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# Research Paper

# 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

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The paper presents results of tests designed for predicting the behaviour of components subjected to variable temperature and mechanical loading conditions. Elbows and tubes, as examples of components widely used in power plant pipelines, have been examined. This analysis includes a description of model characteristics, the operating parameters of devices under industrial conditions, and the results of computational modelling (FEM).

**Key words:** stress-strain behaviour; thermo-mechanical fatigue; thick-walled elements; numerical simulation; heat transfer.

## 1. INTRODUCTION

One major trend in power industry today is to raise the parameters of steam in order to increase the efficiency of fuel burning and minimize its impact on the environment. Another common practice is to operate power boilers with more frequent start-ups. This change in power production makes it necessary to modify current strength and durability calculations of thick-walled elements. Increased (temperature and pressure) parameters of steam require the application of new materials, more resistant to creeping and thermo-mechanical stress in the long run. Creep characteristics have become a decisive factor in the choice of new metal alloys. Unfortunately, this desired feature is linked with less favourable ones. In the case of modern and future supercritical power boilers austenitic steel grades and nickel alloys are used. These materials usually have lower thermal conductivity, specific heat, and a higher coefficient of thermal expansion. These features, contrary to traditional ferritic steel grades, result in higher temperature gradients, which lead to higher thermal stress inside thick-walled elements. More frequent start-ups may speed up fatigue damage in these elements. Such damage is a local phenomenon and is caused by thermo-mechanical stress, which depends on the shape and dimensions of the element, properties of the materials and heat transfer conditions, especially on the inner surface of the elements. In modern power boilers thick-walled elements of complex shapes, such as valves, superheater headers, T-pipes, Y-pipes, four way pipes, and elbows are especially prone to fatigue processes.

The prediction of failure for an element subjected to fatigue requires a detailed analysis considering the temperature, stress and strain fields within its volume. As such elements are complex in terms of their shape, dimensions, and material characteristics, computational modelling of operation parameters seems the most convenient procedure for the analysis of their design and the assessment of durability [1–5]. This article presents finite elements modeling used in order to develop a good understanding of the relationship between geometrical features, operation parameters including thermal and mechanical loadings, and local stress and strain inside thick-walled elbows made of nickel alloy HR6W. This elbow is an example of components which will be used in supercritical boilers. Their properties and operation parameters are likely to induce fatigue because of the low values of thermal conductivity and specific heat and high values of thermal expansion coefficient determining the values of thermal stresses.

The aim of the paper is to assess the influence of feasible temperature oscillations on the course of stress and strain changes in the elements considered. Such oscillations may occur especially in the period of starting steam power units and are related to the start-up procedure and changes in the steam state. Figure 1 shows selected examples of changes in the temperature of steam and steam pressure during such start-ups measured in conventional power units.

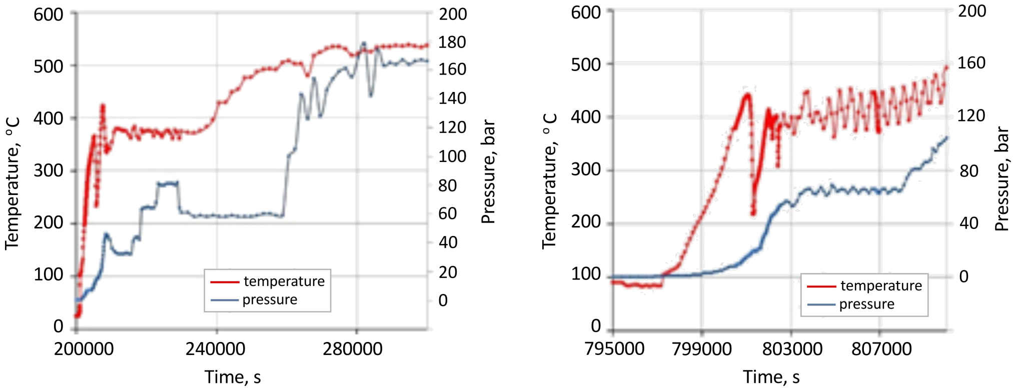

Fig. 1. Examples of steam temperature and pressure versus time characteristics measured under operating conditions (of conventional power plants).

