CONCEPT OF ADVANCED LIFETIME MONITORING SYSTEM FOR STEAM TURBINES

Mariusz BANASZKIEWICZ

Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Fiszera 14,
80-231 Gdańsk, Poland, mbanaszkiewicz@imp.gda.pl

Abstract

The increasing share of renewables in electricity production adversely affects the operation of thermal plants, including steam turbine units. Intermittency of renewable sources results in high variability of steam turbine operating conditions, which together with the inherent scatter of turbine operating parameters significantly complicates their lifetime assessment. The paper presents a concept of lifetime monitoring system in scope of creep-fatigue damage. The system is based on online and offline calculations, performs online analysis of measurement data and takes into account the results of material tests. Functionality of the system main modules is described and mathematical models suitable for online calculations are presented. A general concept of hardware configuration for the system is proposed as well.

Keywords: monitoring, steam turbines, lifetime assessment, low-cycle fatigue, creep

KONCEPCJA ZAAWANSOWANEGO SYSTEMU MONITOROWANIA ŻYWOTNOŚCI TURBIN PAROWYCH

Streszczenie

Wzrastający udział odnawialnych źródeł energii w produkcji prądu ma niekorzystny wpływ na pracę elektrowni cieplnych, w tym bloków parowych. Niestabilność źródeł odnawialnych skutkuje dużą zmiennością warunków pracy turbin parowych, co w połączeniu z nieodłącznym rozrzutem parametrów pracy turbin w znaczący sposób komplikuje ocenę ich żywotności. W artykule przedstawiono koncepcję systemu monitorowania żywotności w zakresie zużycia zmęczeniowo-pełzaniowego. System ten oparty jest na obliczeniach w trybie online i offline, wykonuje na bieżąco analizę danych pomiarowych oraz uwzględnia wyniki badań materiałowych. Omówione zostały funkcje głównych modułów systemu wraz z propozycją modeli matematycznych odpowiednich do obliczeń w trybie online. Zaproponowano również ogólną koncepcję konfiguracji sprzętowej systemu.

Słowa kluczowe: monitorowanie, turbiny parowe, ocena żywotności, zmęczenie małocyklowe, pełzanie

1. INTRODUCTION

Steam power plants (nuclear and coal) are still the main source of electricity production in the world. The share of these plants in the world gross electricity production in 2018 reached nearly 50% [20] and only coal-fired power generation was 36% of the global power mix in 2019 [16]. In Poland, coal is still a dominating fuel which in 2019 covered 75% of electricity production [25].

The observed rapid development of renewable sources and decreasing investments in new steam plants give rise to significant change in operation profile of the existing plants. The ageing and declining fleet of steam turbines, mostly designed for base load operation, is forced to faster produce more and more power to balance the intermittency of renewables [2]. The required flexibility parameters of thermal power plants are high load gradients, low minimum load and short ramp-up times [31].

These new requirements adversely affect the steam turbines lifetime as flexible operation and cyclic duty result in increased low-cycle fatigue damage. Accumulation of fatigue damage leads to crack initiation and growth compromising the operational safety and availability [8, 11].

The changing operating profiles are a new factor, in addition to the inherent variability of operating conditions, complicating the lifetime assessment of steam turbines. It is well recognized that one of the main source of inaccuracy in lifetime assessment of steam turbines is scatter of operating conditions resulting from a large variation of initial thermal states and variability of load and temperature rates [33]. An example of this is shown in Fig. 1 which presents variation in time of steam temperature measured for several starts from a warm state (each curve represents one start-up). The real changes of temperature are compared with a steam temperature design curve (shown as bold red line) assumed in design calculations. The initial steam temperatures

are significantly different than the design temperature and their scatter reaches 100°C. This is caused by varying initial metal temperatures resulting from different cooling times and the required adjustment of steam temperature to actual metal temperature. Also the temperature profile is subject to considerable fluctuations which are a result of unstable boiler operation.
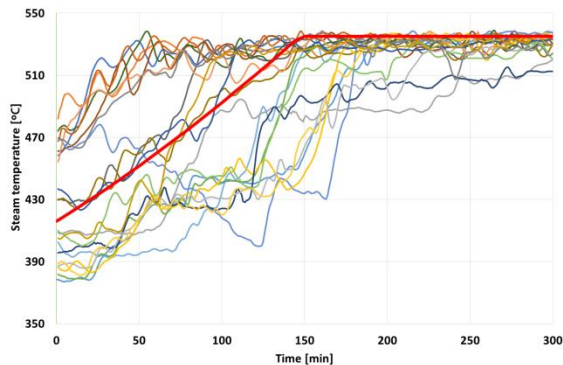

