Archives of Materials Science and Engineering

Volume 62
Issue 1
July 2013
Pages 28-35

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Boundary conditions in models of power plant components under thermal loading

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Received 15.04.2013; published in revised form 01.07.2013

ABSTRACT

Purpose: The main purpose of the work is the description of conditions of fatigue process of power plant components working under mechanical and thermal loading. The work focuses on the chosen component characteristics. The issue of influence of the heat transfer conditions on the component surface on stresses changes in time has been discussed.

Design/methodology/approach: The FEM modelling method has been used to describe the behaviour of the chosen component. The models have been validated on the basis of temperature measurements during operation period.

Findings: It has been shown that the determination of the effects induced by unsteady conditions of start-up and shut-down of installations requires application of unconventional methods of research and analysis of their results. In such a case, a methodology can be applied consisting in combining the methods of computer modelling of temperature fields with temperature measurements in selected points of the component.

Research limitations/implications: The presented analysis is the part of the complex investigation method which main purpose is increasing the accuracy of the thermo-mechanical fatigue process description. In such situation the investigations curried out in the work give the model approach and data for the comparison the real behaviour with the predictions. However the work is focused only on the chosen component and chosen characteristics of loading.

Practical implications: The method of the chosen component behaviour analysis used in the paper could be useful in the practical cases when the real components mechanical behaviour would be analysed and their fatigue life would be assessed.

Originality/value: The main value of this paper is the own method of the mechanical behaviour analysis of the power plant components. This method includes FEM modelling and assumption that the heat transfer coefficient should be treated as dependent on time. The material stress-strain behaviour has been treated as the local phenomenon that could be modelled.

Keywords: Applied mechanics; Power plants; Heat transfer; Fatigue

Reference to this paper should be given in the following way:

J. Okrajni, M. Twardawa, Boundary conditions in models of power plant components under thermal loading, Archives of Materials Science and Engineering 62/1 (2013) 28-35.

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The currently applicable strength calculation procedures regarding equipment components subjected to elevated temperatures and pressure include methods for estimating thermal stresses based on the difference in temperature between the inner and outer surface of a pressure vessel related to the rate of heating or cooling of the component in question [1]. The influence of the shape and proportions of the particular dimensions of a component is captured by the stress concentration factors selected on the basis of diagrams or mathematical relationships contained in standards. The influence of the surface condition on the calculation of the stress values which constitute the basis for strength assessment of pressure vessels is presented in the same way.

The stress values calculated on the basis of standards apply to steady states of operation or to idealized characteristics of the start-up and shut-down of the plants for which constant heating and cooling rates are assumed. Also, the acceptable rates are determined of the temperature change over time which ensures the formation of stresses within values acceptable for them [1]. To control the operating parameters, thermocouples are installed in selected points of pipelines, the indications of which are considered by the operators who control the start-up and shut-down a power generation unit.

In modern power units, these processes are carried out by means of automatic control systems. However, both in the first and in the second case, during transient states of boiler operation, there are deviations in temperature from the instantaneous nominal values assumed for it, which are caused, among other things, by the inertia of the control system and of the controlled thermo-mechanical system itself. Hence, the rate of temperature changes in time during transient states differs from the assumed average values, which results in time-varying effects of thermal stress whose instantaneous values may significantly differ from those calculated for the assumed characteristics of start-up and shut-down of the power unit [2-4]. The observed differences between the nominal temperature of the individual points of the installation and the temperature measured in the operating conditions are the measure of stability of the unit.

Determination of the effects caused by unstable operation of a device requires the use of unconventional methods of research and analysis of the research results. A methodology can be applied in this case, which combines computer modelling with temperature measurements performed at selected points of a pipeline [3].

2. Characteristics of the object

The problem of determining the time-varying stresses caused by the instability of temperature and pressure changes in the conditions of start-up of a power is presented using the example of a Y-branch of a live steam pipeline operating in one of the domestic power plants.

The Y-branch in question (Fig. 1) is equipped with two thermocouples located at different depths in relation to the outer surface. One of them is located at a depth of 65 mm with respect to the outer surface-“shallow”. The other thermocouple is located at a distance of 5 mm from the inner surface-“deep” in relation to the outer surface. Thermocouples are placed in the holes drilled perpendicularly to the outside spherical surface.

In these points, temperature is measured and recorded during the operation of the power unit. Measurements of the temperature and pressure and of the steam flowing through the pipeline are made as well.

