardening; r - isotropic hardening; $\mathbf{J}_r$ - diffusive flux of r; $S_{pl}, S_{\boldsymbol{\alpha}}, S_r$ sources of plasticity , kinematic and isotropic hardening typical for the Chaboche model. The system of equations and the way of CSD and CFD solutions are analogical to each other. Both methods use the basic balances: mass, momentum and energy. However, the difference often occurs in the way of discretization by applying the finite element method (FEM) in CSD and the finite volume method (FVM) in CFD. It is a kind of numerical challenge to combine both methods to transfer boundary conditions.

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2 Results

As mentioned above, analysis was conducted in order to reconstruct the working conditions of stage control node by the preparation of flow and constructional geometry, discretization the space, and then measure the boundary conditions during the operating of the block. The geometry used in analysis is presented on Fig.4, where: a) the area of control stage; b) the rotor with the control stage c) cutting from 1st blade and discretization of both liquid and solid and d) internal casing of HP, used to CSD strength analysis. The calculation area includes in the part of turbine inlet to the HP by nozzle boxes, the blades of control stage (64 blades in accordance with the profile used in this construction), the chamber control stage to the outlet of the first stage rotor palisade the unregulated part of the HP. So it shows four inlet pipelines, nozzle sectors, internal casing, control stage rotating wheel and the control stage chamber (with the casing protection ring), and first full-arc admission stage.

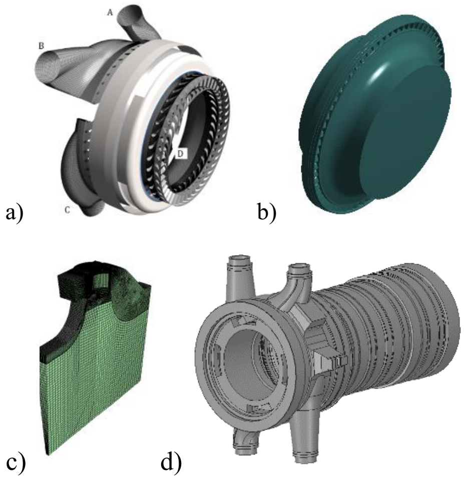

Fig. 4. The elements of geometry: a) fluid domena of the area of control stage; b) the rotating wheel of control stage; c) cutting from 1st blade and discretization of both liquid and solid; and d) internal casing.

Examples of the results of flow analysis are presented in Fig.5, which shows the cold start-up after 68 minutes with taking into account: a) the state of pathlines coming out of the nozzle box and passing through the chamber of control stage up to the first unregulated stage; b) the view of the local changes in the field of static pressure in both the axial cross-sectional and circumferential view; and c) swirling at the outlet of the nozzle up to the control wheel (velocity field). Thanks the obtained results it is possible to determine the force acting on the individual components of the turbine. The results from Fig. 5 correspond to the turbine operating with partial load. This operation mode differs from the nominal load by opening of two nozzle boxes only. The remaining two are fully closed by the stop valves and steam is flowing only through the boxes with a smaller number of nozzles. Consequently, higher non-uniformity of pressure Fig.5b) and velocity distribution Fig.5c) is observed for the steam leaving the two loaded boxes. It can be noticed that the flow forms the main core of higher velocity beginning at the exit from the boxes with a smaller number of nozzles. Next in the control stage chamber, fields of pressure and temperature are more uniform. As was mention before Fig.5a) presents the temperature fields at selected time step however additionally shows the state of pathlines coming out of the nozzle box and passing through the chamber of control stage.

