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Description of the thermo-mechanical fatigue of thick-walled pressure vessels

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Abstract

The paper discusses the issue of the modelling of strains and stresses resulting from heating and cooling processes of the components in power plants. The main purpose of this work is to determine the mechanical behaviour of power plant components operating under mechanical and thermal loading. The heat-transfer coefficients as time-dependent variables have been introduced. Computer FEM modelling of the temperature strain and stress fields with temperature measurements have been used as the methods of research. It is readily apparent from the stress versus time graphs that under unsteady operating conditions, components analysed in the paper, especially in the case of boiler restarts, may operate with transient thermal stresses which sometimes reach values higher than a yield point. Consequently, a thermo-mechanical fatigue process takes place in the materials of the components in question. The stress-strain diagrams for the selected points of the plant components have been determined. The paper will be a contribution to the justification of the necessity of the application of design methods of highly reliable pressure vessels, which take into consideration an influence of TMF processes on these vessels durability.

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Keywords: Thermo-mechanical fatigue; power plant components, heat transfer, finite element method, stress-strain behaviour

1. Introduction

The engineering design of the components of conventional power generation equipment working under high pressure and temperature conditions is largely based on methods which ensure that the equipment is durable in terms of creep in operating conditions. This is specified by standards concerning the design of pressure equipment, such as Standard EN 12952-3 (2001) which is binding in the EU.

Stresses caused by the influence of variable temperatures are determined, according to this Standard, on the basis of simple mathematical relationships which take into consideration the temperature difference between the outer and

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inner surfaces of the pressure vessel. This difference is estimated on the basis of data concerning the expected warm-up and cooling rates in the conditions of the start-up and shut-down of the boiler. At times, stresses calculated in such a way seem to be significantly lower than those found in operating conditions, and the effects of fatigue are observed in the form of cracking on the inner surfaces of the thick-walled components of complex shapes. These effects of fatigue might suggest that thermal stresses in operating conditions exceed the values taken into account at the design stage.

The issue of accurate determination of the values of these stresses is of increased significance both by virtue of the safety of the equipment currently in operation and the continuous attempts at increasing the operation parameters of new equipment. Evaluation of thermal stress values in pressure equipment exposed to mechanical and thermal loading requires a combination of a number of research methods. It is essential to incorporate experimental and service data, computer modelling methods, as well as the material characteristics determined in conditions similar to those found in operation, as it has been shown for instance in our earlier papers: Okrajni (2009), Okrajni (2010) or Okrajni and Twardawa (2013).

2. Mechanical and thermal loads

During the start-up of a conventional power unit, pressure inside the plant grows. This pressure changes in accordance with the characteristic conditioned by the procedure of the power unit start-up. The course of the changes in pressure contains periods of its slower or faster time-dependent growth. Steam temperature also exhibits fluctuations related to concurrent changes in the rate of its flow. Fig. 1 present diagrams of the time-dependent temperature and pressure of steam. The measurements of these parameters were conducted under industrial conditions on a boiler in one of the Polish power plants.

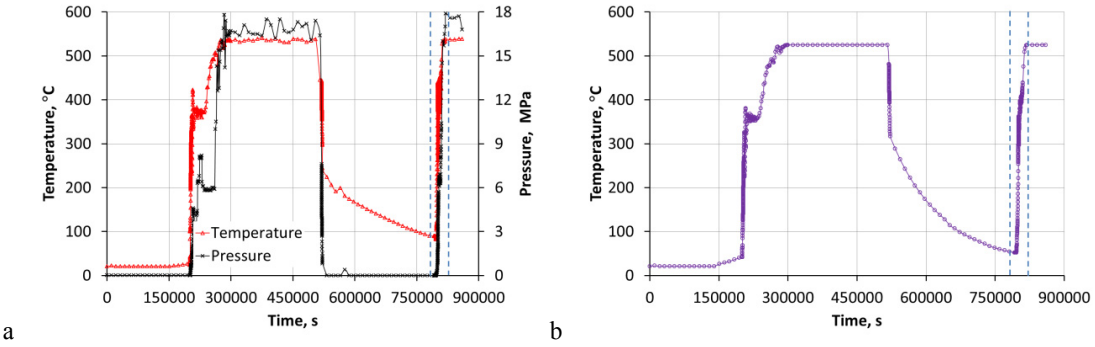


Fig. 1. (a) sample temperature and pressure measurement results for the superheater outlet obtained under industrial conditions (in one of the Polish power plants); (b) the values of superheater header ambient temperature.

The objective was to determine the conditions in which the chosen thick-walled component (which in this case was the superheater outlet header) works during the start-up and shut-down of the power unit. These characteristics only include a minor part illustrating the loads during the steady-state operational conditions of the boiler, as the main focus in this case was placed on the significance of transient states during which the rapidly changing steam temperature leads to thermal stresses. Fig. 1 presents one of the many possible instances of start-ups and shut-downs of a power unit.