Fig. 1. Variation of steam temperature during warm starts

The new operating profiles and requirements for lifetime extension cause a need for improved lifetime assessment and monitoring of steam turbines [17, 24]. The traditional methods based on elastic stress analyses and representative operating data fail to satisfy the present requirements regarding accuracy and reliability of predictions. The main developments in this area aim at improving the calculation models and take into considerations all, or at least most, of the operating history [33]. Developments in monitoring temperature and stresses with the aim of lifetime assessment are on-going for both turbine [5, 7, 10, 27] and boiler components [28, 29]. Research is also conducted on heat transfer conditions during fast start-ups using the advanced thermal fluid-solid interaction modelling techniques [3, 21, 23, 34].

The goal of the paper is to propose a new lifetime monitoring method and concept of a system for steam turbines taking advantage of long-term operating data and advanced calculation models. The concept can be further developed into a system specification enabling building a prototype for validation purposes.

2. CREEP-FATIGUE DAMAGE OF STEAM TURBINE COMPONENTS

2.1. Physical damage characterization

High-temperature creep, thermomechanical fatigue and their mutual interaction are the major life-limiting damage mechanisms of turbine components subjected to elevated temperature [22, 32].

Creep is a time-dependent and thermally assisted deformation of a component under load leading to unacceptable distortions, crack initiation and growth (Fig. 2) or component rupture [32]. At higher temperatures and longer lifetimes, typical for steam turbines, intergranular creep fractures occur predominantly at low strain rates [35]. Creep damage evaluation with respect to crack initiation can be done by strain measurements, replica tests for creep cavitation, hardness and x-ray measurements [32].
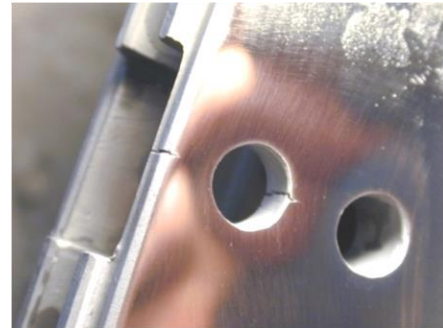

Fig. 2. Creep cracking of a turbine rotor disc

Thermomechanical fatigue takes place under thermal and mechnical loading and involves high strain amplitudes. Fatigue is controlled by cyclic plasticity and failure occurs at $10^3 \div 10^4$ cycles (low-cycle fatigue). In low-cycle fatigue most of the life is spend in crack propagation as cracks typically initiate within $3 \div 10\%$ of the fatigue life [32]. Fatigue cracking of a turbine rotor detected after c.a. 10^3 start-stop cycles is shown in Fig. 3. Low-cycle fatigue cracks initiated in 1CrMoV steels are transgranular [19].

Fig. 3. Fatigue cracking of a turbine rotor shaft

The development of creep-fatigue damage in steam turbine steels depends on temperature, strain range and rate, hold time, and the creep strength and ductility [19]. Creep-fatigue interaction is observed at intermediate hold times and strain rates, and is influenced by creep ductility [19]. When creep ductility is high, creep-fatigue failure is due to damage summation with insignificant interaction. For low creep ductilities, the extent of creep-fatigue interaction can be high [19].

2.1. Creep-fatigue damage modelling

In critical locations of steam turbine components, combined accumulation of cyclic damage due to strain transients and creep damage resulting from primary and secondary stresses can take place [11]. The time fraction method is currently the most

widely used method to determine the accumulated creep-fatigue damage [1, 15, 18, 26, 30]. The creep-fatigue damage for cycle type i is calculated as follows:

$$d_i = \frac{t_h}{t_R(\sigma_p,T)} + \frac{1}{N(\varepsilon_a,t_h)} \qquad (1)$$

where t_h is hold time, t_R is time to creep rupture at given primary stress σ_p and temperature T, N is fatigue endurance at strain amplitude ε_a and hold time t_h. The first term covers the creep damage due to the primary loading and the second term accounts for the fatigue damage and creep damage due to the secondary loading.

