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Computer models of steam pipeline components in the evaluation of their local strength

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Analysis and modelling

ABSTRACT

Purpose: The paper discusses the issue of modelling the heating and cooling processes of T-pipes in a power plant pipeline in the start-up conditions of a boiler. The main purpose of this work is the description of the mechanical behaviour of power plant components working under mechanical and thermal loading and validation of the computer modelling methods.
Design/methodology/approach: The FEM modelling has been used to describe the local stress-strain behaviour of the chosen component.
Findings: The reasons for the presence of high and variable in time temperature gradients in the components of the main steam pipeline include, among other things, variable values of the coefficient of heat transfer between the pipeline material and the medium flowing inside it, which, at this stage of boiler operation, may change its state. Unsteady operation of a pipeline, especially in case of subsequent boiler start-ups, may induce thermal stresses which exceed the values of allowable stress in components of complex shapes.
Research limitations/implications: The possibility of applying the durability criteria currently assumed in standards still requires justification and confirmation in laboratory and industrial conditions to be closer to the real components behaviour. In such situation the presented analysis is the part of the complex investigation method which main purpose is increasing accuracy of the TMF process description and thermo-mechanical life assessment.
Practical implications: The calculations carried out may constitute a basis for developing a material test parameters which would bring closer the fatigue conditions appearing locally in the analysed components. The method of stress-strain behaviour analysis used in the paper could be useful in the practical cases when the real components mechanical behaviour would be analysed.
Originality/value: The main value of this paper is the own method of the mechanical behaviour analysis of the power plant component. This method includes the temperature fields analysis taking into account the boundary conditions based on the operation parameter data and the thermoplastic material model. The material stress-strain behaviour has been treated as the local phenomenon, that could be modelled by FEM.
Keywords: Applied mechanics; Computational material science and mechanics; Fatigue; Metallic alloy

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1. Introduction

The issue of durability of power engineering devices is more and more often the object of interest for not only their users but also scientific centres dealing with the issues of creep, fatigue and cracking of materials subjected to mechanical and thermal interactions [1-8]. New material characteristics are being developed which, to a larger and larger extent, take into account the specificity of using facilities that operate in the power engineering industry. To determine them, new material testing methods are applied, such as tests of thermo-mechanical fatigue or crack growth under creep conditions. The awareness of the necessity to perform systematic accurate control of the operational parameters of power units and keep records of their operation is becoming more and more common.

Power units are equipped with control and measuring equipment to ensure the possibility of recording temperature and pressure in a number of selected measuring points. A problem which still needs solving is to process the data obtained from measurements into information concerning the effects of the recorded temperature and pressure, variable in time. These interactions determine the state of stress in equipment components which, along with the temperature variable in time, may be the cause of changes of the properties of whole facilities from a global perspective, as well as of the properties of the materials they are made of. The consequences of the interactions depend on their speed, frequency and magnitude. When discussing the durability of components of devices, the results of thermal and mechanical load should be considered locally. It is not possible, of course, to make measurements in a random selected point of a device. The number of measurement points is limited. Very often, measuring sensors are located in places which are not critical as far as the intensity of creep, fatigue and cracking processes is concerned. In such case, computer modelling methods are becoming significantly important in the analysis of the measurement results. For example, by applying the finite element method, it is possible to determine the variable in time thermal fields in selected components of devices, where the boundary conditions have been estimated. On their basis, variable fields of stress and strain are then determined. A problem arises, however, to evaluate credibility and technical usability of the computer models applied, which should be subject to validation. In the case under consideration, it is possible to use the results of local measurements carried out during operation.

The paper presents the methodology of strength evaluation of steam pipelines [9,10], which takes into account a combination of methods to measure their operational parameters with computer modelling methods which allow the determination of local parameters, the latter being decisive for the strength and durability.

2. The facility

Steam pipeline T-pipes in one of the domestic power plants were the components that served as examples of the application of the methodology of current strength evaluation of power engineering devices (Fig. 1).