Figure 2 shows courses of the time-varying temperature and steam pressure in the pipeline in the start-up conditions. Figure 3 illustrates the changes in temperature, at points located “shallow” and “deep”, that correspond to the start-up.

The courses of the time-varying temperature determined during the unit’s operation roughly characterise the changes in thermal stresses in the plant component under consideration. More accurate estimates require the determination of time-varying temperature fields within the Y- junction.

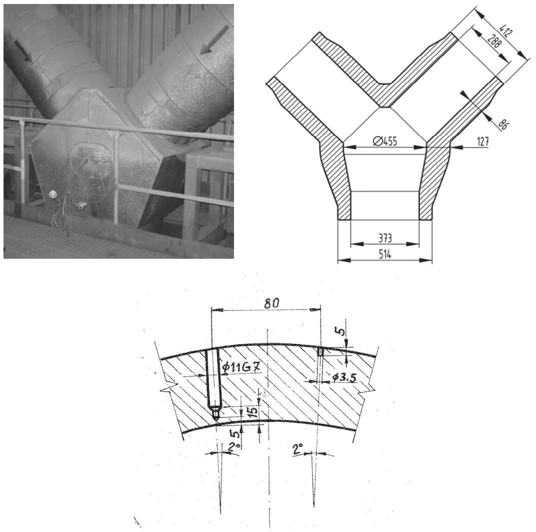

Fig. 1. Geometric features of Y-junction built of a live steam pipeline

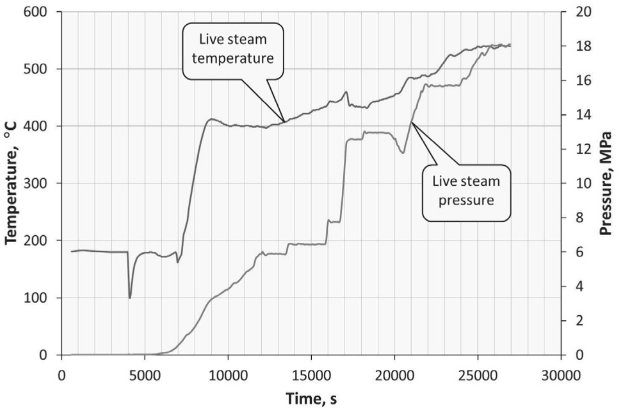

Fig. 2. Courses of the time-varying temperature and steam pressure in the pipeline in the start-up conditions

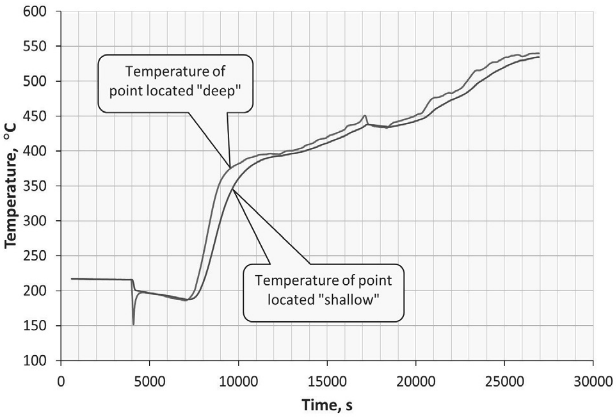

Fig. 3. Changes in temperature, at points located “shallow” and “deep” in the start-up conditions

3. Model of the component

In order to determine the time-varying temperature distributions in the plant component under consideration and the corresponding stress distributions, a model was developed which takes into account the geometric characteristics of the component in accordance with the design documentation of the pipeline (Fig. 4). The Y-junction was divided into 39,000 solid finite elements. Due to its symmetry, one fourth of the component was considered in the calculations while making mental intersections in the symmetry planes. In the calculations of stress distributions, a limitation of linear dislocations in directions vertical to those planes was assumed.

At that stage of the calculations, the external forces were omitted in the planes of 'intersections', Π1, Π2 and Π2, through which the Y-junction was isolated from the pipeline. On plane Π1, a limit was assumed for the dislocation in the direction of the pipeline axis - perpendicular to plane Π1. In planes Π1, Π2 and Π_2`, the impact was not taken into account of the time-varying temperature distribution, pressure and guy wires on the internal forces occurring in the installation a result of the limited freedom of its movements which, in global terms, are conditioned by the constraints.