The majority of power units use metal temperature-measuring systems at selected points of components of complex shapes. The temperature is measured, among other places, in the superheater headers. Thermocouples are placed at different depths relative to the outer surfaces of the components, close to the outer surface, 5mm under this surface (shallow) and near the inner surface, 5mm from this surface (deep). The outcomes of measurements are then presented as time-dependent temperature profiles at a given point, or as the difference between the indications of the

thermocouples in deep and shallow locations. The sensors can be used in order to assess the values of time-variable stress in the components in question. By applying the dependencies specified by the standards, the differences of the temperature enable an assessment of the values of time-variable stresses. These dependencies are, however, a mere approximation based on the application of a stress concentration coefficient which takes into consideration the geometrical parameters of the component in question.

Such an approach to the assessment of stress in components of complex shapes sometimes leads to an over-approximation. Another method is necessary when we want to analyse time-variable stress patterns and to find the most intense damage accumulation areas. Determining time-variable temperature field stresses and strains calls for the application of computer technologies including, predominantly, finite element methods..

3. The temperature and strain fields in a component of a power unit

Methods for the determination of time-variable temperature fields applied in the strength calculation procedures of power unit components assume constant values of the heat transfer coefficient dependent on the kind of medium flowing through the component - Standard (2001). With a view to a precise mapping of a time-variable temperature field in components of power units through computer modelling, it is necessary to take account of the time variability of the heat transfer coefficient which changes in the wide range as it for instance has been described in the work of Orłoś (1991). This issue is currently being investigated with consideration of both the analysis of the operation of the equipment in industrial conditions, and computer modelling methods. In this paper the problem of the description of boundary conditions is presented as essential for the analysis of a temperature field. Such a description is important in the methodology of determining the characteristics of the thermo-mechanical fatigue in components exposed to mechanical and thermal loads. The analysed superheater header is an 8540 mm-long cylindrical thick-walled vessel (Fig.2). The axis of the vessel is lined with 7 stubs connected with the steam superheater pipes. Along the chamber 43 peripheral rows of stubs are arrayed in planes perpendicular to its axis. The distance between these rows is 178 mm.

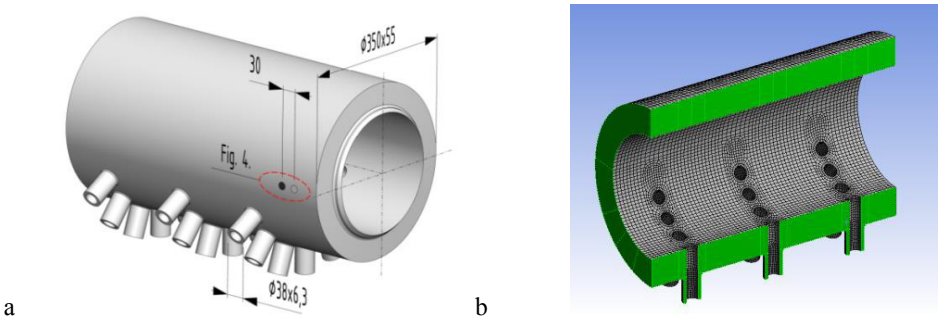
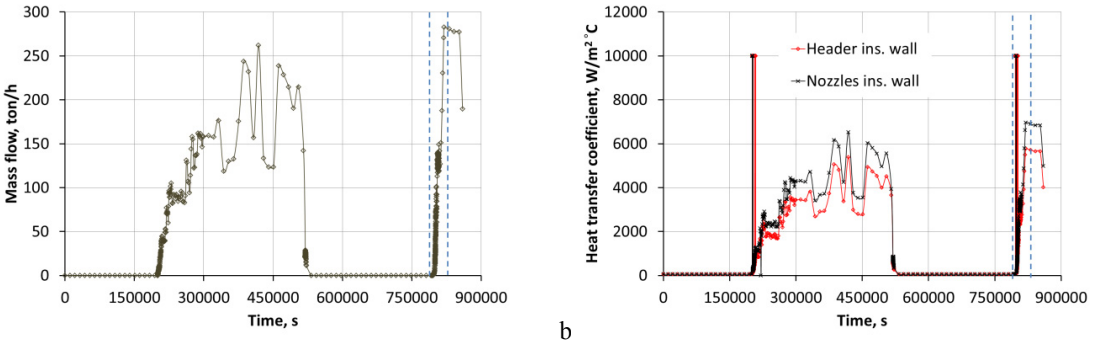


Fig. 2. (a) superheater outlet header of a conventional steam power plant (18MPa nominal steam pressure parameter and 540 ˚C temperature parameter – with the points of thermocouple locations (area with the red dashed line border); (b) FEM model of the superheater outlet header.