In an operation cycle, main steam pipelines are subject to cyclic thermo-mechanical load connected with short intervals of the start-up and shut-down time and long intervals of steady operation. During heating and cooling, especially in the conditions of start-up, a variable in time thermal field occurs in elements of complex shapes, such as T-pipes, knee joints, pipe crosses or gate valves, which results in thermal stresses that locally reach values close to, or sometimes exceeding, the yield point. In some of those elements, temperature measurements are carried out in selected points located at various depths in relation to the outer surface – "shallow" and "deep". These points are located close to the spherical part of the outer surface: shallow, at a depth of 5 mm from the surface and deep, 15 mm from the inner surface. An example of the results of measurements of the steam temperature and the temperature in two points of a T-pipe of the main steam pipeline T-pipe (Fig. 1) is presented in Figure 2.

Fig. 1. Model of the main steam pipeline T-pipe

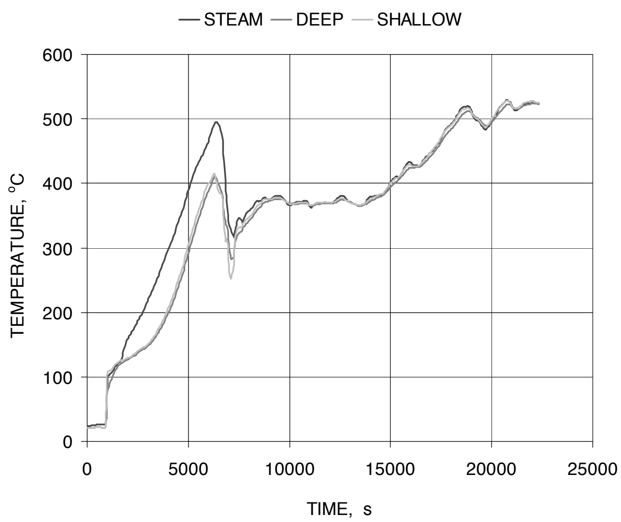


Fig. 2. Measurement results of steam temperature close to the boiler and of metal temperature in selected points of the T-pipe

The characteristics presented in Figure 2 demonstrate that during the start-up, there are time intervals of heating and cooling, characterised with a varied speed of temperature change. In order to specify in what way the varying steam temperature influences the temperature distributions throughout the T-pipe, its model was developed for calculations using FEM.

3. T-pipe model and its validation

The geometric features of the T-pipe model were selected based on the available technical documentation, in which coordinates of the temperature measuring points were provided. One of the most significant problems connected with modelling the behaviour of components of the examined pipeline is the selection of boundary conditions, including the heat transfer coefficients. In the literature available, these coefficients are provided in a wide range of variability and for the case under consideration, they may assume the values presented in Table 1 [11].

Table 1.
Values of heat transfer coefficients

No.	Liquid	State	α, W/m$^{2}\cdot{}^{o}$C
1	Water	heating	290 - 16000
2	Water	boiling	1600 - 50000
3	Steam	superheating	29 - 120
4	Steam	film condensation	5800 - 16000
5	Steam	bubble condensation	29000 - 116000

Therefore, for a medium flowing through a pipeline in the model approach, the heat transfer coefficients can be selected in a wide range of their variability. It seems that an appropriate evaluation criterion of correctness of such a selection may consist of conformity of the nature of distribution and the value of the temperature measured in the selected points of the T-pipe with the values calculated, i.e. the quality of mapping temperature changes in time, in real conditions, by the model. Figure 3 presents a diagram of changes of the heat transfer coefficient, depending on time and the ranges of their variability as given in literature [11]. The value of the heat transfer coefficient is made conditional on the stage of the start-up process, assuming that the medium under consideration is steam in various states (Table 1) or, in a specific case, boiling water.

Assuming an appropriate type of the T-pipe material, the values of constants specifying the course of the heat flow process were adopted. The material under consideration was steel P/T91, for which the following values were assumed:

- thermal conductivity coefficient λ=29.2 J/s$\cdot$m$\cdot{}^{o}$C,
- density ρ=7700kg/m^3,
- specific heat c=460 J/kg$\cdot{}^{o}$C.

At the stage of model validation, heat transfer coefficients were selected and their values were then changed, while taking into consideration the temperature and pressure determining the state of the medium flowing through the pipeline.

A various degree of compliance of the calculations results with temperature measurements was obtained. In Figure 4, the results of temperature measurements and courses of its changes are presented, as determined using FEM for the points where, in industrial conditions, thermocouples are situated.

