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# STRESS ANALYSIS FOR THE START-UP OPERATION ON THE EXAMPLE OF OP-210 BOILER DRUM

**Key words**

Boiler start-up, stress state, Finite Element Method.

**Abstract**

The calculations of stresses acting on the wall of a boiler drum during the start-up process are presented in this paper. Based on the temperature measurements, which were carried out to determine the temperature distribution along the circumference of the outer wall of boiler drum, the temperature at the inner wall surface is determined using the inverse methods. The computations are carried out for the whole operation cycle of the power plant. Therefore, the pressure and temperatures are updated at consecutive time steps. These parameters allow determining the maximum values of circumferential, axial and Von Misses stresses during the operation cycle of steam boiler.

## Introduction

High thermal stresses, which occur during the operation cycle of power unit components such as boiler drums, water separators, outlet headers, steam valves, turbines and heat exchangers [1, 2], can cause the damage of these devices. The loads acting on these components of power units are cyclic; thus, a phenomenon of low-cyclic fatigue occurs, which may lead to the premature wear of pressure components. The allowable limits of maximum heating and cooling rates are prescribed by the manufacturers of pressure components. However, the recommended allowable rates [3, 4] should be treated as estimated values, because they were obtained under the assumption that the quasi-steady state of temperature exists inside a pressure element during the heating and cooling of an element. Moreover, it is assumed that the rate of fluid temperature variation is constant. Such idealistic cases are not observed in practice, because the pattern of temperature changes is strongly irregular. Therefore, attempts are made to develop algorithms for operating power units, which allow determining the temperature field and stresses inside the pressure component. Thanks to these mathematical systems, coupled with the Finite Element Method (FEM) Packages, one can supervise the stress state inside the pressure components of the power plant.

The major problem that is encountered when calculating the temperature and stress distribution in monitored pressure components is a difficulty in determining the thermal boundary conditions. Due to the different thermal properties and phases of fluids flowing inside the power plant components, it is difficult to estimate the boundary condition, which occurs at an inner wall of pressure component. In order to define this condition, one needs to determine the heat transfer coefficient and the free-stream temperature of fluid. The values of these two quantities change in both space and time, thus they are difficult to measure. One way to determine them is to solve the inverse heat conduction problem in monitored components, which was widely described in the literature [5–9]. Inverse methods enable one to determine the entire temporal and spatial distribution of the unknown quantity (temperature, stress) in an element, based on measured temperature histories at selected spatial points. One of the advantages of this numerical method is that it allows finding the grid-point solution even when some thermal boundary conditions are unknown. The practical application of the inverse methods for thermal stress monitoring in the pressure components of large steam boilers is presented in literature [10, 11]. These methods are also used in the present work to obtain the spatial and temporal temperature distribution inside the cross section of boiler drum.

## 1. Operating conditions for boiler drum

The cross-section of boiler drum model is presented in Figure 1a. The tube has an inner radius of $r_i$ = 0.85 m and an outer radius of $r_o$ = 0.94 m. A discrete model of the drum, used for FEM analysis is presented in Figure 1b. The outer surface of the drum is insulated to minimize the heat loses to surroundings. Based on heat transfer physics, the symmetrical temperature field is assumed in the drum cross-section; therefore, only half of tube is necessary to be equipped with thermocouples NiCr-NiAl (K-type). The thermocouples are located with angular pitch $\Delta\varphi = 30°$.

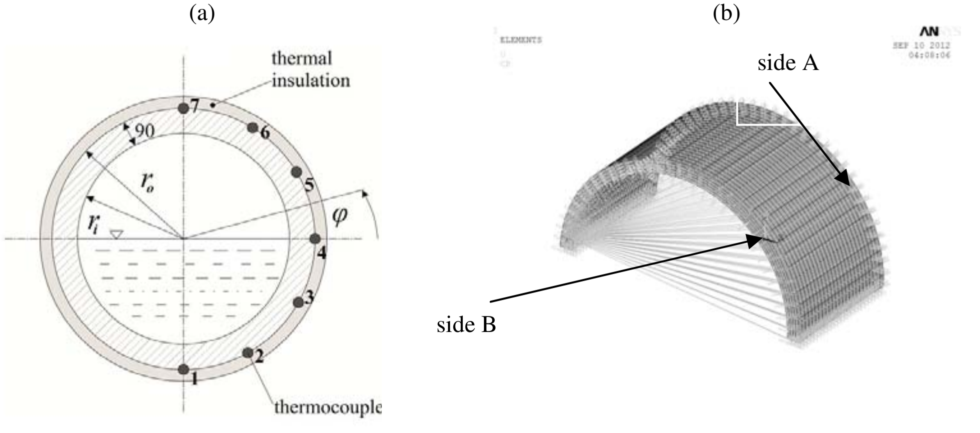


Fig. 1. (a) Scheme of the analysed cross section of the boiler drum, (b) discrete FEM model of boiler drum

The OP-210 boiler drum is made of steel 15Mo3 (DIN), which has the properties listed in Table 1.