In these unsteady periods of operation, steam temperature oscillations are clearly visible. At the current stage of this research, a model analysis of possible oscillations was considered, taking into account both typical rates of steam temperature changes and the range of such changes.

## 2. Outline of mechanical and thermal loadings and the model of the component

Considering the effect of element geometry and loadings on time-dependent mechanical strains and stresses in analysed elements, simplified steam temperature and pressure versus time profiles during operation period have been assumed. Such profiles include heating up periods, a stable operation and shutdown conditions (Fig. 2).

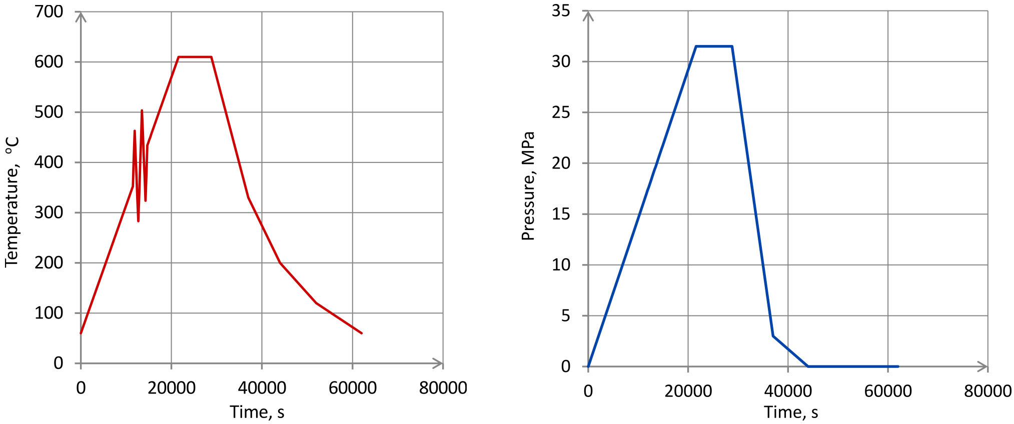

Fig. 2. Steam temperature and pressure versus time profiles including start-up, stable operation and shut-down periods: a) steam temperature versus time, b) steam pressure versus time.

A set of parameters is assumed as follows: a heating-up period of 6 hours, a stable operation of 2 hours (steam temperature and pressure outside of the analysed elements are constant and the temperature within the elements does not change), and a shutdown period of 9.2 hours. The rate of cooling changes during a shut-down period. This change initially results from the decrease in the steam flow rate and temperature, however, with the passage of time, the accumulated energy of thick-walled elements starts governing the heat transfer. Eventually, this energy is conveyed from the mass of thick-walled elements to cool air passing through these elements. Thermal boundary conditions for analysed cases are as follows: time-dependent temperature of the fluid (steam) and a constant convective heat transfer coefficient on the inner surface. The cooling rate is higher at the initial stage of the shut-down period and decreases with time

(Fig. 2a). The temperature of the medium outside of the component is assumed as constant and a constant convective heat transfer coefficient has been adopted as equal to 50 W/($\mathrm{m}^2\cdot$ K) . When the temperature of the element reaches 60°C, the initial temperature of the element, the next heating up period begins and a subsequent stable one. Time-dependent pressure, as less relevant for the problem in question, was taken into consideration in a simplified form as presented in Fig. 2b. Figure 3 shows a view of the analysed component with the straight part of the pipeline connected with the elbow and the scheme of boundary conditions assigned on the cross-section. A linear relationship between pressure and time was assumed at the start-up stage, while under stable operating conditions, pressure was assumed as constant. The rate of pressure changes in the first period of the shut-down was higher than in the following stages. The value of displacements perpendicular of the cross-sections of the straight part elbow's ends was taken as equal to zero. ANSYS simulation software was used. The model contained 110 748 elements and 278 091 nodes (Fig. 4). Such a model was used for the analysis of the temperature, strain and stress fields for different heat transfer coefficients on the inner surface of the elbow. Subsequently, the results were compared. The comparison between the characteristics calculated for the start-up was made both with and without considering temperature oscillations.

