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Determination of temperature and thermal stresses distribution in power boiler elements with use inverse heat conduction method

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Abstract The following paper presents the method for solving one-dimensional inverse boundary heat conduction problems. The method is used to estimate the unknown thermal boundary condition on inner surface of a thick-walled Y-branch. Solution is based on measured temperature transients at two points inside the element's wall thickness. Y-branch is installed in a fresh steam pipeline in a power plant in Poland. Determination of an unknown boundary condition allows for the calculation of transient temperature distribution in the whole element. Next, stresses caused by non-uniform transient temperature distribution and by steam pressure inside a Y-branch are calculated using the finite element method. The proposed algorithm can be used for thermal-strength state monitoring in similar elements, when it is not possible to determine a 3-D thermal boundary condition. The calculated temperature and stress transients can be used for the calculation of element durability. More accurate temperature and stress monitoring will contribute to a substantial decrease of maximal stresses that occur during transient start-up and shut-down processes.

Keywords: Inverse method; Transient temperature; Heat transfer coefficient; Stress distribution

Nomenclature

c – specific heat, J/(kgK)
C – regularization coefficient
E – Young modulus, MPa

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F – additional time steps
f – measured temperature, °C or K
h – heat transfer coefficient, W/m^{2}K
k – thermal conductivity, W/mK
k_2 – number of future steps in elementary time interval
M – number of temperature measurement locations
r – radius, m
r_o – outer radius, m
r_j – coordinate of the temperature measurement point
S – sum being minimized, K^2
t – time, s
T – temperature, °C or K
T_∞ – fluid temperature, °C or K
T_0 – initial temperature, °C or K
w_j – j-th weight coefficient, $w_j \geq 0$

Greek symbols

ρ – density, kg/m^3
Δt – time step, s

1 Introduction

High thermal stresses occur in thick-walled pressure elements of power units during transient operations such as for example start-ups and shut-downs. These stresses limit heating and cooling rates of temperature changes in power block elements.

Many manufactures of power block devices apply indirect thermal stress measurement method, which is based on measured temperature difference between a point located close to the inner surface and a point in the middle of a wall thickness [2,3]. These thermoelements should display the inner surface temperature and average temperature within the wall thickness of an element. Such algorithm has many flaws, such as high temperature measurement errors at inner points caused by a big contact resistance. Due to the fact that there is a considerable distance between the thermoelement and the inner surface, the inner surface temperature measurement is inaccurate, especially during high temperature changes of the medium [9].

This paper presents the method, which solves one-dimensional inverse heat conduction problems. If an inverse one-dimensional heat conduction problem occurs in the element, it is sufficient to only measure temperature at one point, located either inside the element or on the element surface. Proposed method is used for determining unknown heat transfer coefficient on the inner surface of a Y-branch spherical part. This is where the heat conduction is assumed to be one-dimensional. Next, calculated heat transfer coefficient transient is assumed to occur within the whole inner surface of the Y-branch. It is necessary to make this estimation, because it is still not possible to solve a 3-D inverse heat conduction problem in a complex geometry as the Y-branch. Next, finite element method is used to calculate thermal stresses and stresses caused by other loads such as internal pressure. The presented method can be applied to monitoring systems that work in conventional as well as in nuclear power plants.

2 Description of the method

Temperature distribution in a spherical wall is described by the heat conduction equation:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 k\left(T\right)\frac{\partial T}{\partial r}\right] = \rho\left(T\right) c\left(T\right)\frac{\partial T}{\partial t} \,, \tag{1}$$

the boundary condition on the outer surface:

$$\left.\left[k\left(T\right)\frac{\partial T}{\partial r}\right]\right|_{r=r_o} = 0 \tag{2}$$

and the initial condition:

$$T\left(r,0\right) = T_0 \,. \tag{3}$$

The temperature histories are known from the measurements at M locations inside the component:

$$T\left(r,t\right)\left|_{r=r_j}\right. = f_j\left(t\right), \quad \text{for} \quad j = 1,...,M \,. \tag{4}$$

However, the heat transfer coefficient on the inner surface of the body is unknown, and it can depend on time and temperature of the inner surface. In order to determine this coefficient it is necessary to measure the fluid temperature $T_\infty(t)$.