Table 1. Material properties for 15Mo3 (DIN)

| Property | Symbol, Unit | Value |
|---|---|---|
| **Specific heat capacity** | $c$, J/(kg·K) | 445 |
| **Density** | $\rho$, kg/m$^3$ | 7860 |
| **Thermal conductivity** | $k$, W/(m·K) | 45 |
| **Young's modulus** | $E$, MPa | $2.1\cdot10^5$ |
| **Poison’s ratio** | $v$, - | 0.29 |
| **Thermal expansion coefficient** | $\beta$, 1/K | $1.25\cdot10^{-5}$ |

The temperature field across the drum length may be assumed as two-dimensional. Therefore, only the cross-section of the drums tube is considered. Furthermore, the symmetry boundary conditions are assumed; therefore, only half of the cross-section is used in the thermal calculation procedure [10, 12]. On the other hand, the stress state must be modelled as a three-dimensional case, because of the large wall thickness of pressure component. Hence, the radial, the tangential, and the axial components of stress tensor exist.

As aforementioned, the drum is subjected to the thermal loads, which change magnitude with time and space. Furthermore, the pressure load $p_{in}$ acting on the inner surface of drum wall is time-dependent. The symmetry boundary conditions assumed in the FEM model allows considering only half of the drum. In order to avoid the rigid body motion, the one side of the boiler drum is constrained as presented in Figure 1b (see side A). The nodes, which are adjacent to this side, are constrained in an axial direction; moreover, one node on this side is constrained in the radial direction. The coupling equations are prescribed for the nodes located on Side B of boiler drum to ensure plane cross-sections after deformation. Only the sector of the tube is analysed; therefore, the loading from the remaining parts must be considered. This is done using the value of the equivalent pressure given by Equation 1.

$$p_e = p_o \cdot \frac{r_i^2}{(r_o^2 - r_i^2)} \tag{1}$$

The value of $p_e$ is taken as the pressure load acting on the sides A and B of boiler drum. The time history of operating pressure $p_o$, which is acting on the inner surface of drum wall, is shown in Figure 2a. These measurements were conducted for the drum of power unit OP-210.

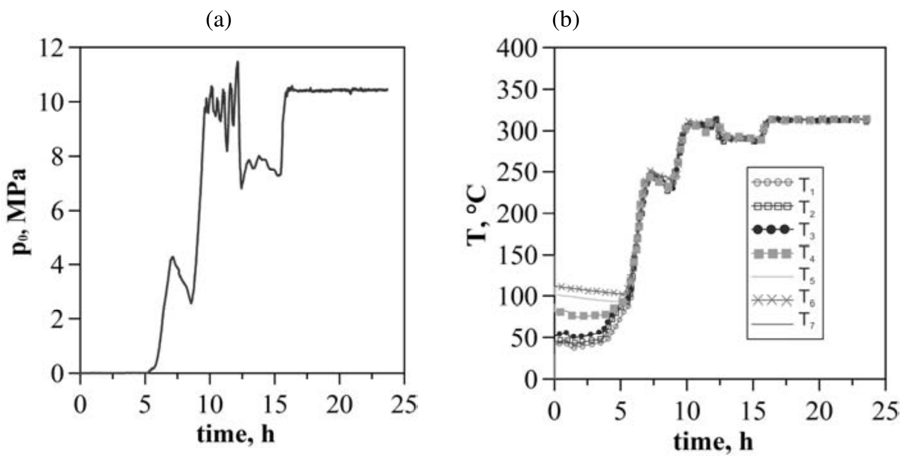


Fig. 2. Measurement history of (a) operating pressure $p_0$ and (b) temperatures at $r = r_o$

The temperature distribution obtained at the outer surface of drum wall ($r = r_o$) is presented in Figure 2b. The thermocouples $T_1$-$T_7$ (see Fig. 1) allow measuring the temperatures at different angular coordinates. During the analysed cycle (see Fig. 2b), the temperature increases at first to achieve maximum value then it slightly decreases, and finally it is adjusted to the operating temperature, $T_{op}$ = 312ºC. A similar cycle was performed for the operating pressure. This operating cycle was carried out for testing the combustion process for different kinds of biomass fuels.