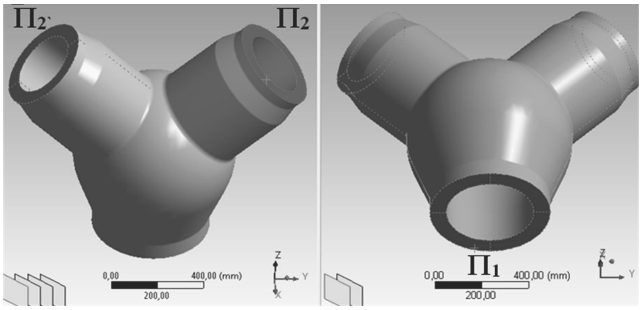

Fig. 4. Geometric characteristics of the component in accordance with the design documentation of the pipeline

This issue is the object of a separate analysis in which the behaviour of the pipeline under the influence of the above-mentioned factors is considered, while taking into account the characteristics of fixings. On the inner surface of the Y-branch, heat exchange was assumed between the liquid flowing down the pipeline and the material of the component in question. The fact was taken into account that the heat exchange conditions alter as a function of time at the start-up stage. This phenomenon is associated, among other things, with a change in the state of aggregation of the medium for which the heat transfer coefficient may adopt values within a wide range of variation interval, depending on time, pressure, the nature of flow and geometry of the investigated component [3].

For instance, at the initial stage of start-up, a rapid change of the live steam temperature to ca.100˚C, which testifies to intensive heat exchange on its inner surface.

An effect of this type can be explained by a change in the state of aggregation of the steam which contacts the cold metal surface. A comparison of the characteristics of the dependence between the temperature of a medium inside the pipeline and its pressure, determined experimentally from the Clausius-Clapeyron equation, may serve as evidence for such a course of the phenomenon.

In Figure 5 the area where the liquid behaves in an unstable way is clearly visible. The heat transfer coefficient on the inner surface was therefore assumed to be a value dependant on the state of the medium, as well as on its pressure, temperature and flow rate. A calculation algorithm was developed to enable the determination of the value of this coefficient, depending on the operating parameters of the pipeline. It was assumed that at the start-up stage, there was no heat exchange on the outer surface with the environment [5].

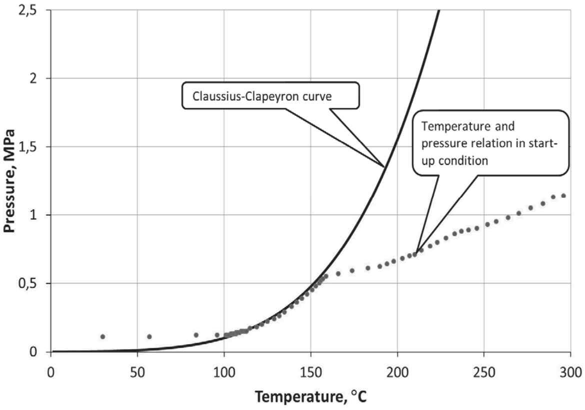

Fig. 5. Clausius - Clapeyron relation

4. Verification of the model

The FEM method was used for the calculations. With the given data which characterised the time-varying temperature of steam, its pressure and flow rate, the variable temperature field within the Y-branch was determined. Thermal conductivity coefficient λ, specific heat α and density were adopted for the Y-branch material, i.e. steel 13HMF (14 MoV 6-3), as values depending on the temperature (Table 1).

Table 1.
The properties of steel 13HMF (14 MoV 6-3)

Property	Temperature, °C 20	100	300	400	500	550
E 10^{-5}, MPa	2.13	2.10	1.93	1.87	1.77	1.70
Re^t, MPa	360	335	265	245	226	---
λ, W/(m^{o}C)	47	47	44	42	38	37
$\alpha \cdot 10^6$, °C^{-1} (20 - t)	---	11.8	13.4	13.8	14.1	14.3
Cp, kJ/kg^{o}C	0.46	0.50	0.54	0.63	0.71	0.76