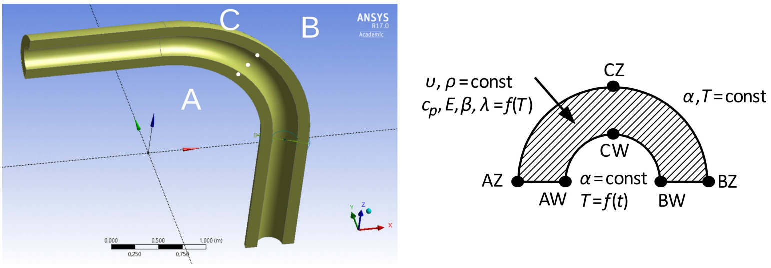

FIG. 3. A schematic presentation of boundary conditions for thermal analysis.

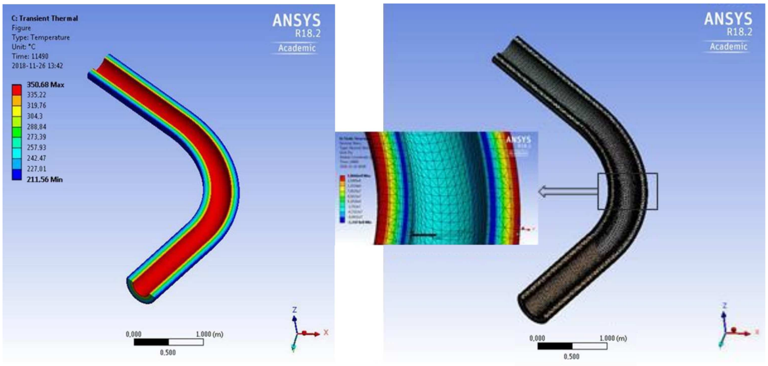

FIG. 4. Presentation of the FEM model with selected results.

## 3. Material properties and computation results

Changes in thermal conductivity and temperature-dependent specific heat were taken into account, the values of which are shown in Fig. 5. These properties were used in thermal computations, whose partial results are presented in Fig. 6.

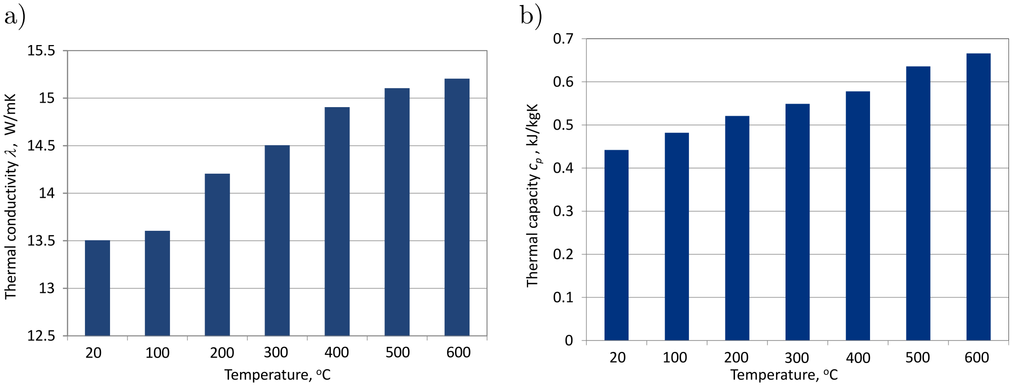

Fig. 5. Temperature dependent thermal conductivity (a) and specific heat of the HR6W alloy (b).