The total damage due to all cycles D_{CF} is calculated by using the linear damage accumulation rule by summing the damage fractions due to each individual cycle:

$$D_{CF} = \sum_{i=1}^{n} d_i \qquad (2)$$

In our case the cycle means any type of turbine start-stop or load change cycle.

3. ADVANCED LIFETIME MONITORING SYSTEM

3.1. Modular structure of the system

Several lifetime monitoring systems for power plant equipment have been developed over the last decades. All these systems focus mainly on thermal stress monitoring and control and/or creep-fatigue damage calculation providing valuable information supporting operation and maintenance of steam turbine units. In most cases, simple mathematical models for temperature and stress calculations are used which significantly influence the accuracy of lifetime predictions. Moreover, lifetime monitoring usually covers the crack initiation life and is conservatively based on minimum material property data.

It is expected that the proposed lifetime monitoring system will provide enhanced monitoring capabilities and deeper information about component condition. The functional concept of the system is presented in the block diagram of Fig. 4. This is a hybrid online-offline system composed of the three major groups of functionalities:
- online data counting and recording;
- online calculation of damage, failure probability and crack growth;
- offline operating data analysis, damage calculation, failure probability calculation and damage detection;

Exchange of information between the groups and the flow of information in both directions is foreseen. The online data module will provide input data for online and offline calculation modules. The calculation modules will mutually exchange information in both directions. Continuous exchange of data done online is indicated by the continuous lines, while offline exchange done periodically is given by the dashed lines. The results of damage monitoring will be taken into account in failure probability and crack growth monitoring. It is foreseen that offline damage calculation considers the results of damage monitoring and operating data analysis. Also the outcome of physical damage detection will be considered in crack growth monitoring and remaining life assessment. Damage calculated offline using more advanced models will be periodically used for updating the damage calculated online and to calculate more accurately the failure probability. This will be then used for updating the failure probability computed online. More detailed descriptions of the modules are given in section 3.3.

3.2. Hardware configuration

Proposed hardware configuration of the system is shown in Fig. 5. It covers online data (data counting and recording) and online calculations (damage, failure probability and crack growth monitoring) functionalities. Dedicated measurement system is foreseen for advanced lifetime monitoring. It will include, in addition to the standard process data like steam temperatures and pressures, rotational speed, load, mass flow rates, also special temperature measurements of the turbine critical components. Metal temperatures of valve and turbine casings will be taken at specific locations representing component thermal behavior during normal operation and cooling process.

The measurements will be fed via a turbine controller to a dedicated data server where data validation, recording and preprocessing take place using special algorithms. The system will also comprise an additional computer serving as graphical user interface facilitating data display, analysis and monitoring.

3.3. Modules functionality

As described in section 3.1, the major system functions are online data counting and recording, online calculations and offline analysis and calculation.

Data counting will be responsible for automatic detection and counting the operational events important from the point of view of lifetime calculation like number of starts from various thermal conditions, number of overspeeds or number of load changes. Counting of operation times at different load, temperature and pressure ranges will also be performed.