In Figure 2b, one can notice that the temperature differences along the circumferential direction are up to 70ºC. This is clearly observed at the beginning of presented cycle, when evaporation begins. This measurement history is used as the input for the inverse heat conduction procedure described in [10] to determine the nodal temperatures inside the heat transfer domain. The transient temperature profiles for angular coordinates corresponding to $T_1$-$T_7$, evaluated using this method at $r = r_i$ and are shown in Figure 3.

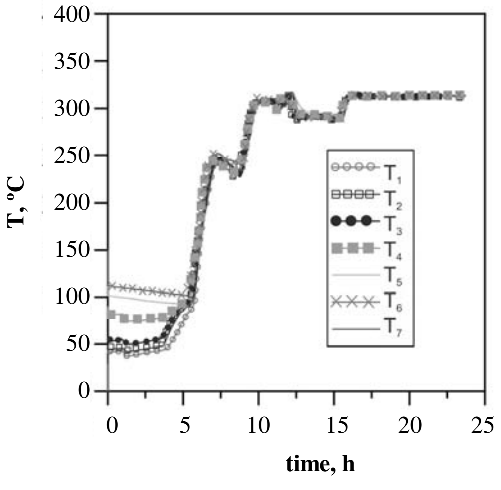


Fig. 3. The temperatures obtained from solving inverse heat conduction problem [10] at inner surface of the boiler drum for $r = r_i$

Comparing Figures 2a and 3, one can notice that the differences between temperatures evaluated at $r = r_\mathrm{i}$ and $r = r_\mathrm{o}$ are slight. That can be explained by the large value of the heat transfer coefficient associated with the fluid flowing inside the tube. If the thermal insulation works fine, then the heat is quickly transferred from inner to the outer surface of the tube, and the temperatures are nearly equal in the radial direction. However, due to the different flow patterns (condensation, evaporation processes) on the circumference of the tube, the differences in temperature along the circumference may be large and can cause a significant increase in thermal stresses. We can observe this for time $\tau = 0 – 5$ h at the beginning of the operating cycle.

## 2. Stress monitoring during the operation of boiler drum

In the previous subsection, the pressure and temperature distributions on the inner wall and the temperature distribution on the outer wall of boiler drum were presented. The operating pressures (see Fig. 2a) and temperatures (see Fig. 2b and Fig. 3) are assumed as the loads in the structural analysis, which allows determining the stresses inside the pressure component. The Finite Element Method, which is the widely used as a tool for the structural analysis, allows evaluating the vector of nodal displacements $\{\boldsymbol{u}\}$ according to the following equation:

$$[\mathbf{K}_e]\cdot\{\boldsymbol{u}\}-\{\boldsymbol{F}_e^{th}\}=\{\boldsymbol{F}_e^{pr}\} \tag{2}$$

The element stiffness matrix $[\mathbf{K}_e]$ is obtained from the following formula:

$$[\mathbf{K}_e]=\int_V[\mathbf{B}]^T\cdot[\mathbf{D}]\cdot[\mathbf{B}]dV \tag{3}$$

where $[\mathbf{B}]$ is the strain displacement matrix evaluated based on the element shape functions matrix [N]. The elasticity matrix is denoted as $[\mathbf{D}]$ and $V$ relates to the volume of finite element. The thermal load vector $\{\boldsymbol{F}_e^{th}\}$ is calculated as

$$\{\boldsymbol{F}_e^{th}\}=\int_V[\mathbf{B}]^T\cdot[\mathbf{D}]\cdot\{\varepsilon_{th}\}dV \tag{4}$$

The vector of thermal strains $\{\boldsymbol{\varepsilon}_{\mathrm{th}}\}$ is given by

$$\{\boldsymbol{\varepsilon}_e^{th}\}=\beta\cdot\left(\{\boldsymbol{T}\}-T_{ref}\right) \tag{5}$$

The vector of nodal temperatures $\{\boldsymbol{T}\}$ is obtained solving the inverse heat conduction problem. The ambient temperature $T_{ref}$ is assumed to equal 22°C. The vector of pressure loads $\{\boldsymbol{F}_e^{pr}\}$ is given by

$$\{\boldsymbol{F}_e^{pr}\}=\int_A[\mathbf{N}_n]^T\cdot\{\boldsymbol{p}\}dA \tag{6}$$

where $[\mathbf{N}_n]$ is the matrix of shape functions for normal motions at the surface, and $\{\boldsymbol{p}\}$ is the nodal pressure vector, and $A$ is the area of finite element's face.