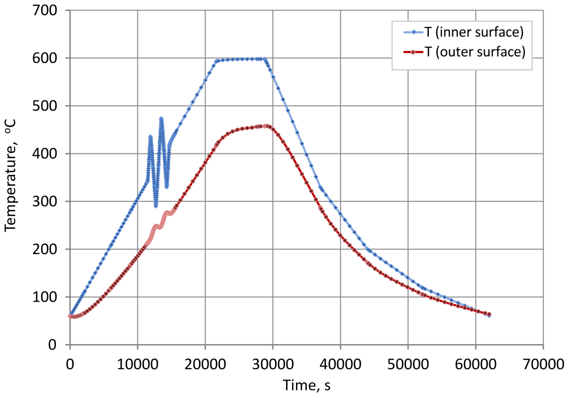

Fig. 6. Temperature versus time values for point AW on the inner surface and point AZ on the outer surface in area A (Fig. 4) close to the center of the elbow (with heat transfer coefficient on the inner surface equal to 3000 W/($m^2 \cdot$ K)).

A more significant impact of steam oscillations on the inner surface temperature was observed (Fig. 6), which strongly influences the stress-strain behaviour of the material in this area.

A multilinear kinematic hardening model was used, based on the Besseling model [6–8], which assumed the elementary volume of elastoplastic material to be composed of various portions, sub-volumes, with equal values of the modulus of elasticity and total strain, but with different values of yield strength. Each sub-volume is assumed to exhibit perfectly plastic behaviour, but when combined, the model can represent complex behaviour as a multilinear stress-strain curve that exhibits kinematic hardening (Bauschinger) effect. The portion of the total volume (the weighting factor) and yield stress for each sub-volume was determined by matching the material's response to the uniaxial stress-strain curve. Material HR6W was described as elastic-plastic with kinematic hardening, and temperature-dependent features such as Young's modulus and thermal expansion coefficient (Fig. 7a,b). The temperature dependent stress-plastic strain curves for HR6W alloy taken from uniaxial stress-strain tests are shown in the Fig. 7c.

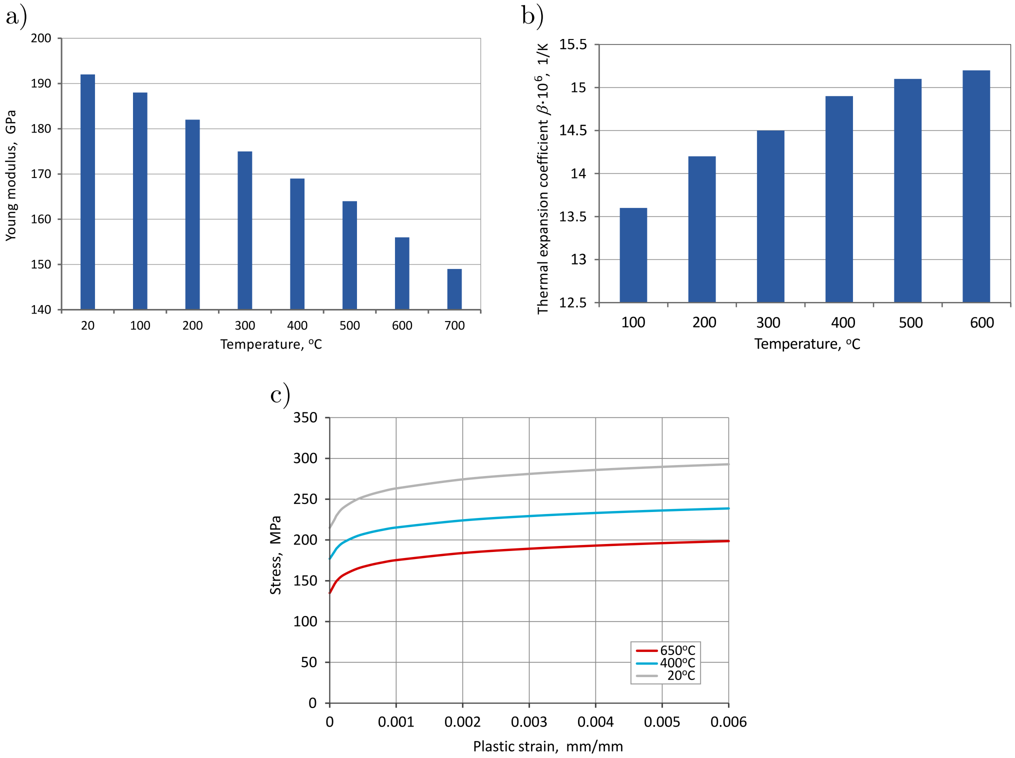

Fig. 7. HR6W alloy characteristics: a) Young's modulus, b) coefficient of thermal expansion, c) temperature dependent stress-plastic strain curves taken from uniaxial stress-strain tests.