It is assumed that operating data recording will be done for both raw and validated data, as well as post-processed data prepared in the form of input files for temperature and stress calculation procedures.
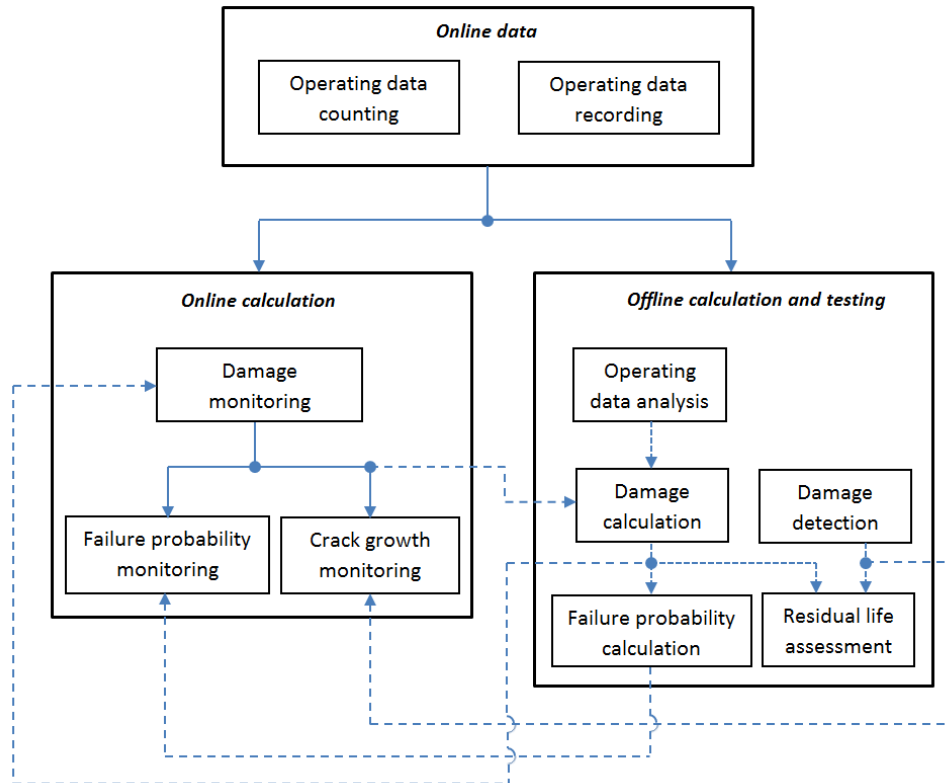
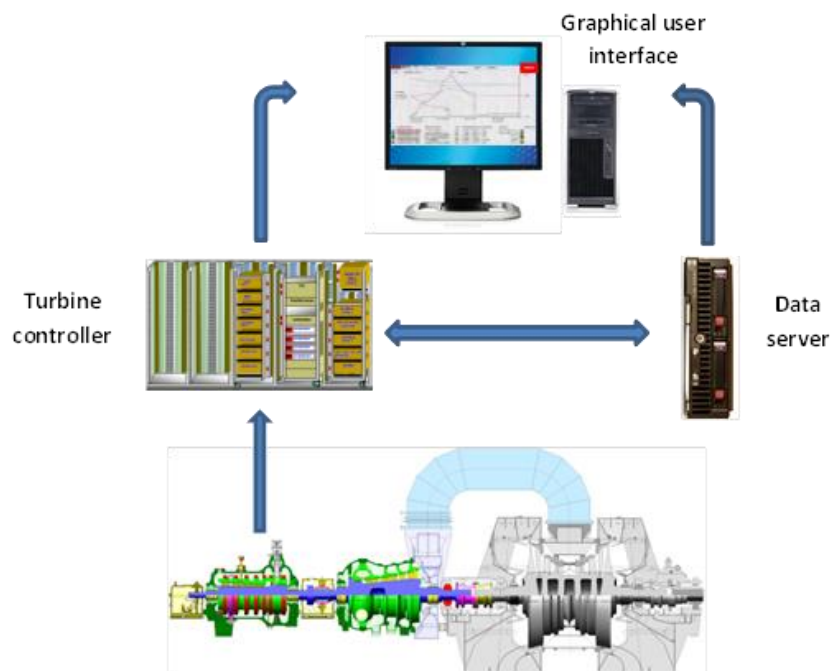Fig. 4. Modular structure of advanced lifetime monitoring system.

Fig. 5. Hardware configuration of advanced lifetime monitoring system

All online calculations will be carried out basing on the recorded data and using the appropriate mathematical models. Thermal stresses and temperature required for low-cycle fatigue damage monitoring will be computed using Duhamel's integral for stress [5, 7, 10]:

$$\sigma_{ij}(r,t) = \int_0^t G_{ij}(r, t-\tau) \frac{\partial T_s(\tau)}{\partial \tau} d\tau \qquad (3)$$

and for temperature [5, 7, 10]:

$$T(r,t) = \int_0^t X(r, t-\tau) \frac{\partial T_s(\tau)}{\partial \tau} d\tau \qquad (4)$$

In Eqs. (3) and (4), $\sigma_{ij}(r,t)$ is thermal stress component, $T(r,t)$ is metal temperature, $G_{ij}(r,t-\tau)$ is Green's function for stress, $X(r,t-\tau)$ is Green's function for temperature, $T_s(\tau)$ is steam temperature.

