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Transient heat transfer as a leading factor in fatigue of thick-walled elements at power plants

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Abstract The authors present a numerical study of a start-up of a boiler with a thick-walled element subjected to thermomechanical loading. The significance of calculations of real heat transfer coefficients has been demonstrated. Fluid dynamics, mechanical transient thermal and static structural calculations have been conducted in both separate and coupled modes. Strain-stress analyses prove that the effect of the heat transfer coefficient changing in time and place in comparison with a constant one as recommended by standards is the key factor of fatigue calculations.

Keywords: Thick-walled elements; Transient heat transfer; Thermomechanical fatigue

1 Introduction

The developments observed in the contemporary power industry are conditioned by both environmental and economic criteria. Research into new options for the use of more renewable energy sources and the application of less environmentally harmful fuels is accompanied by exploration of new technical solutions intended for power plants running on conventional fuels. All such investigations are aimed at various targets, including those oriented towards increasing service parameters of power units in order to ensure higher performance and reductions in carbon dioxide emission. For

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these purposes, the existing power plants are revamped more and more frequently, whereas power units currently under construction must face increasingly demanding requirements. On the other hand, due to the economic criteria an increased availability of power units as well as serviceability under the conditions of frequent changes in demand for electricity have become a prerequisite. Therefore, it is also necessary to adapt power plants to frequent changes of their operating loads.

Increased power plant service parameters lead to changes in operating conditions for power unit components. In order to ensure that they conform with the relevant strength criteria, new materials are used, characterised by increasing creep resistance and matching the requirements of operation under higher temperatures. However, the use of these materials triggers some further issues connected with the possibility of predicting their behaviour under operating conditions. In view of expected higher values of loads and temperatures, the available data pertaining to their basic mechanical properties and creep resistance prove insufficient for the assessment of operational safety of machinery in several cases. The increasing importance of cyclic effects emphasises the necessity of considering fatigue processes taking place in materials. Higher operating temperatures and pressures as well as increased thicknesses of walls of individual elements, which accompany the former with frequent load changes, require that both engineers and users pay more attention to thermal stresses which may lead to thermal and mechanical fatigue.

Contemporary methods in the design of pressure components for power units take into account the values of these stresses through the application of simplified computational procedures and methods for estimating service life based on fatigue characteristics developed for selected groups of materials and transformed into dependences between the number of cycles before rupture and the range of stress changes. These characteristics are obtained and matched in the designing process, relying on the material's tensile strength [1]. The values of the temperature gradient considered in thermal stress calculations are established in the simplified way as dependent on the assumed characteristics of the power unit start-up and shut-down [2–6]. An interesting way of finding allowable temperature change for a transient operation of boilers in supercritical power plants was presented in a paper in 2010 [7]. Authors numerically investigated stress and strain fields in thick-walled elements of P91 steel grade and compared them with German boilers regulations. In many cases, the said characteristics depart considerably from the actual pressure and temperature changes under unsteady service conditions of such installations. Due to the higher degree of uncertainty in the designing process and the possibility that more serious threats to the operational safety of power units working under increased service parameters may occur, traditional methods of strength analysis may prove insufficiently accurate in certain specific cases, particularly when new materials are introduced into service. The currently applicable standards for the design of pressure equipment do not fully take account of this complex issue. What seems vital now is to determine to what degree a change in the operating conditions for new materials used in the power industry in components working under conditions of increased service parameters will affect their strength and service life. In this respect, one should bear in mind their fatigue properties determined under conditions like those of the service process, including the characteristics of strain and durability in the processes of low-cycle fatigue and thermomechanical fatigue. Particularly important are well-selected and defined boundary conditions which influence the rate of heat transfer. The paper presents a methodology for stress-strain behaviour modelling, which considers the influence of heat transfer in components of steam pipelines on the local stress and strain fields.

The issue addressed in this study is the development of an accurate method of description of the time-variable temperatures which influence the thermal stress fields in selected components. However, the main attention has been paid to the influence of the boundary conditions on the temperature fields in models of the components. These conditions strongly influence the accuracy of the modelling of transient temperature fields.