If nodal displacements are known, then the element strain vector can be determined according to

$$\{\boldsymbol{\varepsilon}_e\}=\left[\varepsilon_r,\ \varepsilon_\varphi,\ \varepsilon_z,\ \gamma_{r\varphi},\ \gamma_{rz},\ \gamma_{\varphi z}\right]^T=[\mathbf{B}]\cdot\{\boldsymbol{u}\} \tag{7}$$

Finally, the components of the element stress vector are obtained from

$$\{\boldsymbol{\sigma}_e\} = \left[\sigma_r,\ \sigma_\varphi,\ \sigma_z,\ \tau_{r\varphi},\ \tau_{rz},\ \tau_{\varphi z}\right]^T = [\mathbf{D}]\cdot\{\boldsymbol{\varepsilon}\} \tag{8}$$

For the given thermal and pressure loadings, the computational procedure given by Equations 2 through 8 is carried out using a commercial FEM package – ANSYS Structural. To model the three dimensional stress distributions inside the boiler drum tube, the 8-node structural solid element – SOLID 185 is used. For each time step, the maximum value of Von Misses stress is determined as follows for the whole FEM model is calculated:

$$\{\sigma_{vm}\} = \left(1/\sqrt{2}\right)\cdot\sqrt{\left(\sigma_r-\sigma_\varphi\right)^2+\left(\sigma_\varphi-\sigma_z\right)^2+\left(\sigma_z-\sigma_r\right)^2+6\cdot\left(\tau_{r\varphi}^2+\tau_{rz}^2+\tau_{\varphi z}^2\right)} \tag{9}$$

Moreover, the maximum values of radial, circumferential, and axial values of the stress tensor are determined. The results are presented in Figure 4.

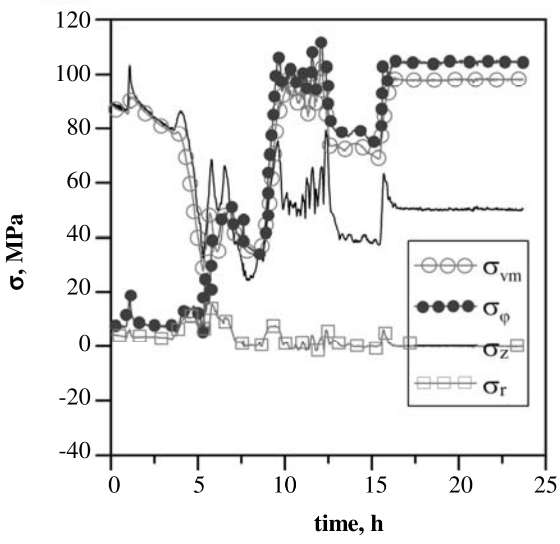


Fig. 4. The maximum stress value as a function of time for the operation cycle of boiler drum

The quasi steady state is obtained for time $\tau_q = 10$ h. If time τ is larger than $\tau_q$ then the circumferential component of normal stress $\sigma_\varphi$ is two times larger than the axial component of normal stress $\sigma_z$. The radial component of stress has the lowest value from all. The maximum stresses occur when the operating pressure and the temperature inside the boiler drum are the largest. The stresses occurring during the operation of the boiler drum are significantly lower than the yield strength of material. The thermal loading, Von Misses stress, and the axial and the circumferential components of stress tensor are presented in

Figures 5 and 6 for the time step when the nodal temperatures and operating pressure are the largest.