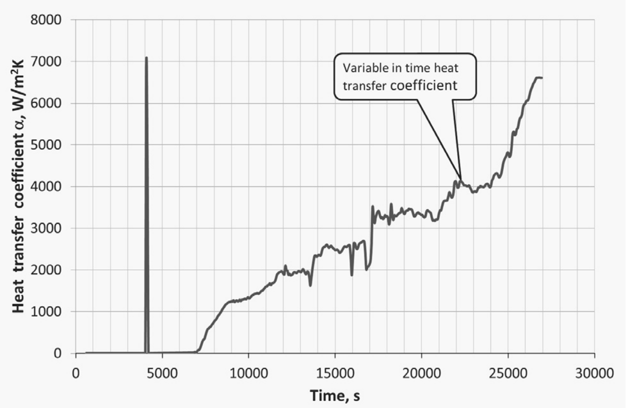

Fig. 6. The heat transfer coefficient for data determined in the operating conditions as a function of time

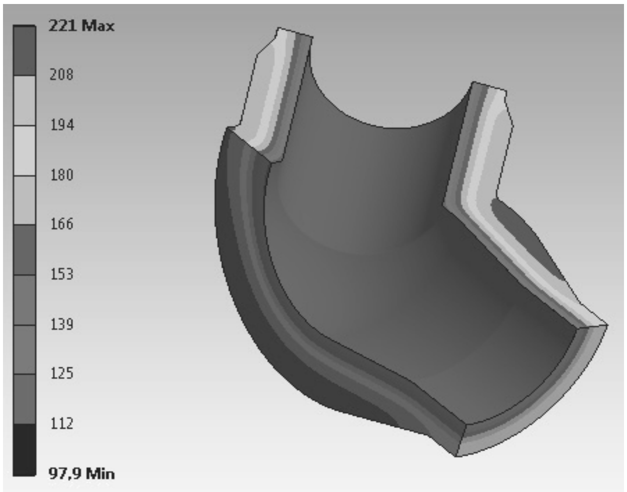

Fig. 7. Time-varying temperature distributions on the surface of the Y-branch and across its sections in 4080 s of start-up condition

The heat transfer coefficient calculated based on the previously developed algorithm for data determined in the operating conditions as a function of time is presented in Figure 6 as a value depending on time. Figure 7 shows the example of time-varying temperature distribution on the surface of the Y-branch and across its sections, as determined based on the calculations carried out using the finite element method. In Figure 8, the courses of changes in temperature in points where thermocouples were installed are compared. They were determined both experimentally and based on calculations. Consistency of the characteristics obtained in this way testifies to the correctness of the developed model approach.

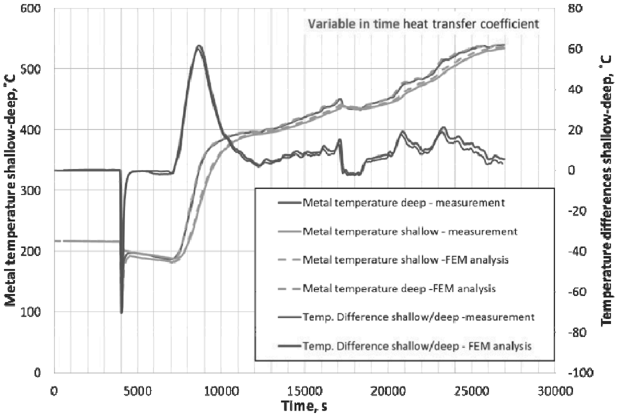

Fig. 8. Changes of the temperature at the points where the thermocouples are positioned; determined experimentally and based on FEM calculations

5. Stress field in Y-junction of a pipeline

Characteristics of the time-varying temperature field and of the pressure on the inner surface of the Y-junction served as data for calculating the time-varying stress fields. It is necessary to take into consideration that the material changes its properties during operation period [6-9]. A thermo-elasto-plastic model of material was adopted for the investigated case. Kinematic linear hardening was assumed. The elasticity modulus, yield point and hardening coefficient were assumed to be temperature-dependent values. Dependence of the linear heat expansion coefficient on temperature was also taken into account in the calculations (Table 1). The cyclic stress-strain curves that depend on temperature have been assumed as the material characteristics (Fig. 9). These characteristics have been worked out for the material in the state after long operation period.

The consecutive Figures 10-13 illustrate distributions of the extreme stress state components, and reduced stresses during analysed period of time.

In Figures 10-13, areas particularly exposed to the time-varying stresses with high instantaneous values can be observed.

As an example at point P1 located inside such area (Fig. 14), the courses of time-varying stresses were determined, whose diagrams are shown in Figure 15.