2 Assumptions of modelling

The problem outlined above has been analysed in two steps including transient numerical simulations of heat transfer from steam to a metal thick-walled element followed by an export of its transient temperature field to a static analysis of thermomechanical loading. The second step uses time-temperature and pressure history of the nickel-based alloy component for calculations of stress to determine final stress-strain fields during a several hour start-up and a period of stable operation. A Y-junction made of HR6W alloy has been used in the test discussed below. The mechanical and thermal loadings have been assumed at values close to those predicted for high efficiency boilers. The geometrical features of the Y-junction in question are shown in Fig. 1. The model shown in Fig. 1 contains the Y-junction and straight parts of pipes which are connected with this component. Taking into account the symmetry of the element, only a quarter of the analysed component of the pipeline has been considered.

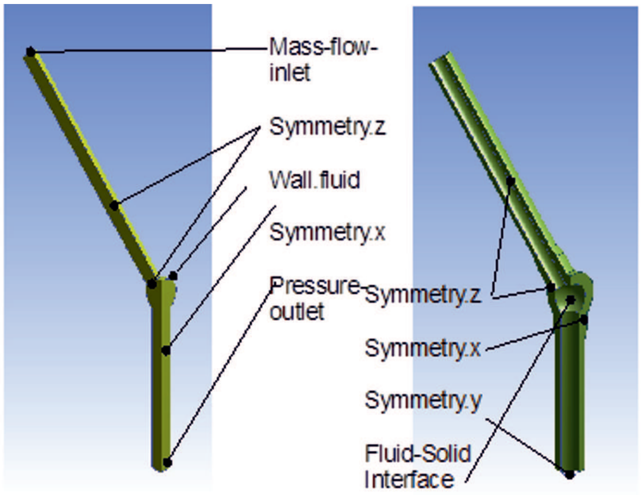


Figure 1: Model of Y-junction tubing split into a fluid (left), a solid (right), along with boundary zones for a fluid (finite volume method approach) and solid (transient thermal and static structural, finite element method approach) analysis.

2.1 Outline of thermal boundary conditions

The test began with a transient simulation of heat transfer from steam to metal tube with the boiler start-up described by steam temperature changes, as well as pressure and mass flow rate. It was assumed that temperature increase is exponential from the initial value of around 100 to 610 °C. As it is assumed that the steam is always superheated, the pressure growth was set to fulfil this, and it rises linearly from around 0 to 31.5 MPa (positive pressure) (Fig. 2). Steam properties such as density, heat capacity, thermal conductivity and dynamic viscosity have been determined on the basis of literature data [8]. The lacking parameter of steam mass flow rate was assumed to ensure no rapid change of its velocity accompanying the density changes. The operational mass flow rate was assumed at 2450 t/h, as for a 900 MW class boiler. Figure 2 shows how density and mass flow rate of steam change in function of operation time. Table 1 presents the assumed steam properties.

Table 1: Assumed in numerical modelling properties of steam.

Temperature	Density	Heat capacity	Thermal conductivity	Dynamic viscosity $\times 10^5$	Pressure
°C	kg/m^3	kJ/kgK	W/mK	kg/m	MPa
100	12.5	2.1	0.02	1.2	0.1
377	14.6	2.4	0.05	1.5	4.0
503	24.1	2.5	0.07	2.9	8.0
561	33.8	2.6	0.08	3.2	12.0
588	44.2	2.7	0.10	3.3	16.0
610	91.2	3.2	0.10	3.5	31.5

Coupled calculations have been done. Both fluid (steam) and solid (thick-walled Y-junction of HR6W alloy) were numerically analysed during their transient heating. Apart from the mentioned properties and parameters of steam, the lacking boundary condition on the outer surface of the tube was described as free convection with the ambient temperature of 40 °C and a heat transfer coefficient of 1 W/m^{2}K. Apart from the physical properties of steam, the thermal ones of HR6W nickel alloy were assumed in function of temperature. The data have been taken from research described in [9].