Creep damage calculation will be based on the creep damage curves for constant temperature [12] which are obtained from creep calculations conducted using a characteristic strain model of creep [6, 13, 14]. The model is described by the following relation between creep strain ε_c and time t at constant stress σ [6]:

$$\varepsilon_c = \frac{\varepsilon_D(\sigma_{R1}/\sigma_{D1})}{\frac{\sigma_{R1}}{\sigma}\left(\frac{t_1}{t}\right)^{1/m}-1} \qquad (5)$$

where: σ_{R1} – creep rupture strength at time t_1, σ_{R2} – creep rupture strength at time t_2, σ_{D1} – stress of creep strain ε_D at time t_1, m – exponent in the power-law relationship for creep rupture stress.

It is assumed that creep-fatigue damage will be computed online at most critical locations of all critical components and its value will be displayed together with the permissible limit, typically between 0.75 and 1.0.

For creep-fatigue damage determined with the help of Eqs. (1) and (2), failure probability can be evaluated describing the scatter of creep and fatigue properties by log-normal distribution. The operation time t required to reach the failure probability p is given by the following relationship [4]:

$$t = \frac{t_R(P=p_{min})}{\left[\frac{t_R(P=p_{min})}{t_R(P=p)}\cdot\frac{1}{D_{cr,C}}+\frac{D_F}{D_C}\cdot\frac{N(P=p_{min})}{N(P=p)}\cdot\frac{1}{D_{cr,F}}\right]} \qquad (6)$$

where: p_{min} – probability of minimum value of time to rupture or number of cycles to crack initiation, $D_{cr,C}$ – critical value of creep damage and $D_{cr,F}$ – critical value of fatigue damage. Probability of crack initiation is very low when damage is below the critical value, but significantly rises when this limit is exceeded.

Crack growth monitoring will consist in calculation of crack propagation due to creep, fatigue and their interaction and relating its size to the critical crack size. Crack growth analysis can be performed for pre-existing flaws or for cracks initiated due to creep-fatigue damage accumulation. For steam turbine components Ammirato formula [32] can be used for this purpose:

$$\frac{da}{dn} = C'\Delta K^m + b(C^*)^l t_h + C\Delta K^x t_h^z \qquad (7)$$

In Eq. (7) a is crack size, ΔK – stress intensity factor range, C^* - crack-tip driving force, C', m, b, l, C, x and z – material constants. Crack growth is computed for each detected cycle (described by ΔK) and each steady state period (described by t_h) between cycles.

Actual crack sizes predicted in the turbine components subject to monitoring will be displayed with reference to the critical sizes. The critical crack size will be determined taking into account crack geometry, material properties and failure mechanism. The most common failure mechanisms considered in steam turbine analyses are brittle fracture and high-cycle fatigue [4].

The online monitoring will be based on mathematical models suitable for application in online calculations, and thus having a certain level of accuracy and providing rather conservative estimations. More accurate predictions of creep-fatigue damage, crack size and failure probability will be achieved by offline calculations. It mainly applies to temperature, stress and strain computations that are performed offline by solving heat conduction and visco-elasto-plasticity problems by means of a finite element method [9]. The main advantage of the proposed methodology for advanced lifetime monitoring is the expected enhanced accuracy of lifetime predictions that can be achieved by considering the online calculation results in offline simulations supported by finite element analyses. The key development is a method of correcting the creep-fatigue damage computed online for all detected cycles by means of damage values obtained on the basis of finite element analyses of selected extreme cycles and off-design operating periods. This approach is a compromise between limited accuracy of offline calculations but considering the entire operation history, and high accuracy of finite element analyses but considering only a small fraction of operation history. Details of the proposed method are beyond the scope of this paper and will be described elsewhere.

Having the new more accurate damage values obtained by analysing the operating data and performing finite element calculations, it is also expected to improve the accuracy of failure probability predictions. The new values of damage and failure probability will be then transferred to the online monitoring modules and their outcomes updated in this way. Moreover, the results of physical damage detection, and in particular crack existence will be considered in crack growth monitoring. Finally, residual lifetime of a component will be assessed taking into account theoretical damage and the results of material testing (damage detection)

CONCLUSIONS

The new requirements for operating profiles of steam power plants result from increasing share of renewables in energy production. High load gradients, low minimum load and short ramp-up times are the main factors characterising operation of power plants in flexible markets. This adversely affects the steam turbines lifetime and results in increased low-cycle fatigue damage.