With a view to determining the temperature and stress distributions a model of the superheater was developed. A finite element method has been used in this case. Due to the symmetry of the unit with respect to the vertical plane, one half was considered with the cross section on the aforementioned plane. Additionally, a part of the superheater model was isolated from its whole length with planes perpendicular to its axis. The model is presented in Fig. 2b.



a b

Fig. 3. (a) the characteristic of the mass flow of the steam ; (b) the characteristics of the heat transfer coefficient for the inner surface of the superheater header.

In the planes of the intersections a zero value of heat flow was assumed. Such an assumption is obvious for the plane of symmetry. The FEM was used for the construction of a model made up of 56,000 brick-type elements. The heat transfer coefficient on the inner surface of the header was assumed to be dependent on the steam flow rate (Fig. 3a), steam pressure and temperature (Fig. 3b). On the outer surface of the header the heat exchange is less intensive and the zero value of this steam flow rate for the external surface of the header may be used. Taking into consideration these conditions on the outer surface a constant value of 50 $W/m^2°C$ for the heat transfer coefficient was assumed, whereas the values of time-variable ambient temperature were assumed with characteristics as presented in Fig. 1b. For boundary conditions specified in this way the time-variable temperature field was determined in the component in question. The course of temperature determined on the basis of the model approach for the locations of the thermocouples was compared with the results of the measurements in industrial conditions (Fig. 4) for a selected period of the operation of the power unit. This period is marked in Figs. 1a,3a,3b by vertical dashed lines.

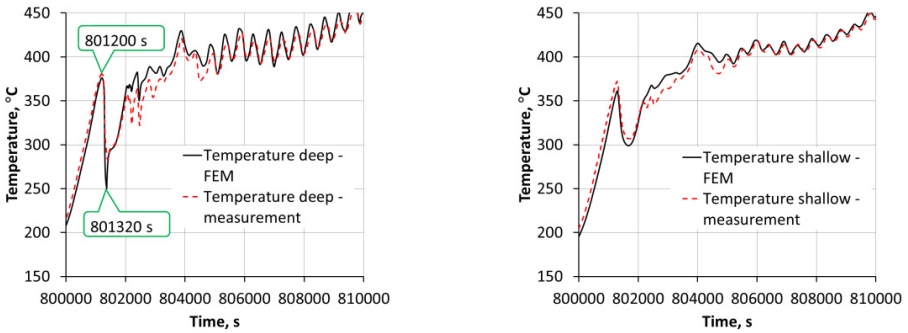
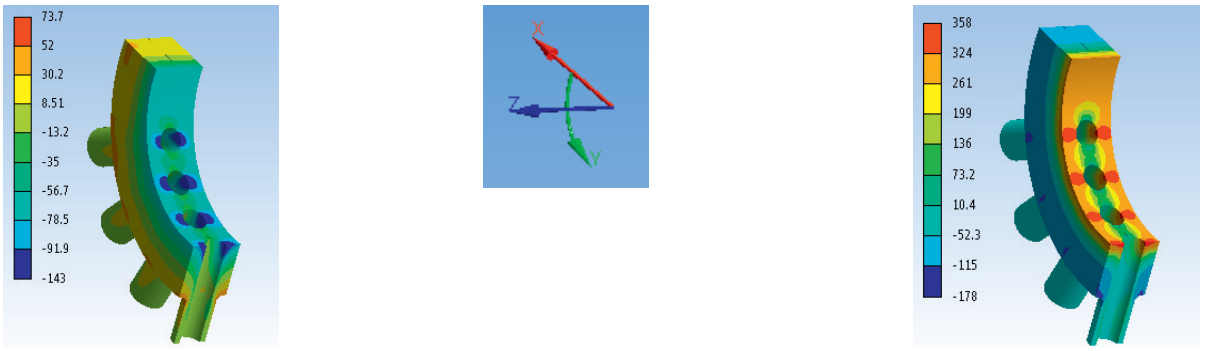


Fig. 4. The course of temperatures determined on the basis of the model approach for the selected locations (Fig. 2a) in comparison with the results of the measurements in industrial conditions for a selected period of operation of the power unit.