2.2 Outline of mechanical boundary conditions

As this paper focuses on the heat flow and stress-strain behaviour during thermomechanical fatigue of thick-walled boiler elements, the major loading comes from the temperature gradients. However, it is accompanied by pressure of steam. Its time profile is shown in Fig. 2 along with the temperature of steam flowing inside the pipeline. Restrictions on displacements perpendicular to the symmetry planes have been assumed. The same restriction on displacements has been assumed on the cross-section perpendicular to the vertical part of the pipeline – located at the end of the considered part.

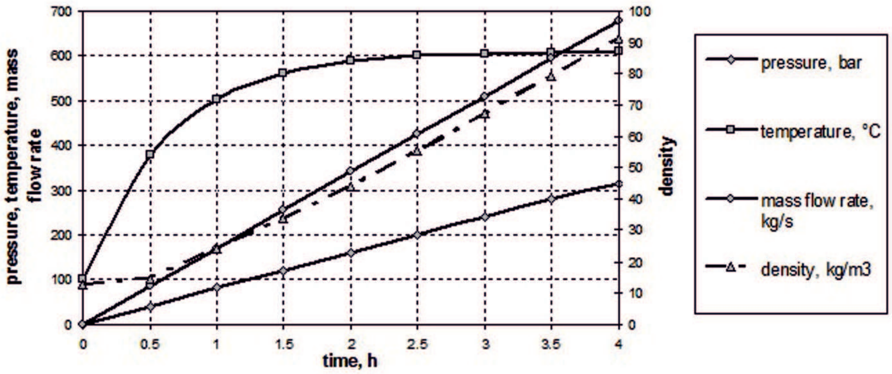


Figure 2: Pressure, temperature, density and mass flow rate of steam in function of boiler operation time.

3 Results

First, an attempt to calculate the range of heat transfer coefficient changes was made. Commercial general-purpose computational fluid dynamics software package Fluent (code uses the finite-volume method) [10] has been used in the present study. A simulation included a geometry-definition in the form of a thick-wall pipe. Fluid flow through the modelled Y junction was analysed to show the facet minimum, maximum and the area-weighted average of heat transfer coefficient from steam to the solid material of the wall. Average thermodynamics parameters of steam were reported as well. Overall results are shown in Tab. 2. The heat transfer through the solid wall has been simplified by software to a one-dimensional heat conduction with the following values: wall thickness of 0.127 m, density of 7840 kg/m^3, thermal conductivity of 19 W/mK, and heat capacity of 550 J/kgK. Outside the wall natural convection was described by the ambient temperature of 40 °C and the heat transfer coefficient of 1 W/m^{2}K. Some relationships have been presented in Fig. 3. Especially interesting is how an average of heat transfer coefficient changes during the time of the boiler operation. The assessment of the dependency of the heat transfer coefficient on steam parameters and time is very important in the process of thermal stress calculations during the design of power plant components operated under mechanical and thermal loading. In standards used by designers [1] the proposed value of this coefficient is constant for steam and water. The values calculated in this study considerably differ from those specified in the standard [1] at the value of 1000 W/m^{2}K. The differences are both global and local. This factor strongly influences the accuracy of the stress strain fields assessment and will determine the accuracy of the assessment of the strength and durability of the designed components. The results shown in Tab. 2 are largely qualitative, however, they clearly demonstrate that the values of heat transfer coefficient in conditions close to those occurring in actual operation strongly differ from those assumed by designers. In Fig. 3 charts present some results of Tab. 2. The assessment of the influence of this coefficient on temperature, stress and strain fields requires a more detailed analysis that takes into consideration an accurate description of the component's geometry.