The heat transfer coefficient will be calculated sequentially. In order to eliminate the influence of the random measurement errors, F additional time steps called the future time steps were taken for analysis [1,4-8]. Knowing the temperature distribution in the component wall, the heat transfer coefficient can be calculated using the condition of square sums of calculated and measured temperature deviations in the same points being minimal:

$$S\left[h\left(t_F\right)\right] = \sum_{i=1}^{k_2+F} \sum_{j=1}^{M} w_j \ \left[T(r_j, t_i) - \right.$$
$$\left. - f_j(t_i)\right]^2 + C\left\{\frac{h(t_F) - h[t_F - (k_2+F)\Delta t]}{(k_2+F)\Delta t}\right\}^2 \to \min \ . \qquad (5)$$

The second part of the formula Eq. (4) is a regularization factor of the first order and is the approximation of the square of the first derivative *(dh/dt)*^{2}. In order to determine heat transfer coefficient at which the sum Eq. (4) is minimal, the golden section method was applied. In order to achieve high accuracy of the results, apart from the above mentioned future time steps and regularization, the local polynomial approximation of the measured time histories was applied.

The temperature distribution in the component wall was calculated using the method of lines, accounting for the temperature-dependent thermophysical material properties of the material: c, ρ, k. The wall was divided into twelve control volumes. The temperature changes in 13 nodes are described by the system of 13 ordinary differential equations of the first order, obtained from the Eq. (1) after applying the method of lines. The system of ordinary differential equations was solved using the Runge-Kutta method.

3 Y-branch monitoring

Presented method can be applied in practice to the on-line temperature and stress distribution monitoring in construction elements of power boilers. An analysis of temperature and stress field is presented for the Y-branch during its operation. Its geometry and material properties, as the functions of temperature, are presented in Figs. 1 and 2. Y-branch is insulated on the outer surface, while its inner surface is in contact with steam. Temperature and stress distribution in the whole element depends on steam temperature, steam pressure and the value of heat transfer coefficient. The first two transients are measured, while the third is determined on the basis of temperature measurement points, which were installed throughout the Y-branch wall thickness. The locations of thermocouples are presented in Fig. 1. Point P1 is located 5 mm from the inner surface, while point P2 is installed in the middle of the wall thickness. All measured values are shown