A hoop stress versus time graph was determined for the points selected on the inner and outer surfaces (Fig. 8). It can be seen that stress versus time curves for points AW, BW and CW located on the inner surface close to the center of the elbow show only minor differences in the behaviour of the material (Fig. 8a). However, the behaviour illustrated by stress versus time curves calculated for the points located on the inner surface from that on the outer surfaces (Fig. 8b)

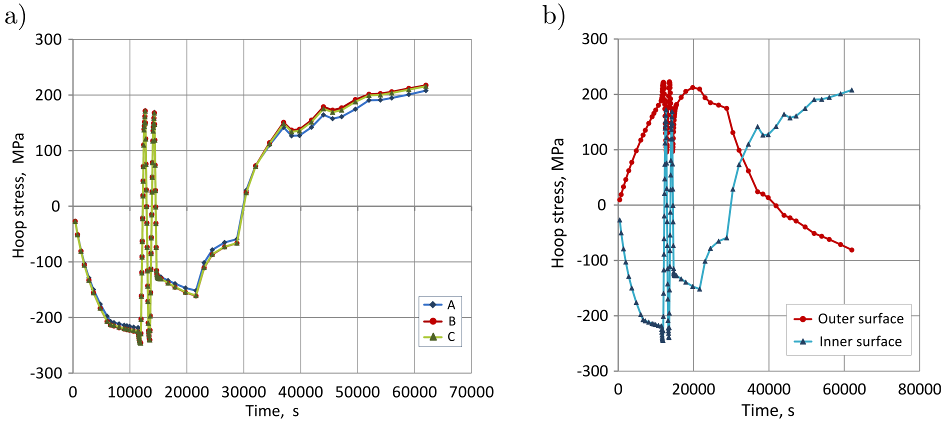

FIG. 8. Hoop stress versus time for the points AW, BW and CW (Fig. 3) (a) and comparison of the hoop stress versus time on the inner and outer surfaces – points AW and AZ (Fig. 3) (b) (diagrams calculated for temperature and pressure changes shown in Fig. 2).

which leads to the conclusion that the influence of temperature oscillations on thermal stresses is more evident on the inner surface.

Calculations were done for two cases referring to an entire cycle of boiler operation:

- a start-up with temperature oscillations during the first cycle, steady warm period and cooling down,
- a similar cycle without temperature oscillations.

Temperature oscillations in power plant components may induce changes in local stresses. Examples of characteristics shown in Fig. 9 reveal that oscillations of the temperature significantly influence the course of stress changes over time. During the start-up period oscillations lead to cyclic changes in stress. Oscilla-

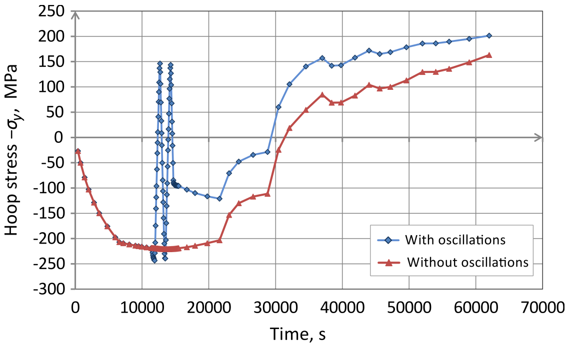

FIG. 9. Hoop stress versus time for the point AW (Fig. 3) calculated for temperature and pressure changes shown in the Fig. 2, without and with temperature oscillations in the start-up period.

tions may lead to changes in stresses following their occurrence, which is visible in Fig. 9 as the increase in stress levels.