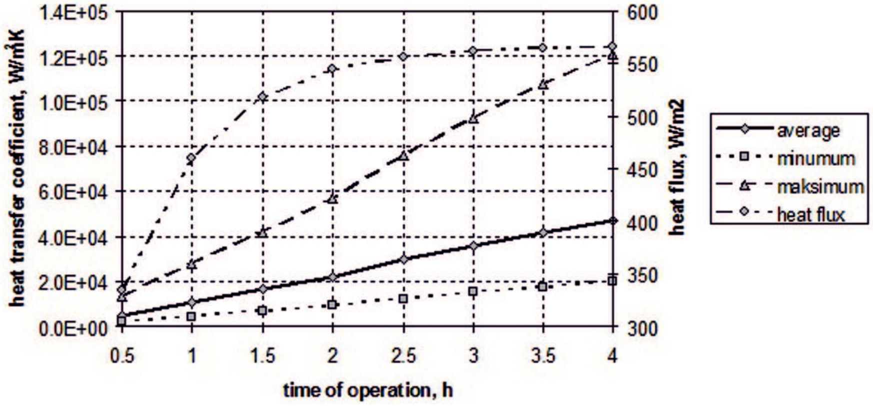


Figure 3: A range of heat transfer coefficient and heat flux from steam to Y-junction calculated for a simulated 4-hour start-up of a boiler with a simplified method.

The step followed the assessment of the influence of fluid flow parameters on the heat transfer coefficient was the analysis of the global and local values of this coefficient on the temperature, stress and strain fields. This time it was a computational fluid dynamics (CFD) analysis as well, but the solid tubing was considered with its real geometry and material properties in function of temperature (without the simplifications mentioned for the previous step). Considering the characteristics shown in Fig. 2 the fluid flow characteristics and temperature distributions in the component have been described as time dependent. The transient heat transfer coefficient has been calculated for the points located on the inner surface of the Y-junction (Fig. 4a). The obtained distributions of the value of heat transfer coefficient enabled a more precise evaluation of the temperature field. Finally, coupled simulations were done. CFD software provided a simulation of a heat flow from steam to the tube wall, while the transient thermal of finite element method (FEM) software (commercial code based on FEM Ansys) [11] sent back the wall temperature. This way the start-up period of the boiler was simulated.

Table 2: Heat transfer parameters calculated for a 4-hour start-up period.

Time	Fluid to solid transfer				Volume (fluid) inside the Y-junction domain				
	Heat transfer coefficient, average/min/max			Heat flux	Temperature	Density	Heat capacity	Thermal conductivity	Velocity
h	W/m^2K			W/m^2	°C	kg/m^3	kJ/kgK	W/mK	m/s
0.5	5136	2218	13352	335	377	14.6	2.42	0.005	79
1.0	10736	4532	27914	460	503	24.1	2.42	0.007	96
1.5	16538	6958	41882	518	561	33.9	2.57	0.008	103
2.0	21997	9250	56578	544	588	44.1	2.57	0.009	105
2.5	29485	12432	75938	556	602	70.6	2.92	0.096	82
3.0	36060	15217	92798	562	605	83.0	3.08	0.098	84
3.5	41792	17738	107473	564	608	88.7	3.16	0.100	92
4.0	47102	20094	120986	565	609	91.2	3.19	0.100	102

Eventually, the temperature field of the solid was imported to a static structural analysis of FEM software where along with pressure loading stress and strain fields were calculated for the selected characteristics of the start-up period of operation. Figure 5 shows a comparison of temperature fields on the inner surfaces of the Y-junction calculated for transient heat transfer and constant heat transfer coefficients. The patterns shown in Fig. 5 have been calculated for the same instant of time. The maps reveal differences in temperature fields which result from the application of different methods in these calculations. The nonuniform field of the temperature causes thermal deformation, which at restrictions of internal movement leads to thermal stress. So the stress and strain fields will be different when they are calculated for constant or varying with time heat transfer coefficients.

Sample results of the stress and strain analysis are shown in Fig. 6. The characteristics presented in this figure represent the stress-strain curves calculated for x-components of stress and strain at points A and B located on