Specific heat C_p, thermal conductivity λ and thermal expansion β coefficients were assumed, for the component material (X20CrMoV12-1 steel), as temperature-dependent values. Mechanical properties for selected temperatures are presented in the form of cyclic stress-strain curves. A thermo-elastic-plastic model of kinematic hardening material was assumed. Another assumption was a limited displacement in the direction perpendicular to the plane of symmetry of the model. On one of the planes of the cross sections, perpendicular to the axis of the header, the limitation of any possibility of displacement in its perpendicular direction was assumed. On the parallel plane opposite, a uniformly distributed load balancing the axial force caused by internal pressure was posited. The model also assumes elastic supports at the ends of the stubs at the points of the finite element mesh, which represent the

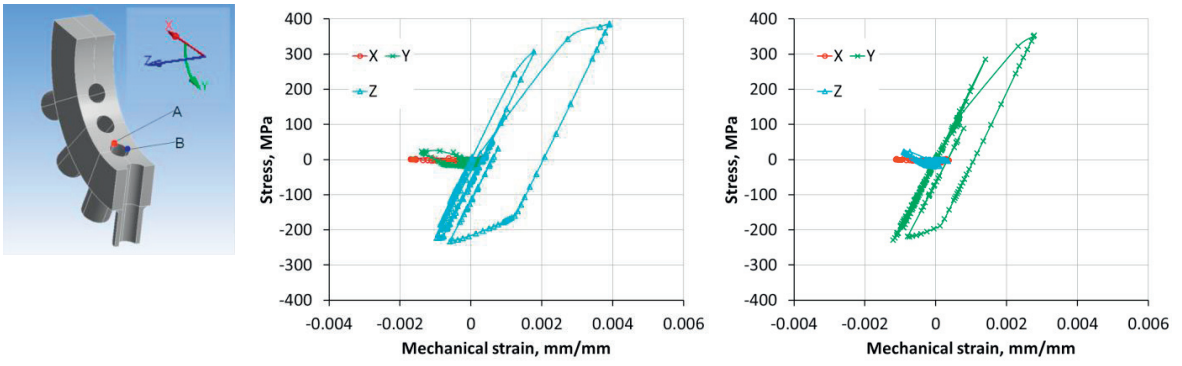
flexibility of the pipes connecting the header with the steam superheater. Components of strain and stress fields, as well as their equivalent values, were determined (Fig. 5).



a b

Fig. 5. (a) distributions of hoop stress state component σ_{yy} in MPa, in the volume of superheater header 801200 s after start-up; (b) distributions of axial stress state component σ_{yy} in MPa, in the volume of superheater header 801320 s after start-up.

The presented stress distributions indicate areas of their concentration in the vicinity of the holes. It is in these areas that cracks appear in operational conditions. In order to calculate the characteristics which determine the intensity of the damage accumulation process, a local analysis of the relationships between temperatures, stress and mechanical strain is necessary. The points A and B have been selected in the areas of stress concentration (Fig. 6a) and the strain-stress characteristics for these points have been worked out. The course of a chosen local strain-stress characteristics is typical for thermo-mechanical fatigue (TMF), as we may see in the works of Farragher et al. (2013), Bressers and Remy (1996), Hähner et al. (2008), Sehitoglu (2008), Okrajni et al. (2008) and Okrajni and Plaza (1995) for instance.



a b c

Fig. 5. (a) location of points A and B; (b) characteristics of the relationship between stress components and mechanical strain components $\sigma(\varepsilon_M)$ at point A; (c) characteristics of the relationship between stress components and mechanical strain components $\sigma(\varepsilon_M)$ at point B.

4. Discussion

In the case of the simultaneous interaction of variable temperatures, stresses and strains the development of a universal method for estimating the fatigue life assessment of materials is a very complex issue. The life assessment methods applied so far refer to selected particular characteristics of strain, stress and temperature cycles and strain or stress states. Considering the possibility of a review of the existing criteria, coupled with the creation of the foundations for the development of new fatigue life prediction methods, a precise characterization of the time-

varying physical fields affecting the phenomena of the accumulation of damage is an extremely important issue. This study is devoted to this issue, with the main emphasis on the methodological aspects of the description of local processes of deformation in power unit components.

One of the main conclusions from the research concerns the necessity of using the time-dependent heat transfer coefficients in problems of heat transfer modelling. Only in such a case can we obtain a correspondence between the temperature measurements and modelling. The local temperature measurements offer us the possibility of validation of the models, and should be used together with the modelling for the assessment of actual damage conditions.

It is important that the hysteresis loop $\sigma_{zz}(\varepsilon_{zz})$ for point A has a higher width, representing the plastic strain range, comparing it with the loop $\sigma_{yy}(\varepsilon_{yy})$ for point B (Fig. 5). This might suggest that more intensive damage could be accumulated near point A compared with point B. This is in agreement with the observations of the processes of internal surface cracking during the operation of the components. Cracks often appear between holes in planes perpendicular to the chamber's axis. In such circumstances a more destructive process could take place not as a result of the hoop stresses near point B, but as a result of axial stresses near point A. This phenomenon is quite unexpected when the mechanical loading character is taken into consideration.

Thermo-mechanical fatigue may play a very important role in power plant damage. The number of studies concerning 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 the derivation of these parameters, methods from mechanics of materials, heat flow theory and mechanics of fluids, combined with computer modelling should be used. A precise description of heat transfer conditions is particularly important when the model approach is used, and the study is an attempt at such a description for the selected component.

Acknowledgements

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