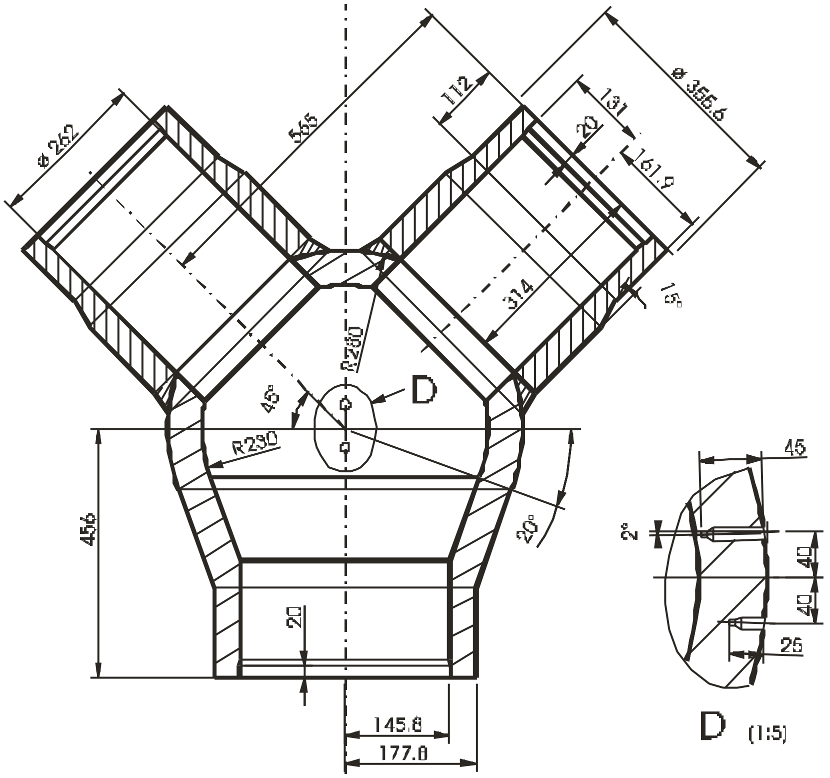


Figure 1. Y-branch geometry.

in Fig. 3. Knowing the heat transfer coefficient, determined by solving the inverse problem, the temperature and heat stress distribution on the Y-branch has been calculated, with the use of the Ansys application. The identified pressure run within the element was also used for the calculations (Fig. 3). Figure 5 shows the division of the Y-branch into finite elements, together with the specification of points, in which the thermocouples have been installed (points P1 and P2). Figures 6a and 6b show the comparison of temperatures measured and those calculated with the use of the ANSYS application in points P1 and P2, respectively. By analysing Fig. 6, one can notice a very high compatibility between the determined and the measured temperatures. Figures 7 and 8 show the calculated temperatures and reduced stresses within this elements, for time $T = 22000$ s.

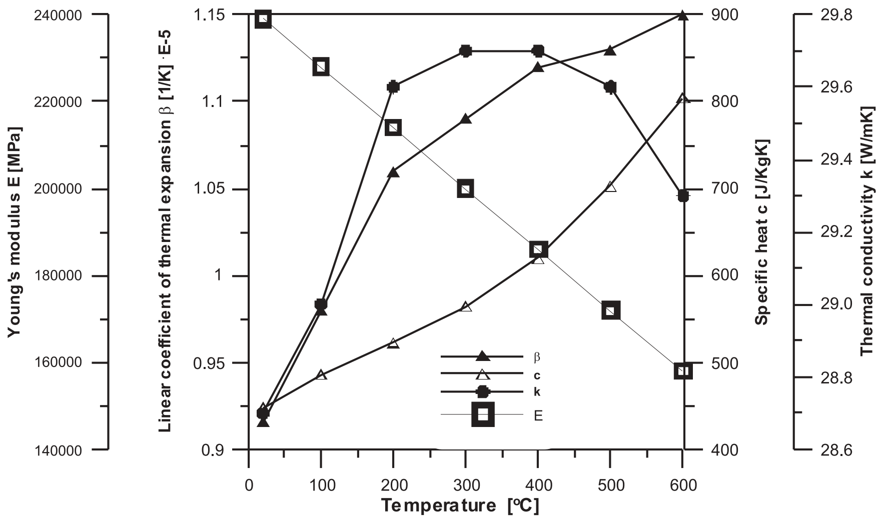


Figure 2. Thermal and mechanical properties of steel P91.

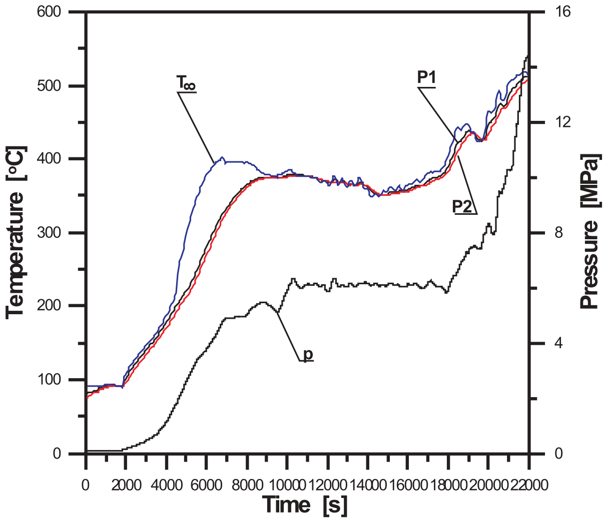


Figure 3. Measured data: steam temperature, temperature at point P1, temperature at point P2 and steam pressure.