(a) (b)

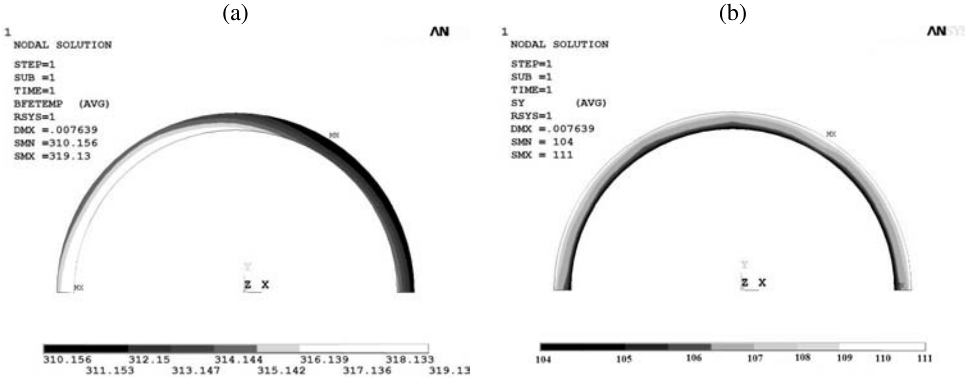


Fig. 5. The temperature (a) and the circumferential normal stress (b) distribution, for the time when the largest temperature and pressure loading occurs

The temperature map shows that the temperature differences variations are low, and do not exceed 9°C. Therefore, the influence of thermal loading on the value of Von Misses stresses is not significant. The maximum value of the circumferential component of normal stress $\sigma_{\varphi}$ is obtained at the outer wall of the tube (see Fig. 5b). Similarly, the maximum value of $\sigma_{\mathrm{a}}$ is obtained at the outer wall of tube (see Fig. 6b). The largest value of Von Misses stress is calculated at the inner surface of boiler drum.

(a) (b)

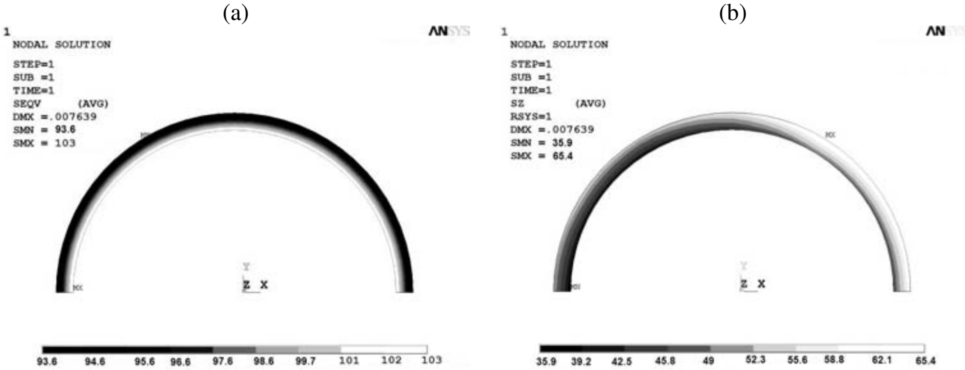


Fig. 6. The map of (a) Von Misses stress – $\sigma_{vm}$ and (b) axial component of normal stress – $\sigma_a$ for the time when the largest temperature and pressure loading occurs

**Summary**

The paper demonstrates a method of monitoring the stress state for a boiler drum. This method can be extended for other pressure components of the power plant. Knowing the temperature distribution along the circumference of the outer wall is sufficient to solve the inverse heat conduction problem and determine the temperature distribution inside the drum's cross section. If the temperature and pressure fields are given, then it is possible to carry out the structural analysis and evaluate the stress level.

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## Analiza pola naprężeń w walczaku kotła OP-210 podczas rozruchu

### Słowa kluczowe

Faza rozruchowa kotła, stan naprężeń, Metoda Elementów Skończonych.

### Streszczenie

W pracy przedstawiono obliczenia naprężeń w przekroju poprzecznym walczaka kotła OP-210 podczas jego rozruchu. Na podstawie pomiarów uzyskano wartości temperatury powierzchni zewnętrznej ścianki walczaka oraz poziom panującego w nim ciśnienia. Na podstawie znanych temperatur na powierzchni zewnętrznej ścianki walczaka rozwiązano zagadnienie odwrotne przewodzenia ciepła i wyznaczono pole temperatury w przekroju poprzecznym. Dla znanych obciążeń termicznych i ciśnieniem wyznaczono stan naprężenia w przekroju poprzecznym walczaka: maksymalne naprężenie zredukowane liczone według hipotezy HMH oraz maksymalne wartości składowych naprężenia: obwodowej, osiowej i promieniowej.