A concept of advanced lifetime monitoring system is proposed for better lifetime assessment and monitoring. Creep-fatigue damage is the focus of the system and its key elements are:
- online data counting and recording;
- online calculation of damage, failure probability and crack growth;
- offline operating data analysis, damage calculation, failure probability calculation and damage detection.

It is believed that the broad scope of monitoring will ensure deeper insight into the components condition and improve availability and operational safety of steam turbines.

REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, Division 1: Sub-section NH, Class 1 Components in Elevated Temperature Service, ASME, New York, 2001.
2. Badur J, Bryk M. Krajowe nadkrytyczne bloki weglowe: praca podstawowa czy elastyczna?. Nowa Energia. 2018; 62: 38-40.
3. Badur J, Bryk M. Accelerated start-up of the steam turbine by means of controlled cooling steam injection. Energy 2019; 173: 1242-1255. https://doi.org/10.1016/j.energy.2019.02.088
4. Banaszkiewicz M, Multilevel approach to lifetime assessment of steam turbines. Int J Fatigue. 2015; 73: 39-47. https://doi.org/10.1016/j.ijfatigue.2014.10.009
5. Banaszkiewicz M, On-line monitoring and control of thermal stresses in steam turbine rotors. Applied Thermal Engineering 2016; 94: 763-776. https://doi.org/10.1016/j.applthermaleng.2015.10.131
6. Banaszkiewicz M. Analysis of rotating components based on a characteristic strain model of creep. Journal of Engineering Materials and technology – Transactions of the ASME. 2016; 138: 031004-1-11. https://doi.org/10.1115/1.4032661
7. Banaszkiewicz M, On-line determination of transient thermal stresses in critical steam turbine components using a two-step algorithm. Journal of Thermal Stresses 2017; 40: 690-703. https://doi.org/10.1080/01495739.2016.1249988
8. Banaszkiewicz M. The low-cycle fatigue life assessment method for online monitoring of steam turbine rotors. International Journal of Fatigue. 2018; 113: 311-323. https://doi.org/10.1016/j.ijfatigue.2018.02.032
9. Banaszkiewicz M. Numerical modelling of cyclic creep-fatigue damage development for lifetime assessment of steam turbine components. In: Madejski P, ed. Thermal Power Plants – New Trends and Recent Developments. IntechOpen; 2018. https://doi.org/10.5772/intechopen.73186
10. Banaszkiewicz M, Badur J. Practical methods for online calculations of thermoelastic stresses in steam turbine components. In: Winczek J, ed. Selected Problems of Contemporary Thermomechanics. IntechOpen; 2018. https://doi.org/10.5772/intechopen.75876
11. Banaszkiewicz M. Numerical investigation of crack initiation in the impulse steam turbine rotors subjected to thermo-mechanical fatigue. Applied Thermal Engineering. 2018; 138: 761-773. https://doi.org/10.1016/j.applthermaleng.2018.04.099
12. Banaszkiewicz M. Creep life sssessment method for online monitoring of steam turbine rotors. Materials at High Temperatures. 2019; 36: 354-367. https://doi.org/10.1080/09603409.2019.1570701
13. Bolton J. A 'characteristic strain' model for creep. Matls at High Temp. 2008; 25: 101-108. https://doi.org/10.3184/096034008X357573
14. Bolton J. Analysis of structures based on a characteristic-strain model of creep. Int Journ Press Vess Piping. 2008; 85: 108-116. https://doi.org/10.1016/j.ijpvp.2007.06.013
15. Chmielniak T, Kosman G. Thermal loads of steam turbines. 1st ed. Warsaw: WNT; 1990. Polish.
16. Enerdata, Global Energy statistical yearbook 2020.
17. Helbig K, Banaszkiewicz M, Mohr W. Advanced lifetime assessment and stress control of steam turbines, PowerGen Europe, Milan, 2016.
18. Holdsworth SR. Creep-Fatigue Interaction in Power Plant Steels. Materials at High Temperatures. 2011; 28: 197-204. https://doi.org/10.3184/096034011X13123676561681
19. Holdsworth SR. Creep-Fatigue Failure Diagnosis. Materials 2015;8:7757-7769. https://doi.org/10.3390/ma8115418
20. IEA, World gross electricity production, by source, 2018, IEA, Paris. https://www.iea.org/data-and-statistics/charts/world-gross-electricity-production-by-source-2018
21. Kraszewski B. A study of thermal effort during half-hour start-up and shutdown of a 400 MW steam power plant spherical Y-pipe. Case Studies in Thermal Engineering. 2020; 21, 100728. https://doi.org/10.1016/j.csite.2020.100728
22. Leyzerovich AS. Steam Turbines for Modern Fossil Fuel Power Plants, 1st ed. Lilburn: The Fairmont Press Inc.; 2008.
23. Okrajni J, Wacławiak K. The impact of temperature oscillations and heat transfer conditions in thick-walled elbows and tubes on the local stress-strain behaviour during the fast start-up of power boilers. Engineering Transactions 2019; 67: 579-591. https://doi.org/10.24423/EngTrans.896.20191210
24. Radin YA, Kontorovich TS, Golov PV. Monitoring the Thermal Stress State in Steam Turbines. Power Technol Eng. 2020; 53: 719-723. http://doi.org/10.1007/s10749-020-01146-6
25. Raport KSE 2019 https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2019
26. RCC-MR. Design and Construction Rules for Mechanical Components of FBR Nuclear Islands. AFCEN, Paris, 1985.
27. Rusin A, Nowak G, Lipka M. Practical Algorithms for Online Thermal Stress Calculations and Heating Process Control. Journal of Thermal Stresses. 2014; 37, 1286-1301. https://doi.org/10.1080/01495739.2014.937219
28. Taler J, Dzierwa P, Jaremkiewicz M, Taler D, Kaczmarski K, Trojan M, Węglowski B, Sobota T. Thermal stress Monitoring in thick walled pressure components based on the solutions of the inverse heat conduction problems. Journal of Thermal Stresses. 2018; 41, 1501-1524. https://doi.org/10.1080/01495739.2018.1520621