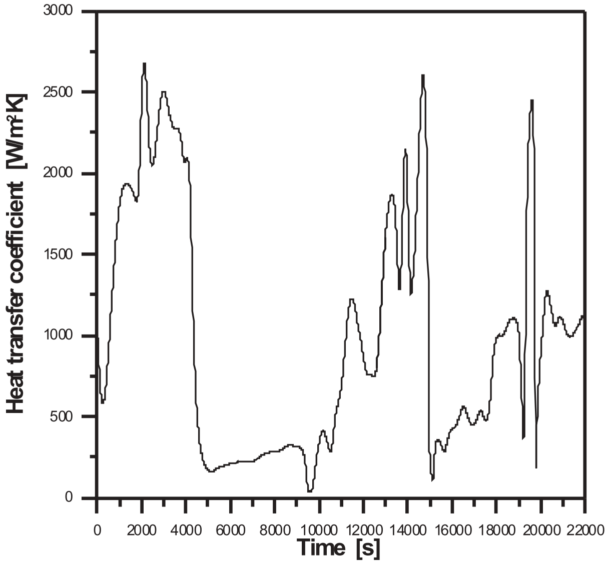


Figure 4. Calculated heat transfer coefficient.

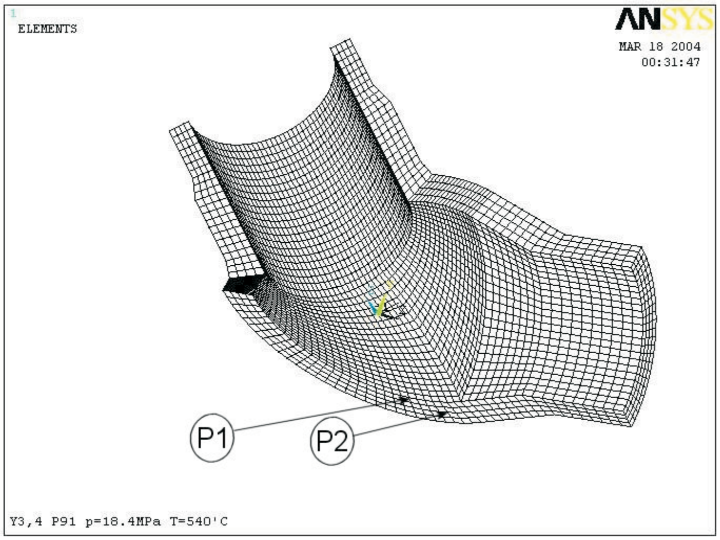
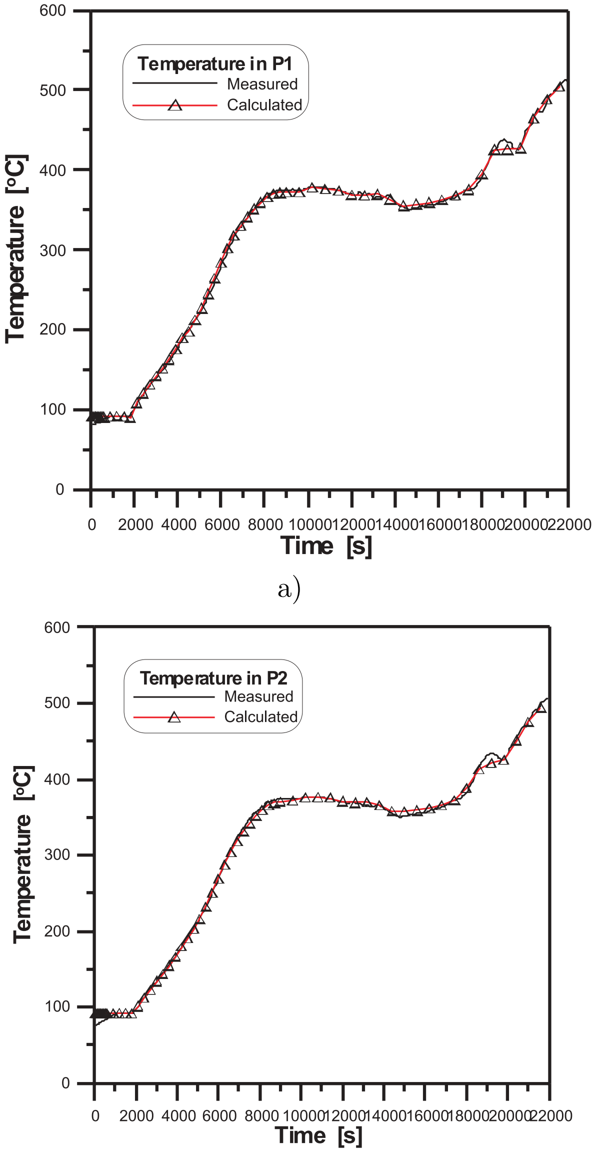