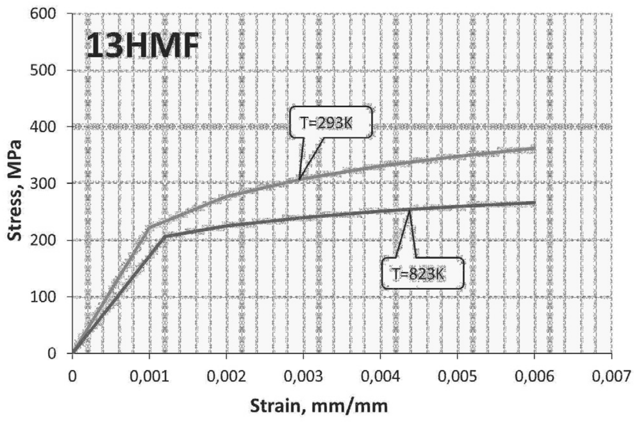

Fig. 9. Cyclic stress-strain curves of the Y-junction material

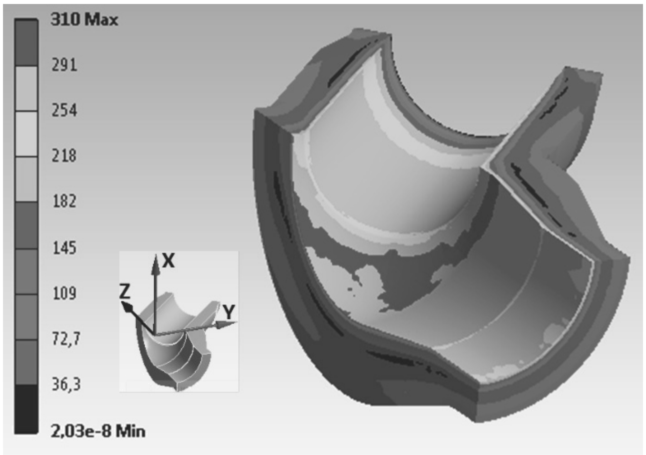

Fig. 10. Distributions of maximum (during analysed period of time) reduced stresses in the volume of Y-junction during the start-up

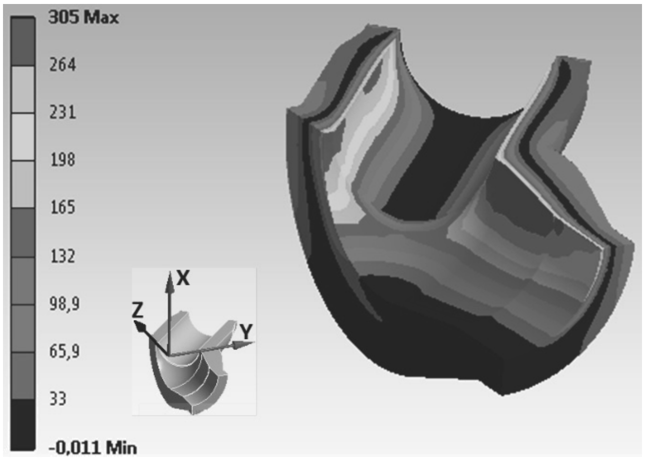

Fig. 11. Distributions of maximum stress state components σ_{xx} in the volume of Y-junction (maximum over time value)

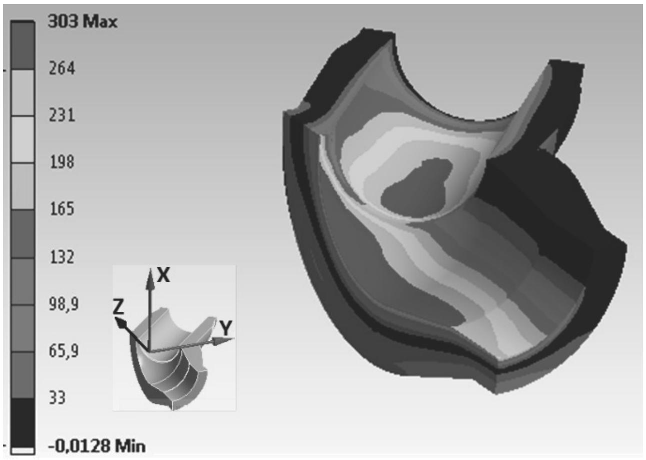

Fig. 12. Distributions of maximum stress state components σ_{yy} in the volume of Y-junction (maximum over time value)