Figure 4 presents one of many cases which were subjected to an analysis. It is possible to note compliance in terms of the nature of the calculated the measured courses of the temperature change in time (Fig. 3). However, there are some discrepancies between the values determined based on the calculations and measurements. These discrepancies result from adopting hypothetical values of the heat transfer coefficient. More precise determination of temperature distributions variable in time would require carrying out steam temperature measurements along the pipeline axis, including in particular the surroundings of the T-pipe, as well as measurements of the medium flow speed. At the present stage, the model was adjusted to the data available to the user of the device under consideration and to the authors of the study.

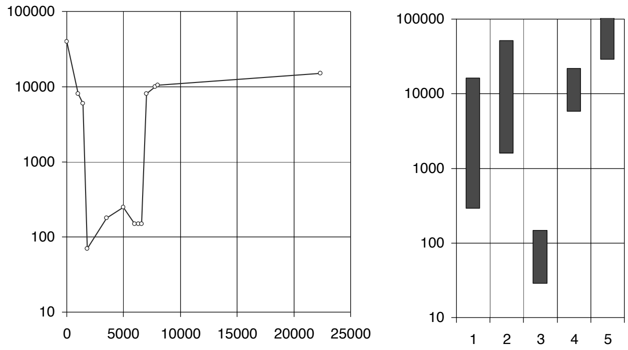


Fig. 3. Diagram of changes in time of the heat transfer coefficient values (a) and the ranges of their value for various states of medium (b)

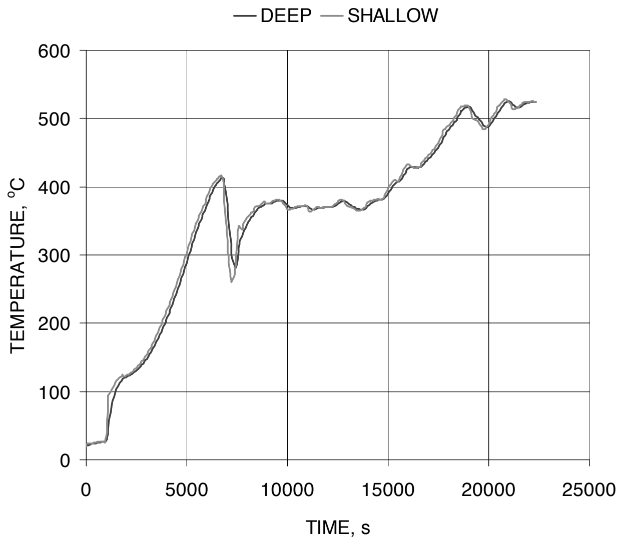


Fig. 4. Results of checking the correctness of the T-pipe model functioning: a diagram illustrating changes in time temperature, determined, using a computer model, in the same places (deep and shallow) as sensors

4. Evaluation of the T-pipe strength in the start-up conditions

The calculations of the variable temperature distributions were next used for assessing the state of strain and stress in the T-pipe. For that purpose, a thermo-elastic-plastic model of material was adopted (Fig. 5). A variable in time temperature field (Fig. 6) and internal pressure, also variable in time, were the load for the T-pipe (Fig. 7). Two T-pipe with different wall thickness were taken into consideration. The stress and strain fields were determined in the different instants of time.

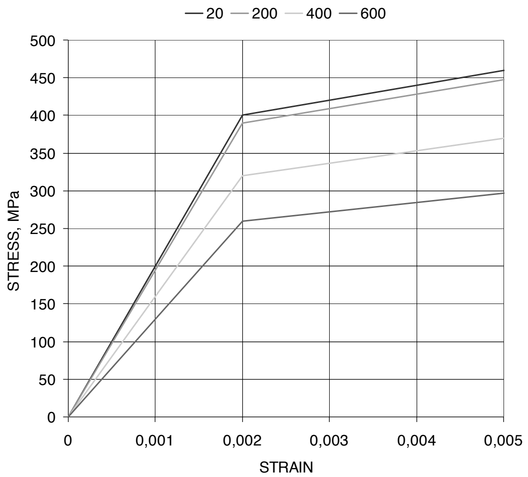


Fig. 5. Stress-strain characteristics of thermo-elastic-plastic model of material