29. Taler J, Dzierwa P, Jaremkiewicz M, Taler D, Kaczmarski K, Trojan M, Węglowski B, Sobota T. Monitoring of transient 3D temperature distribution and thermal stress in pressure elements based on the wall temperature measurement. Journal of Thermal Stresses. 2019; 42, 698-724.
https://doi.org/10.1080/01495739.2019.1587328

30. TRD 301. Annex I – Design: Calculation for Cyclic Loading due to Pulsating Internal Pressure or Combined Changes of Internal Pressure and Temperature, Technical Rules for Steam Boilers. 1978.

31. VGB PowerTech, Electricity Generation - Facts and Figures 2019/2020, August 2019 https://www.vgb.org/en/data_powergeneration.html?dfid=98054

32. Viswanathan R. Damage Mechanisms and Life Assessment of High-Temperature Components. 2nd ed. Metals Park: ASM International; 1989

33. Vogt J, Schaaf T, Helbig K. Optimizing lifetime consumption and increasing flexibility using enhanced lifetime assessment methods with automated stress calculation from long-term operation data, ASME Turbo Expo. 2013. GT2013-95068.

34. Wacławiak K, Okrajni J. Transient heat transfer as a leading factor in fatigue of thick-walled elements at power plants. Archives of Theremodynamics. 2019; 40: 43-55.
10.24425/ather.2019.129549

35. Webster GA, Ainsworth RA. High Temperature Component Life Assessment. 1st ed. London: Chapman & Hall; 1994.

dr hab. inż. **Mariusz BANASZKIEWICZ**
Graduate of Mechanical Engineering at Politechnika Gdańska (1994). Received PhD in mechanics in 2000 r. (IMP PAN Gdańsk). Has long experience in working in power generation industry (ABB, ALSTOM, GE). Developed thermal stress and lifetime monitoring systems installed on steam turbines worldwide. Prepared over 30 lifetime assessment studies. His scientific research focuses on thermal stress modelling, lifetime assessment methods and material effort hypotheses.