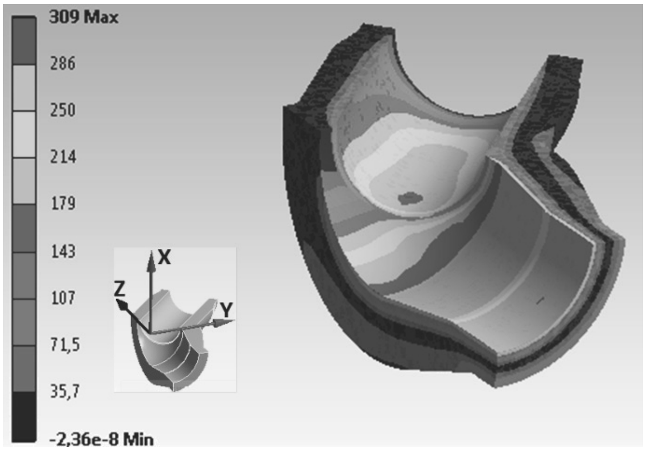

Fig. 13. Distributions of maximum stress state components σ_{zz} in the volume of Y-junction (maximum over time value)

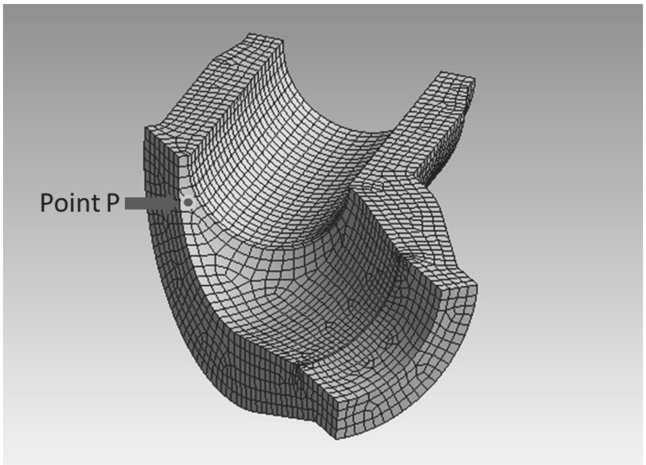

Fig. 14. Localisation of point P1where the courses of time-varying stresses were determined

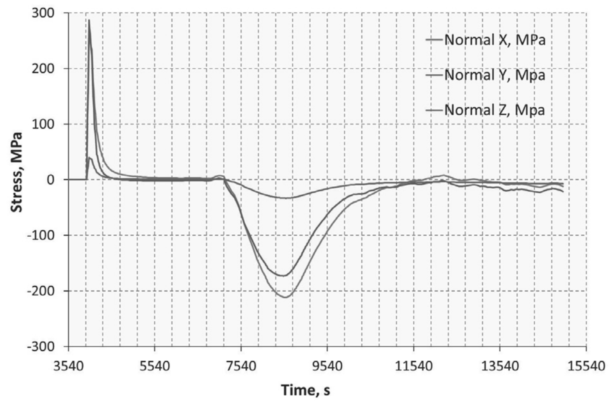

Fig. 15. The courses of time-varying stress state components in point P1 during the start-up

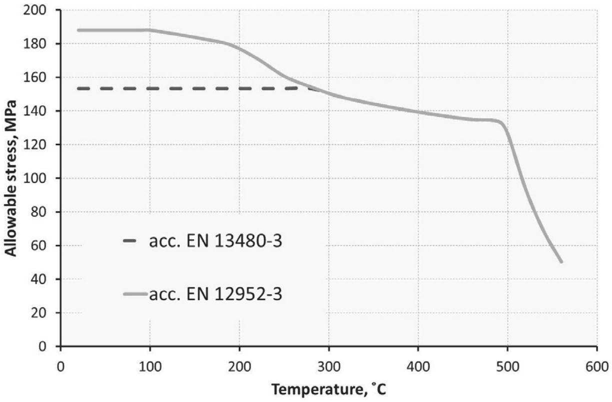

Fig. 16. The allowable stress as the function of temperature for the 13HMF (14 MoV 6-3) steel