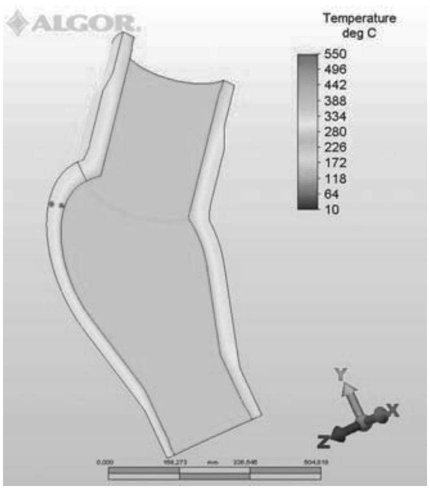


Fig. 6. Temperature distributions in the thin T-pipe with the lower value of thickness in selected instant of time: t=7200 s

Both of the T-pipe models have been prepared on the background of the geometrical features and material's properties of the components that work in Polish power plants. The temperature fields in the T-pipe with the higher value of thickness shows higher values of temperature gradients. The courses of changes of the stress state components in selected points of the T-pipe show that their extreme values occur in moments when the differences in temperature between the inner and outer surfaces of the T-pipe reach their extreme values. The temperature and stress distributions computed for T-pipes with different wall thicknesses (Figs. 6, 8 and 9-12) show that the thickness has the strong influence on the thermal stresses. The values of stress in some instants exceed the values of the creep strength (Figs. 13, 14).

Models used in the work give possibility to determine the local stress-strain behaviour of the material. This behaviour can be characterized by the diagrams that show relationships between the strain and stress components as for instance in the Fig. 15.

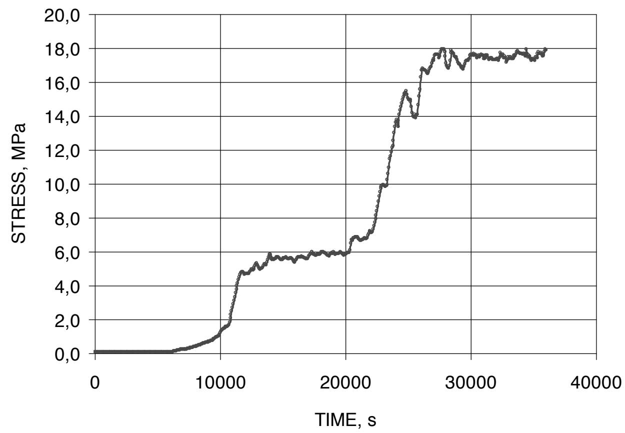
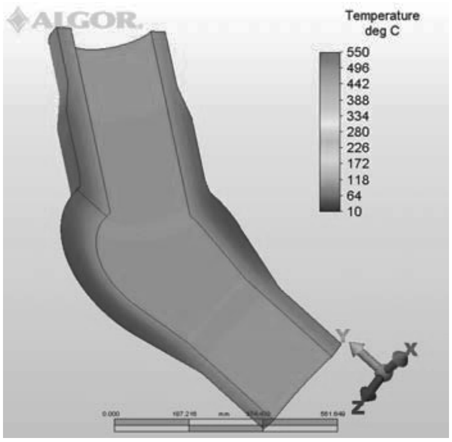


Fig. 7. Graph of pressure changes as a function of time during the boiler start-up

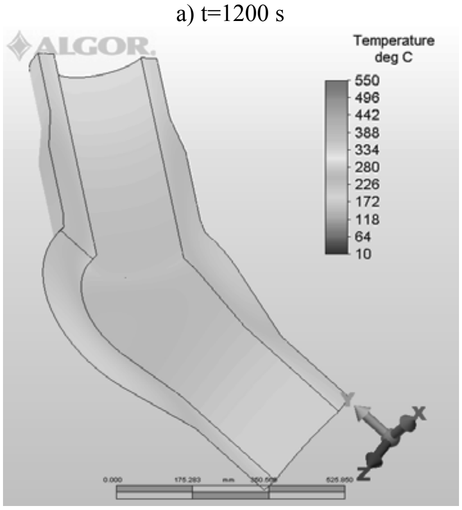
Fig. 8. . Distributions of equivalent stresses in the T-pipe with the lower value of thickness in a moment of time: t=7200 s from the start-up beginning

The hysteresis loop shown in the Fig. 15 and mechanical strain-temperature characteristics (Fig. 16) exhibit the typical character of the OP (out of phase) thermo-mechanical test [6]. Such information is crucial in such situation, when the material test parameters are determined.