One of the important factors that influences the values of strains and stresses in components under mechanical and thermal loading is the intensity of heat transfer on the components' surfaces. In the FEM model this intensity depends on the heat transfer coefficient [4, 5]. In addition to the analysis of how oscillations during the start-up periods affect local strain fields, the significance of the coefficient of heat transfer was highlighted. Results were obtained for a selected point on the surface of the elbow. Additionally, the change in convective heat transfer coefficient describing forced convection was tested. A draft analysis was carried out for inner point AW on a cross section of the elbow (Fig. 3).

The local behaviour of the material during the start-up stable period and shut-down period was characterized using four types of the graphs in order to determine: mechanical hoop strain *versus* time, hoop stress *versus* time, mechanical hoop strain *versus* thermal strain, and hoop stress *versus* mechanical hoop strain. These graphs were calculated for different values of heat transfer coefficient as shown in Figs 10 and 11.

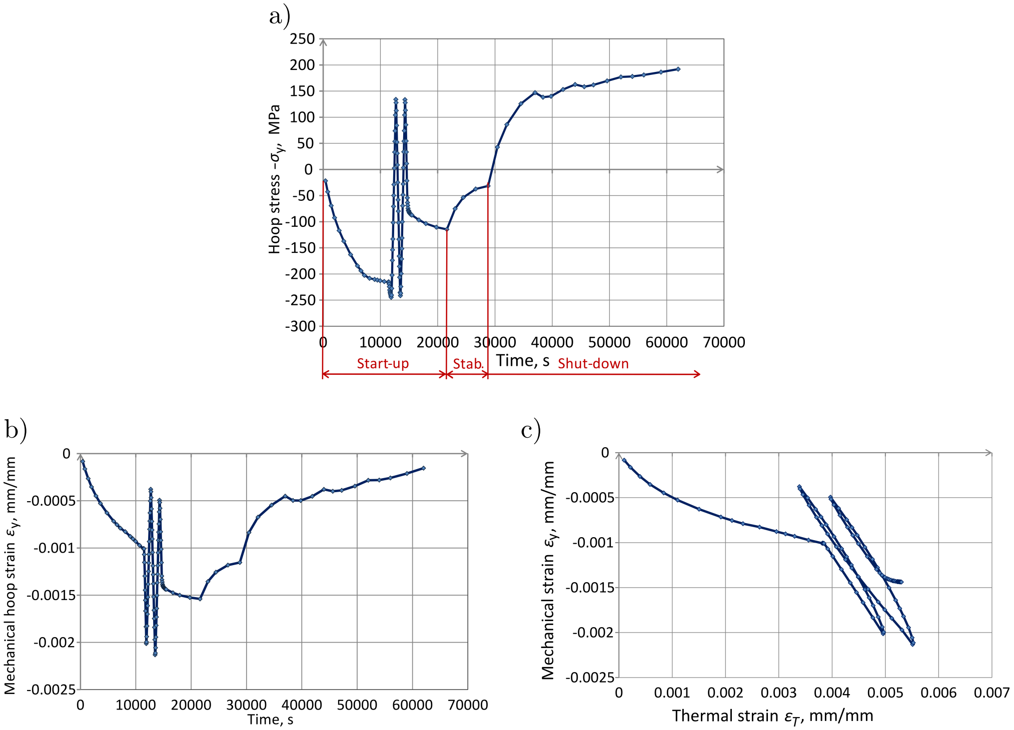

Fig. 10. Characteristics determined in FEM modelling for point AW; heat transfer coefficient $\alpha = 1000$ W/(m$^2$·K): a) mechanical hoop stress versus time, b) hoop strain versus time, c) mechanical hoop strain versus thermal strain.