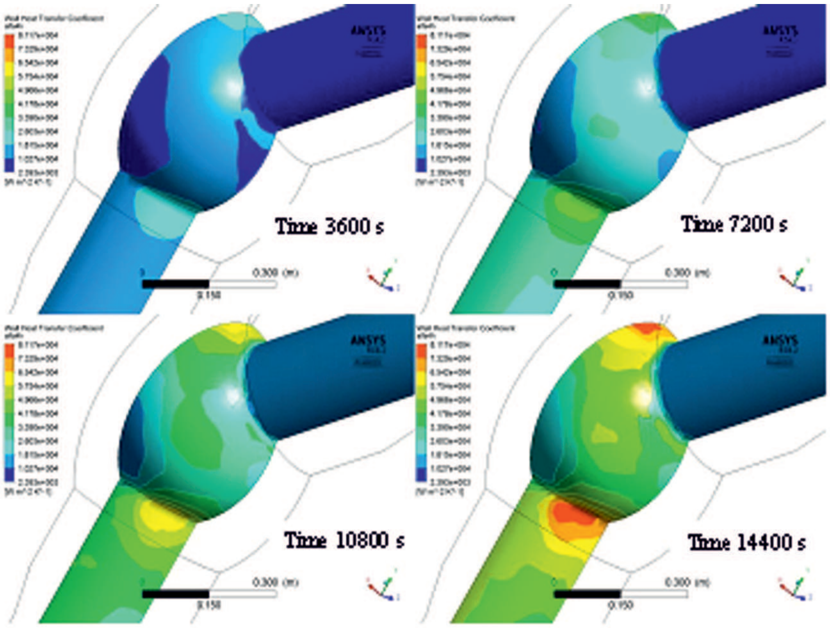
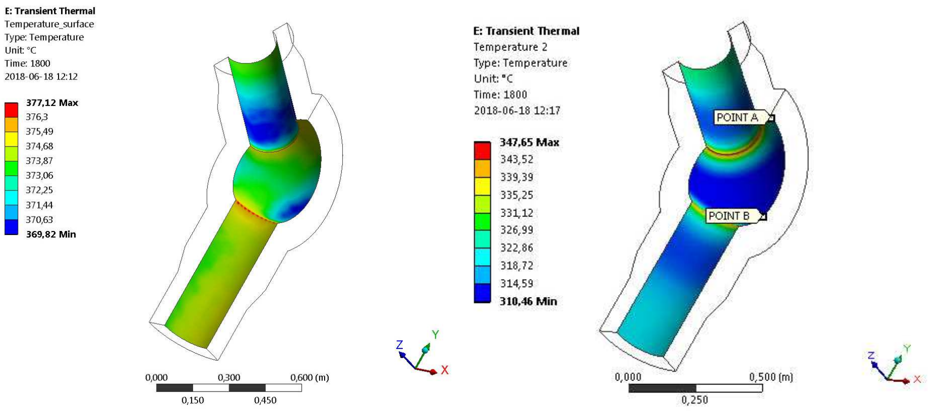
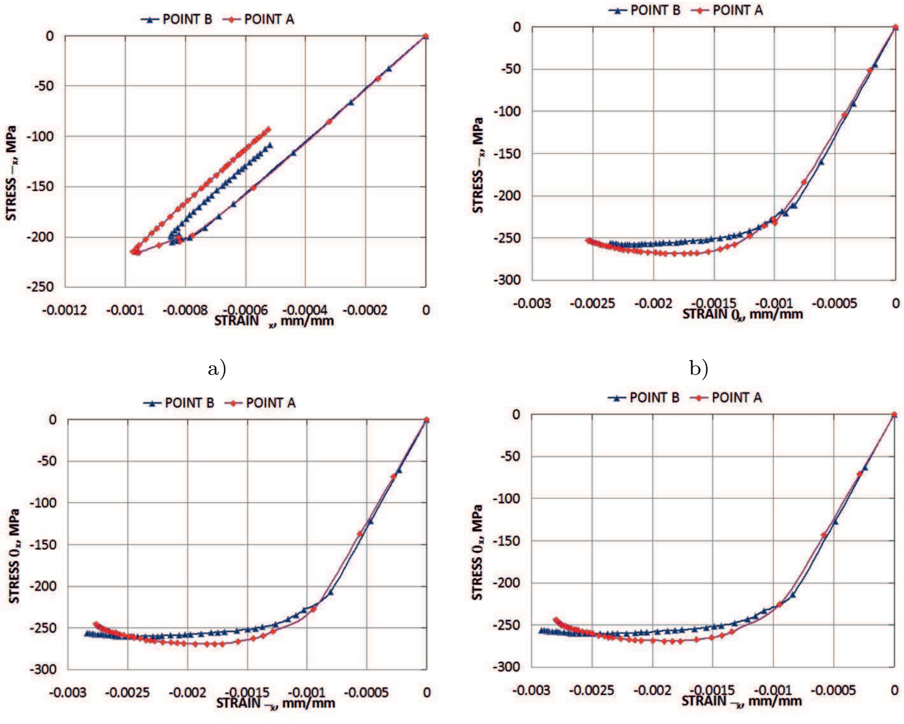