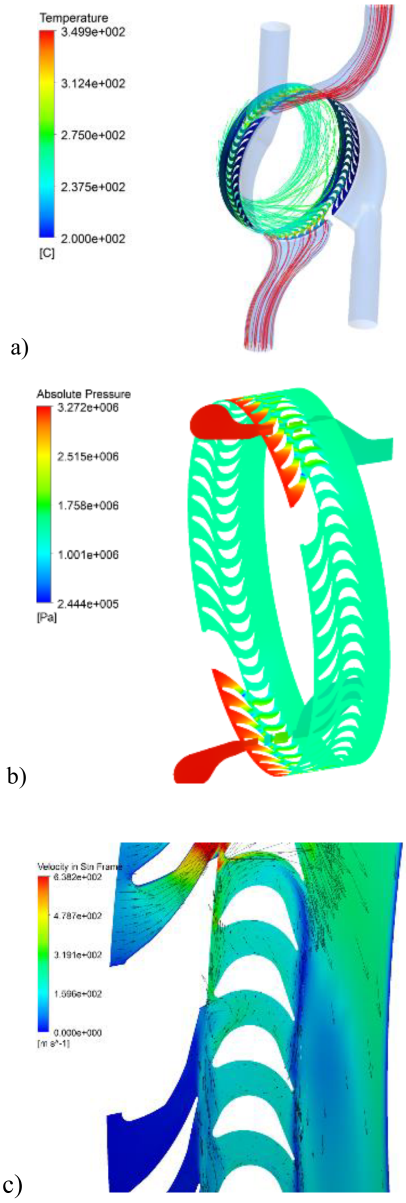

Fig. 5. CFD results after 68 minutes of cold start-up: a) pathlines with temperature distribution in the and nozzle boxes; b) pressure field in the circumferential view and axial cross-sectional and c) velocity field.

Another important information obtained from the CFD analysis is temperature distributions over time (Fig. 6) which could determine the speed of heating of the solid from flowing steam. Temperature fields during cold start-up in the following seconds, where a) the 1600s .; b) 2400s .; c) 5200s; d) 14400s has been

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presented in Fig.6. Local temperature variations do not exhibit significant fluctuations. At this type of heating, after examining distribution of the flow parameters and its character, it can be stated that the flow at the control stage chamber is stable and does not exhibit symptoms of uncorrected start-up.

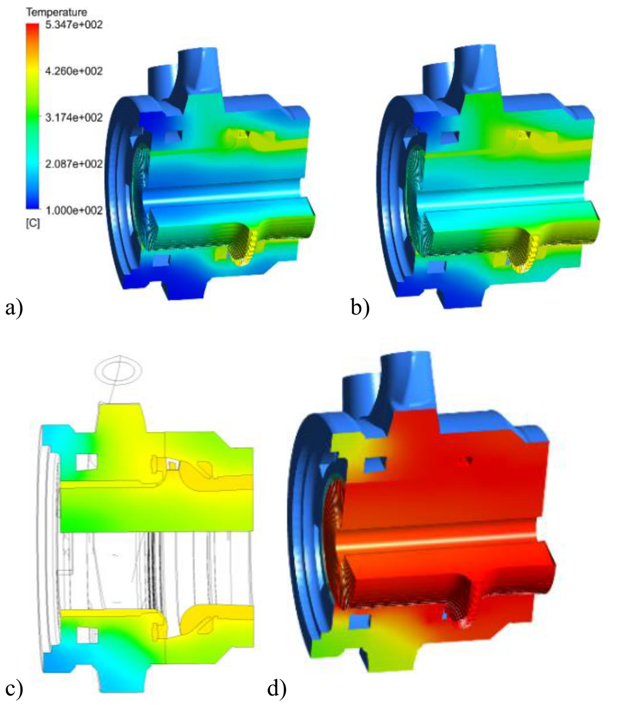

Fig. 6. Temperature fields during cold start-up in the following seconds, where a) the 1600s .; b) 2400s .; c) 5200s; d) 14400s.

The example of the effect on stress state is shown in Fig.7. Analysis of CSD aimed to reconstruct the stress state, and then in perform a study on the opportunity to increase the rate of change in power (start-up, shutdown, part load, increase and decrease of part load power) with respect to the referential data by using the modified regulation and discuss and compare these solutions, which are currently used in power plant. The steam forces calculated in CFD simulations were used as loads in mechanical integrity analysis. The calculated distributions of stress field resulting from the centrifugal forces at a rotating speed of 3000 rev/min are presented in Fig. 9. Based on this it can be stated that the static stress criteria are fulfilled.

It should be added that the kind used regulation was verified and confirmed its safety. The important issue while improving the safety of the turbine regulation is also an algorithm for accurate and reliable calculation of the temperature in control stage chamber based on the turbine measurement in one point. Starting from well known the measuring, the model is calibrated, and then the CFD tools are used to estimate the value of the remaining points. In turn, the algorithm counts the lifetime loss of control stage is based on FSI model, which allow to compare the critical point (the blade of the rotating wheel) with measurements made in points quite distant from the critical point. In other words, those tools allow to correlate measurements of pressure and temperature, as measured on the casing with the state of mechanical and thermal stresses in the rotating blade and any point on the internal casing and the control stage.