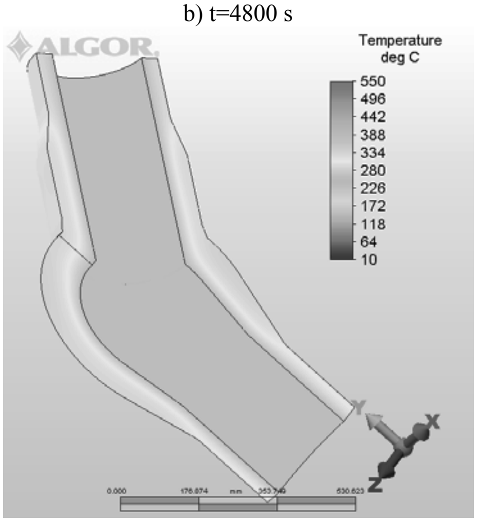
The proper material characterisation needs the test which parameters are defined individually for the components and taking into accounts their local temperature, stress and strain cycles, which characteristics are important in the methodology of fatigue life assessment.



a) t=1200 s

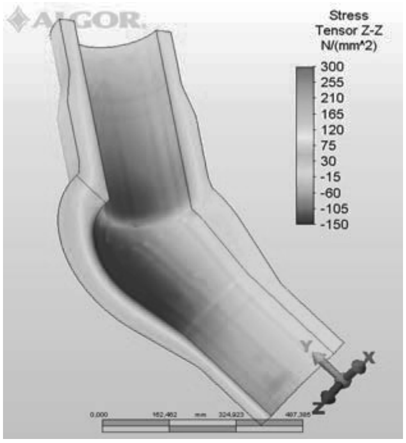


b) t=4800 s

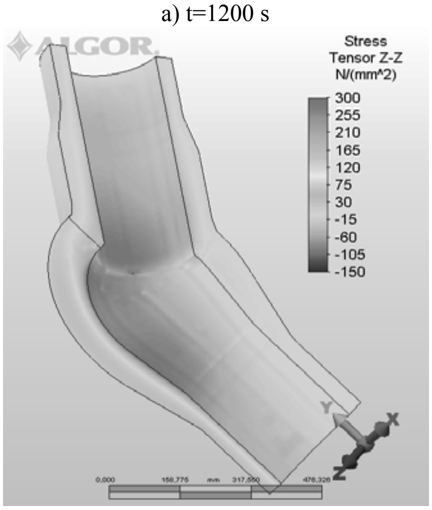


c) b=7200 s

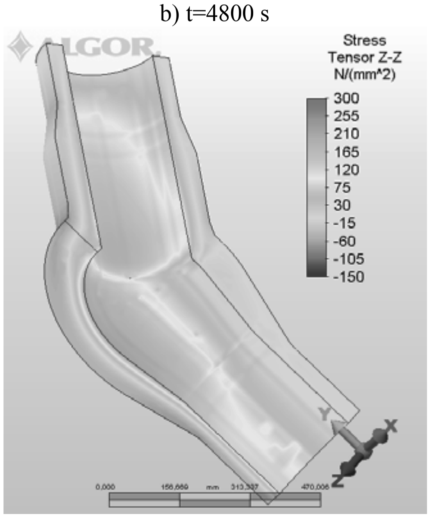
Fig. 9. Temperature distributions in the thick T-pipe in selected instant of time