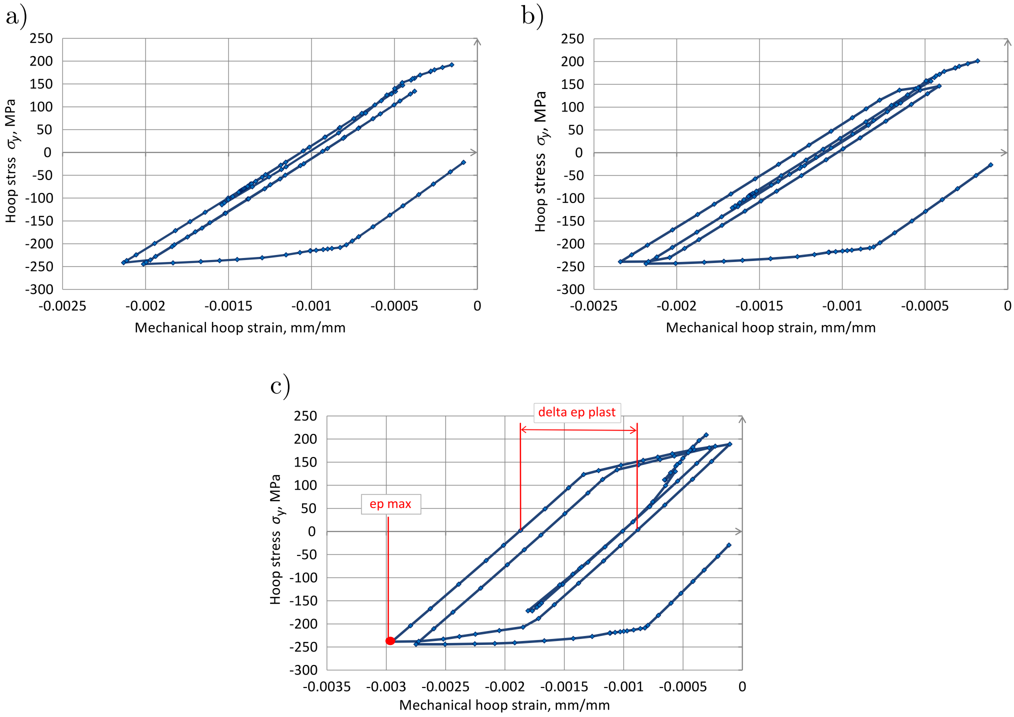

FIG. 11. Hoop stress versus mechanical hoop strain for point AW: a) heat transfer coefficient $\alpha = 1000$ W/(m$^2\cdot$K), b) heat transfer coefficient $\alpha = 3000$ W/(m$^2\cdot$K), c) heat transfer coefficient $\alpha = 15\,000$ W/(m$^2\cdot$K).

For the selected elbow four different convective heat transfer coefficients were used to test their influence over stress and strain curves. Results for a set of points selected on the inner and outer surface were presented in form of graphs.

At the beginning some calculations were done in order to assess which points should be analysed to indicate different trends with reference to stress and strain curves under analysis.

Figure 8a shows that the point position bears little relation to hoop stress versus time curves, which is also the case with axial stress curves versus time. The same weak correspondence was observed for points AW, AZ, BW, BZ, CW and CZ for axial and hoop stresses. The results show changes in the sign of values of stresses and strains during the operation periods (Figs 10 and 11). It can be seen that the values of the range of stress change in the period of oscillations are higher for the point on the inner surface (Fig. 8b). On this surface the fatigue process is expected to be more intensive. An attempt was made to find the influence of the convective heat transfer coefficient on stress-strain curves. This impact is illustrated by the graphs for point AW on an elbow with a bend radius of 1500 mm (Fig. 11).

It could be posited that the value of the heat transfer coefficient is one of most vital factors influencing the strain range in the period of oscillations. The value of this coefficient influences the values of stresses and accumulated strains in the components in the analysed part of the operating period.

## 4. Discussion and conclusions

The calculations of time-dependent stress and strain characteristics performed for thick-walled elbows at power boilers, done for boundary conditions closely simulating the actual ones, point to the conclusion of the practical importance of such an analysis in the assessment of their behaviour during frequent start-ups expected in modern power plants. The analysis of the behaviour of elbows shows that the position of the tested points located on the inner surface close to the center of the elbow (AW, BW, CW) does not have significant effect on the local stress and strain versus time characteristics. It is worth pointing out that the most important influence in case of thick-walled elements at power boilers, affecting time-dependent stress-strain curves, was determined for temperature oscillations during the heating-up and shutdown periods. Thermal stress and strain depend on the amplitude and time span of the oscillation cycle. They also depend on heating up time span, and convective heat transfer coefficient.