Figure 4: Heat transfer coefficient distributions on the inner surface of the Y-junction for the chosen instant of time calculated for the pipeline under consideration.



a) b)

Figure 5: Temperature distributions in the Y-junction 0.5 h after the start-up calculated for changeable (in time and on inner surface) heat transfer coefficient (a) and for constant coefficient of 1000 W/m^{2}K (b).



a) b)

c) d)

Figure 6: Stress-strain curves calculated for A and B points of the Y-junction in the period of 0.5 h of start-up period of time calculated for changeable (in time and on inner surface) heat transfer coefficient (a), constant coefficient of 1 kW/m^{2}K (b) constant coefficient of 5 kW/m^{2}K (c), constant coefficient of 10 kW/m^{2}K (d).

the inner surface of the Y-junction. From the analysis of the characteristics shown in Figs. 6a and 6b it is evident that the value of the heat transfer coefficient significantly influences the stress state close to the inner surface of the component. The influence of the distribution of heat transfer coefficient on the stress and strain fields in the areas of the most intensive damage accumulation, which could probably be not the same as the areas of the most intensive heat transfer, will be the objective of a following study. Figure 6 reveals the difference in the material behaviour at points A and B. The characteristics shown in this figure have been obtained for the first part of the plant operation cycle, i.e. the start-up. The stress-strain curves worked out for these points show that the different characters of the temperature fields calculated for transient and constant values of the heat transfer coefficient has an essential influence on the local mechanical behaviour of the material. The charts show that the chosen range of constant heat transfer coefficient influences stress-strain relation for the studied points regarding the final strain values. The reasons for a difference between these cases and the one with varying as well as why local heat transfer coefficients is significant regarding range of stress and strain will be studied in detail in the future.

4 Discussion

The results obtained in this simulation made it possible to compare the intensity of the impact of different factors on parameters responsible for fatigue processes, which could occur in components of modern power plants operating under mechanical and thermal loadings. The methodical approach designed for this analysis can be used in future research of this kind.

The results of modelling show that the conditions of the fluid flow strongly affect the temperature field in the analysed components. As a consequence, the stress and strain fields will depend on the fluid flow parameters. A constant value of the heat transfer coefficient in design procedures for components under mechanical and thermal loading – as defined by the standard [1] – seems to be too rough approximation. Changing the operating parameters of materials intended for operation in power units with increased service parameters requires far more attention to be paid to the possibility of the activation of fatigue processes in the components made of these materials. The foregoing outcome stems from several reasons, such as different physical properties of new materials, including those connected with the heat transfer process, and in certain cases, from the different thermal expansion of those materials compared to the conventional ones. In this respect, it should be noted that precision in establishing the thermal fields responsible for the magnitude of thermal stresses depends to a considerable extent on the boundary conditions assumed for calculations, and particularly on the heat transfer coefficient. In computer modelling this coefficient should be considered as a quantity variable in time and changeable at the interface between the solid and the fluid and dependent on the parameters and the state of the medium flowing through individual elements of the system.

Stress-strain curves in Fig. 6 show the effects of plastic strains at points A and B accumulated during the start-up period. The repeated start-ups could lead to damage accumulation at these points as a result of the fatigue process induced by cyclic thermal strains and stresses. Such a process is called the thermomechanical fatigue [12–15]. This kind of fatigue requires special methods of behaviour analysis of components under mechanical and thermal loadings and special methods of material testing which simulate the local material behaviour. This analysis concentrates on one of the problems encountered in the description of the behaviour of components, which should be solved for the elaboration of a reliable method for component fatigue life assessment.

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