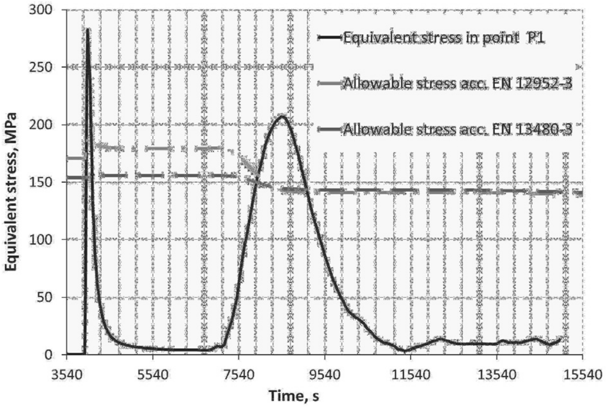

Fig. 17. The allowable stress and the equivalent stress as the function of time diagrams for point P1 (Fig. 14)

The allowable stress-temperature diagram has been calculated for the component and shown in the Figure 16. Taking into account the relationship between temperature and time and stress-time diagrams the characteristics of the changeable in time allowable stress in point P1 (Fig. 14) have been calculated.

The stress-time diagrams have been compared with the allowable stress and the results have been shown in Figure 17.

The results have been presented in the form of diagrams of equivalent stress-allowable stress ratio as the function of time as well (Fig. 18). It was found that the instantaneous stress values exceed the limit values in accordance with standards PN-EN 12952-3 and PN-EN 13480-3 (Figs. 17, 18).

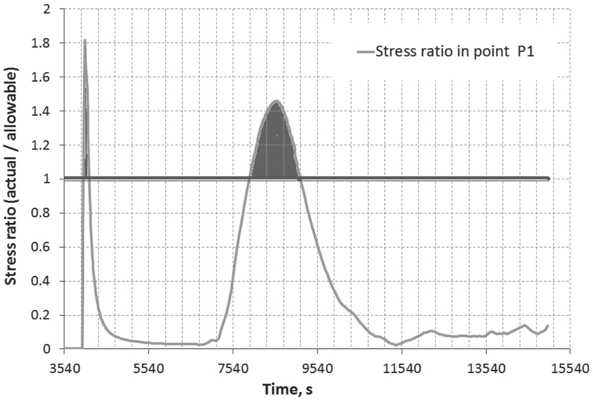

Fig. 18. The equivalent stress - allowable stress (in accordance with standards PN-EN 12952-3) ratio as the function of time; diagram for point P1 (Fig. 14)

High values of stress components during some periods of time suggest that the plastic strains could appear in the areas of the high effort, as near point P1 (Fig. 14). This effect depends on the temperature gradients (Fig. 19), pressure and local value of temperature.

The analysis of the local behaviour of the materials in such a case needs the special kinds of characteristics. Diagrams of the plastic strain as a function of time, as in Figure 20, give information about the periods of time during which the fatigue damage may accumulate.

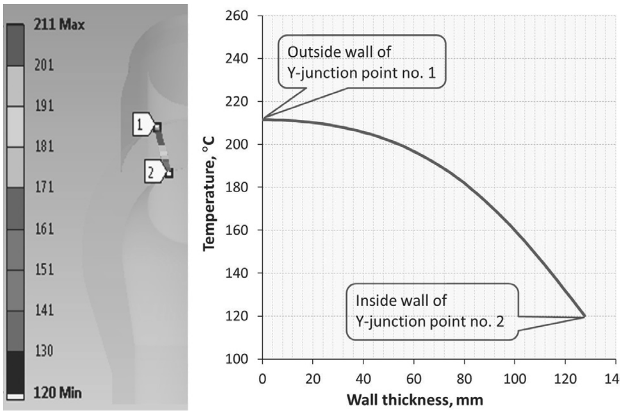

Fig. 19. The temperature distribution between the point P1 and the outer wall at the time 4080 s of start-up

The stress strain behaviour during fatigue under mechanical and thermal loading is characterised by such diagram as for instance stress components dependent on temperature or stress-strain characteristics in the form of hysteresis loops [10-16]. They are necessary when the durability problem is discussed and when we look for the parameters that we can use for the fatigue life assessment.