a) t=1200 s

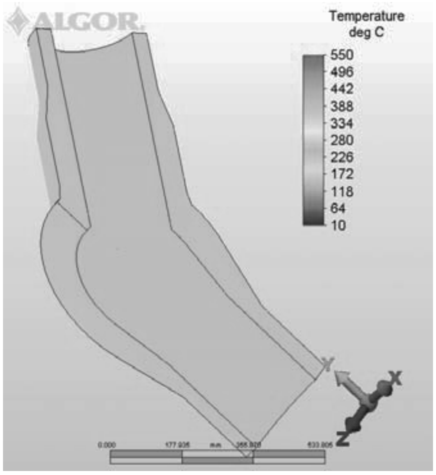


b) t=4800 s

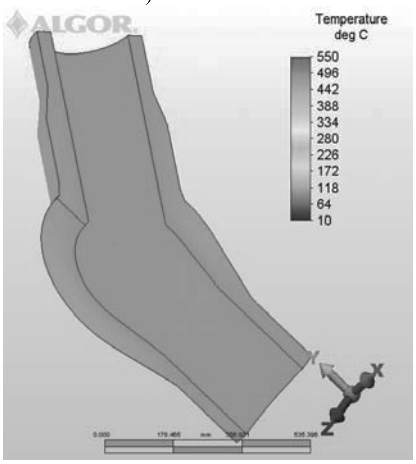


c) b=7200 s

Fig. 10. Distributions of stresses σ_{zz} in the T-pipe in selected instant of time

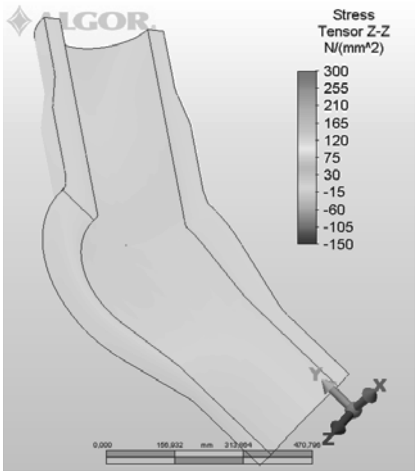


a) t=9600 s

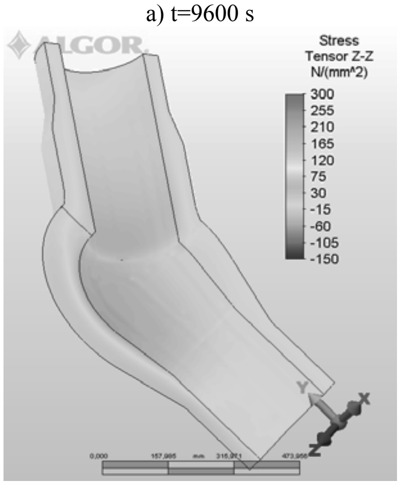


b) t=18000

Fig. 11. Temperature distributions in the thick T-pipe in selected instant of time



a) t=9600 s



b) t=18000

Fig. 12. Distributions of stresses σ_{zz} in the T-pipe in selected instant of time

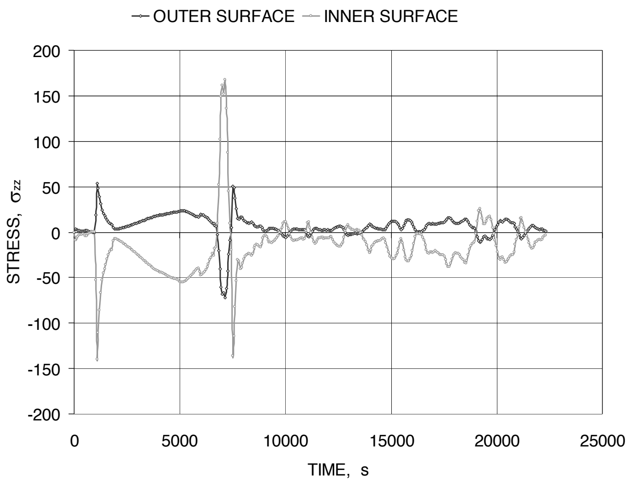


Fig. 13. Diagrams of changes over time of stresses σ_{zz} in the T-pipe in selected points of its inner and outer surfaces - the T-pipe with thin wall (Figs. 1, 6, 8)

The obtained from calculations values of stress and strain, variable over time, may be next used to evaluate durability of the component discussed. The simplest first approximation in such an evaluation may be the results obtained with use of the European Standards as EN 129052-4 [12-14] which contain an algorithm for forecasting durability based on characteristics of circumferential stresses variable over time. The quoted standard does not apply, however, to the problem of a simultaneous effect of variable temperature and stresses on the course of the deformation process and durability, since it treats fatigue as a phenomenon induced by changes of stress in steady ranges of temperature. In the context of the results presented, the material fatigue in the case under consideration should rather be analysed as a local process of thermo-mechanical fatigue [15-17], for which only in some cases approximation is possible by a comparison with isothermal fatigue.