Figure 5. Finite element mesh of Y-branch and chosen points for evaluation of temperature transients.



a)

b)

Figure 6. Comparison temperature transient measured and calculated: a) at point P1 (is located 5 mm from the inner surface), b) at point P2 (is located in the middle of the wall thickness).

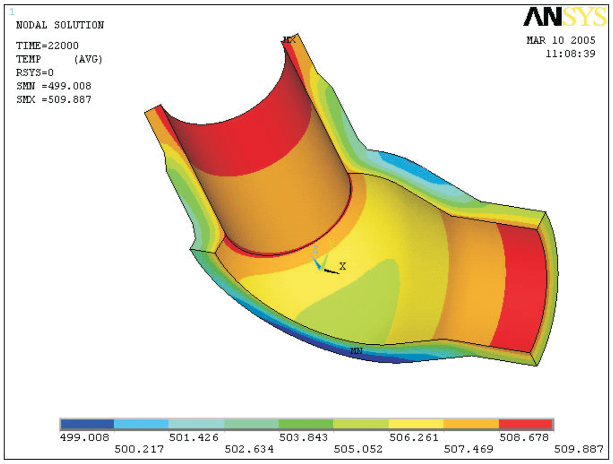


Figure 7. Temperature distribution in °C at time 22000 s.

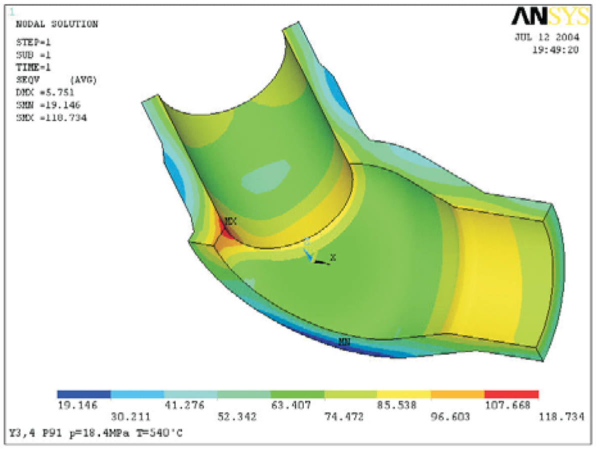


Figure 8. Stress distribution in MPa at time 22000 s.

4 Conclusions

The numerical method of determining the space-time temperature domain distribution within the spherical element, on the basis of measuring temperature in two pints located within the element presented in this paper can be used for both the simple shaped elements and the elements characterised by a complex geometry. The proposed method takes into account the change of the temperature dependant thermophysical properties of the material of the thick walled element. The method allows to solve the over determined inverse problems. It can also be successfully used to determine three-dimensional changes of the heat transfer coefficient in cases, when the number of unknowns equals the number of three-dimensional temperature measurement points.

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