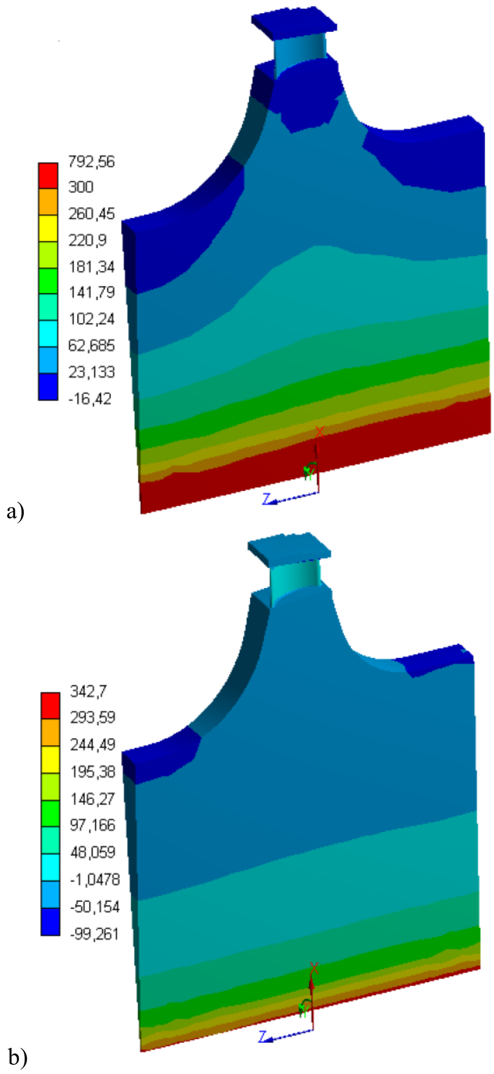

Fig. 7. Stress field resulting from the centrifugal forces at a rotating speed of 3000 rev/min, wherein a) a radial; b) peripheral circulation.

3 Conclusions

The rotating wheel of control stage is an element working under maximum pressure and temperature. Flow analysis using numerical methods allowed to explain the impact of operating regime on the distribution of power and temperature in turbine control stage. The analyses and tests have been showed that present method of control contributes a substantial increase in safety and lifetime endurance, while maintaining the flow parameters such as power, efficiency and mass flow rate.

The temperature of control chamber came as a main parameter related with safety, hence it is reasonable to on-line monitoring, on the basis of measurements at calibration point and other available points. To calculate temperature we dedicated a special algorithm.

Additionally, with the passes of temperature, pressure, stress and deformation, we created the algorithm counting viability of the control stage in sensitive points for safety.

References

1. Bzymek G., Badur J., *III Conference ZRE Katowice*, Krynica-Zdrój 13-15 April 2016, 73-102 (2016).
2. Banaszkiewicz M., Bzymek G., Radulski W., Energetyka **8** 519-524 (2015).
3. Badur J., Kornet S., Sławiński D., Ziółkowski P., Banaszkiewicz M., Rehmus-Forc A., *Energetyka* **10** 647-650 (2016).
4. Taler J., Węglowski B., Cebula A., *Energetyka* **9** 646-650 (2006).
5. Taler J., *Int. J. Heat Mass Transfer*, **35** (6) 1625-1634 (1992).
6. Badur J., Ziółkowski P., Sławiński D., Kornet S., *Energy* **92** 142-152 (2015).
7. Zima W., Nowak-Ocłoń M., Ocłoń P., *Energy* **92** 117-127 (2015).
8. Grądziel S., Majewski K., *Procedia Engineering* **157** 44 – 49 (2016).
9. Taler J., Węglowski B., Taler D., Sobota T., Dzierwa P., Trojan M., Madejski P., Pilarczyk M., *Energy* **92** 153-159 (2015).
10. Marek A., Okrajni J., *JMEPEG* **23** 31–38 (2014).
11. Banaszkiewicz M., *Int. J. of Fatigue* **73** 39–47 (2015).
12. Kosman W., *J. of Power Technologies* **95** 47–53 (2015).
13. Banaszkiewicz M., Rehmus-Forc A., *Eng. Failure Analysis* **51** 55–68 (2015).
14. Dobrzański J., Purzyńska H., Matusik M., *Energetyka* 737 (11) 761-764 (2015).
15. Banaszkiewicz M., *Appl. Thermal Eng.* **94** 763-776 (2016).
16. Banaś K., Badur J., Proc. *11th Int. Cong. On Thermal Stresses*, University of Salerno, Italy, 5-9 June 2016, 19-22 (2016).
17. Kowalewski Z., *IPPT PAN Publishers*, Warsaw, 2005.
18. Odahara S., Murakami Y., Inoue M., Sueoka M., *JSME Int J SerA* **48** (2) 109-117 (2005).