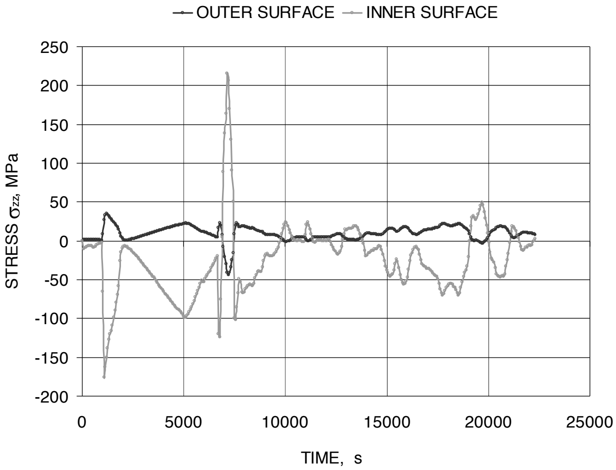


Fig. 14. Diagrams of changes over time of stresses σ_{zz} in the T-pipe in selected points of its inner and outer surfaces - the T-pipe with thick wall (Figs. 9, 10)

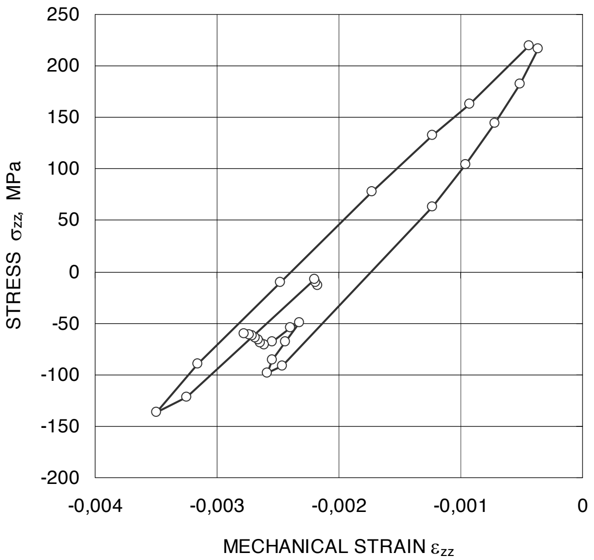


Fig. 15. Stress-strain characteristic in the selected point of T-pipe in the period of time: 6540 s - 8220 s

In such case, the results obtained in the study would form a basis for determining characteristics of this fatigue process. These are, among others, hysteresis loops in the mechanical deformation - stress system [15,16]. The phenomenon of thermo-mechanical fatigue of materials meant for power engineering devices has not been described in literature in a manner sufficient for technical applications. In this sense, the test results presented in the paper

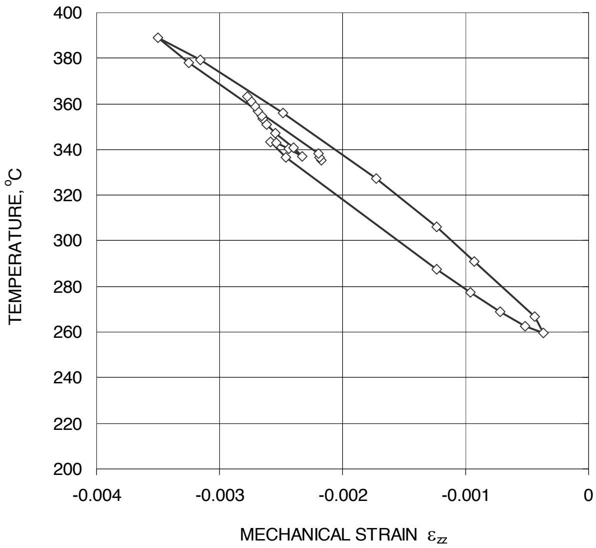


Fig. 16. Mechanical strain - temperature characteristic in the selected point of T-pipe in the period of time: 6540 s - 8220 s

could be another contribution to identification of the conditions of this process in power engineering devices. This study is one of a number of studies carried out at the Silesian University of Technology [15-17] concerning thermo-mechanical fatigue of materials used for devices which operate at an elevated temperature. In this case, the authors focused on exemplifying complex fatigue phenomena, including in particular the examination of the behaviour of a component of the selected device. The paper shows one of problems connected with assessment of state and the life prediction of components under mechanical and thermal loading which still is constantly one of the main in conventional power industry [17-20].