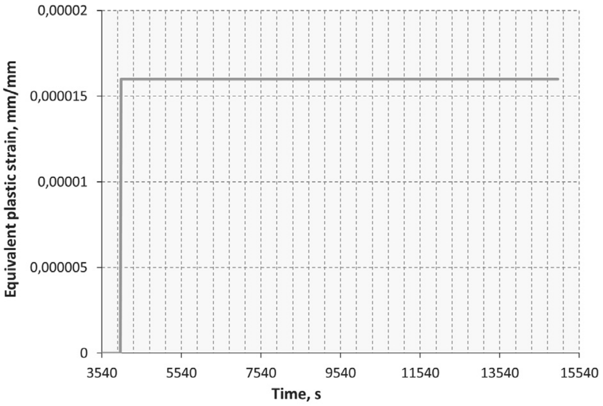

Fig. 20. Plastic strain versus time at the point P1 during start-up

6. Discussion

The cases that were found, where the acceptable stress values, determined in accordance with standard PN-EN 12952-3 [1], were temporarily and locally exceeded one time, do not pose a threat to the component in question. However, it should be borne in mind that repeated actions of this type may cause local fatigue of the material. This is because the effects of transient overloads may add up during operation. In such a case, the developed approach provides data to evaluate the potential effects of the varying operating parameters of a power unit.

The object of the analysis presented in the paper was a selected case of starting up a power unit, based on which it was found that fatigue-like interactions are of significance, for they can induce cracking of the surface of the components under consideration. Determination of the spectrum of the loads which cause fatigue requires an analysis of many cases of start-up and shut-down of a power unit. It is expected that among them, there will be cases where local stress values will be lower than those presented in the paper, as well as ones where stresses will exceed the allowable values as near point shown in Figure 14. They will depend on the design features of a power unit and on the method for controlling its operation.

Among the characteristics that are decisive to the nature and values of changes in stress, special attention should be paid to the type of material from which components of complex shapes are made, as well as to thickness of the component in question which is related to the type of material used.

This finding is becoming particularly important in the case of power plants with higher operating parameters, where the materials applied higher creep strengths and are usually characterised by higher values of the linear thermal expansion coefficient and lower values of the thermal diffusivity coefficient. The simultaneous action of these two properties leads to an increase in thermal stresses. Thus, in the case of new power units, for which higher operating parameters are anticipated, including elevated pressure and temperature, much more attention should be paid to fatigue-like phenomena.

The fatigue processes occurring in plants of this type are of special nature. These processes are connected with simultaneous changes in temperature and stresses and should be approached differently from fatigue under isothermal conditions, both relative to the analysis of the thermo-mechanical load spectrum and to the characteristics of the material [2-4,17,18]. In future works it would be necessary to take into consideration phenomena connected with the crack initiation and growth under mechanical and thermal loading taking into account existing method and procedures [20-27] as well.

Models used in this paper make it possible to determine the local mechanical behaviour of materials. This behaviour can be represented, for instance, by the graphs showing relationships between time and stress components or equivalent stress as a function of time. It is possible to determine in the same way the local strains and local temperature as a function of time to obtain the local stress-strain or strain-temperature characteristics.

From the form of the graphs in Figure 8 and 15 it is evident that one of the main reasons for the high values of transient stresses in the Y-junctions are the consequence of high temperature gradients resulting from temperature fluctuations of the fluid inside the pipes. The main reason for material fatigue in the components under investigation is temperature, which fluctuates, particularly during transient periods of plant operation. The high rates of temperature change lead to very high thermal stress amplitudes that should be taken into account when analysing surface fracture processes.

The fatigue may play a very important role in power plant damage. This fatigue has thermo-mechanical character. The number of studies concerning the thermo-mechanical fatigue phenomena is still inadequate considering the importance of the problem, particularly when operational safety is a factor. Such a situation can be attributed to difficulties in determining the fatigue process parameters in real operational conditions, which depend on mechanical as well as thermal loading. For derivation of these parameters, methods from mechanics of materials, heat flow theory and mechanics of fluids together with computer modelling should be used. The exact description of heat transfer conditions is particularly important when the model approach is used and the work is an attempt at such a description for the selected components.

7. Conclusions

1. The main reason for material fatigue in the components under investigation is temperature, which fluctuates, particularly during transient periods of plant operation.
2. Among the characteristics that are decisive to the nature and values of changes in stress, special attention should be paid to the type of material from which components of complex shapes are made, as well as to thickness of the component in question which is related to the type of material used.

3. One of the important features that influence the fatigue behaviour of the component under investigation is a changeable in time heat transfer coefficient on its inner surface.
4. The fatigue of thermo-mechanical character may play a very important role in the power plant component damage.

Acknowledgements

The results presented in this paper were obtained from research work co-financed by the National Centre of Research and Development in the framework of Contract SP/E/1/67484/10 -"Strategic Research Programme-Advanced Technologies for obtaining energy: Development of a technology for highly efficient zero-emission coal-fired Power units integrated with CO_2 cap".

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