The latter one strongly affects material behaviour during rapid local changes in temperature shown and described in the previous papers on the basis of measurements of real operating elements [4, 5]. With the assumption of a likely phase change for the steam passing through the piping, any reference to its flow and thermal parameters requires the application of varying heat transfer coefficients. Such an approach – more accurate in terms of science – differs from the standard methods for pressure vessels calculations [9]. Calculations conducted with assumed convective heat transfer coefficients higher than the standard one of 1000 $\mathrm{W/(m^2 \cdot K)}$ reveal the importance of transient heat transfer for thermo-mechanical fatigue and, as a consequence, for the assessment of the life cycle for thick-walled elements at power boilers.

The calculated profiles of stresses versus mechanical strains reveal stress-strain behaviour which can be presented in the form of hysteresis loops (stress versus mechanical strain). Such characteristics observed for the points in the central part of the elbows in the heating period of the operation cycle are typical of the low-cycle or thermo-mechanical fatigue of the material [10–14]. This phenomenon may determine the value of the accumulated plastic strain on the inner surface of the elbow and strongly influence material damage on its surface. The intensity of the fatigue process, which depends on the heat transfer intensity in the analysed examples of the components under mechanical and thermal loadings, seems to be one of the major factors which determine the durability of these components.

Two parameters have been introduced in the present analysis, $\varepsilon_{\max}$ and $\Delta\varepsilon_p$, in order to describe the influence of the heat transfer coefficient on the intensity of the damage process caused by temperature oscillations. One of them is the maximal value of mechanical strain, the other is the width of the hysteresis loop (Figs 9c and 12). The usefulness of the parameters defined in this way needs further assessment and discussion, which will be the objective for future research. At this stage, their definitions provided an opportunity to characterize the influence of the heat transfer coefficient on the intensity of fatigue, as presented in Fig. 12. The graphs reveal the essential influence of the heat transfer coefficient on parameters $\varepsilon_{\max}$ and $\Delta\varepsilon_p$ within the range of 1000–7000 $\mathrm{W/(m^2 \cdot K)}$ of the heat transfer coefficient. In the range 7000–15000 $\mathrm{W/(m^2 \cdot K)}$ these parameters actually do not depend on the heat transfer coefficient. This is a very important conclusion for designers as the assumption of the value of $\alpha$ within the range between 7000 and 15000 $\mathrm{W/(m^2 \cdot K)}$ can lead to the boundary assessment of the parameters which condition the intensity of fatigue.

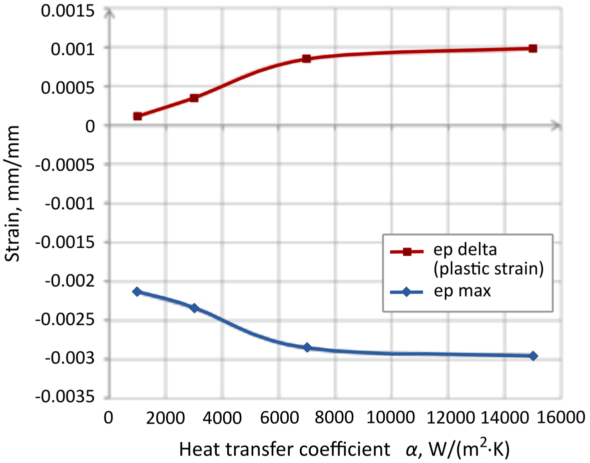

Fig. 12. Calculated parameters $\varepsilon_{\max}$ and $\Delta\varepsilon_{\mathrm{plast}}$ for different values of the heat transfer coefficient.

The simple models presented in this paper contribute to research into a phenomenon which has a significant influence on the stress-strain behaviour of temperature components operating under conditions resembling actual operation periods. The results presented above should be treated as another step in research on fatigue behaviour in new power plant components. The influence of creep characteristics of the materials on local mechanical behaviour should be taken into consideration in future research. In addition, heat transfer phenomena deserve to be analysed in more detail. The latter will be the subject of our next paper. A more complex geometry of components will be taken into consideration, along with their boundary conditions and material properties.

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