5. Conclusions

- The reasons for the presence of high and variable in time temperature gradients in the components of the main steam pipeline include, among other things, variable values of the coefficient of heat transfer between the pipeline material and the medium flowing inside it, which, at this stage of boiler operation, may change its state.
- In this case, particular attention should be paid to the initial start-up phase, when the thermal field in the pipeline changes at a speed exceeding 50 $^{\circ}$C/min.
- Unsteady operation of a pipeline, especially in case of subsequent boiler start-ups, may induce thermal stresses which exceed the values of allowable stress in components of complex shapes.
- The model developed may be used for an analysis of the influence of the boiler start-up and shut-down conditions on the state of local effort of steam pipelines and durability of their individual elements.

Acknowledgements

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References

[1] BS 7910, Guide on methods for assessing the acceptability of flows in structures (replacing PD 6493 and PD 6539), British Standards Institution, London, 1994.
[2] Nuclear Electric Ltd: Assessment Procedure for the High Temperature Response of Structure. Proc, R5/2, UK, 1997.
[3] S. Webster, A. Bannister, Structural Integrity Assessment Procedure for Europe - of the SINTAP programme overview, Engineering Fracture Mechanics 67/6 (2000) 481-514.
[4] Project European Thematic Network FITNET FFS-GIRT-CT-2001-05071.
[5] J. Bressers. L. Remy (eds.), Fatigue under Thermal and Mechanical loading, Kluwer Academic Publishers, Netherlands, 1996.
[6] P. Hähner et al, Research and development into a European code-of-practice for strain-controlled thermo-mechanical fatigue testing, International Journal of Fatigue 30/2 (2008) 372-381.
[7] H. Sehitoglu, Thermal and Thermo-mechanical Fatigue of Structural Alloys, Fatigue and Fracture 19 (1996) 527-556.
[8] S.S. Manson, Thermal Stress and Low Cycle Fatigue, McGraw-Hill, New York, 1966.
[9] J. Okrajni, K. Mutwil, M. Cieśla, Steam pipelines’ effort and durability, Journal of Achievements in Materials and Manufacturing Engineering 22/2 (2007) 63-66.
[10] D. Renowicz, A. Hernas, M. Cieśla, K. Mutwil, Degradation of the cast steel parts working in power plant pipelines, Proceedings of the 15th Scientific International Conference „Achievements in Mechanical and Materials Engineering” AMME’2006, Gliwice-Wisła, 2006, 219-222.
[11] Z. Orłoś, Thermal stresses, PWN, Warsaw, 1991 (in Polish).
[12] Standards EN 12952-3:2001 (E), EN 12952-4:2000.
[13] I.J. Perrin, J.D. Fishburn, A Perspective on the Design of High Temperature Boiler Components, Proceedings of the Conference Creep and Fracture in High Temperature Components, London 2005, DEStech Publications, Inc., Lancaster, Pennsylvania 17601 USA.
[14] J. Okrajni, The durability of power plant pressure vessels from the point of view of obligatory standards, Power Engineering 18 (2008) 93-100 (in Polish).
[15] J. Okrajni, Thermo-mechanical conditions of power plant components, Journal of Achievements in Materials and Manufacturing Engineering 33/1 (2009) 53-61.
[16] J. Okrajni, G. Junak, A. Marek, Modelling of the deformation process under thermo-mechanical fatigue conditions, International Journal of Fatigue 30/2 (2008) 324-329.
[17] J. Okrajni, A. Marek, G. Junak, Description of the deformation process under thermo-mechanical fatigue, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 15-24.
[18] D. Renowicz, M. Cieśla, Crack initiation in steels parts working in boilers and steam pipelines, Journal of Achievements in Materials and Manufacturing Engineering 21/2 (2007) 49-52.
[19] J. Dobrzański, The classification method and the technical condition evaluation of the critical elements’ material of power boilers in creep service made from the 12Cr-1Mo-V, Journal of Materials Processing Technology 164/165 (2005) 785-794.
[20] A. Neimitz, I. Dzioba, M. Graba, J. Okrajni, The assessment of the strength and safety of the operation high temperature components containing crack, Kielce University of Technology Publishing House, Kielce, 2008.