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Inverse estimation of the transient-state stress distribution in the power boiler pressure components

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ABSTRACT

The aim of this work is to present an inverse method of stress estimation in pressure components of power boilers. The proposed algorithm reconstructs the time- and space-dependent temperature, strain and stress distribution in some cross sections of thick-walled cylindrical elements without information concerning the thermal boundary condition on the inner surface. The solution is possible thanks to "measured" temperature histories in easily accessible points located on the component outer surface. In order to stabilize the solution, the data are smoothed out using digital filters based on local polynomial approximation. The material properties of the power boiler elements are assumed as temperature-dependent and the inverse problem is solved iteratively.

The proposed method is verified numerically and experimentally in a steam header located on a laboratory stand in the Cracow University of Technology. The presented method may be used in monitoring systems of both conventional and nuclear power plants.

1. Introduction

The behavior of the power boiler pressure components under different load conditions has been investigated in numerous research projects [1].

A thermal and strength analysis of power engineering equipment, e.g. drums, chambers, valves, turbines or heat exchangers, indicates that high temperature gradients arise in such elements, which creates considerable thermal stresses [2]. Their cyclic character resulting from the cooling and heating of pressure elements in the power unit start-up and shutdown processes causes the low-cycle fatigue phenomenon that may lead to cracks. If the element heating/cooling rates are too high, a shortening of the lifetime of pressure elements needs to be taken into account. The highest risk is posed to the component internal areas that are in direct contact with the fluid characterized by high temperature and pressure. The crack then usually appears on the internal surfaces in stress concentration zones. The use of monitoring systems has a significant impact on remnant life predictions, highlighting hot zones in the boiler and the influence of modified operations on safe extension of the plant life [3].

Power equipment manufacturers usually recommend that set maximum heating and cooling rates of elements should not exceed permissible values so that the values of thermal stresses can be minimized. Still, the recommended allowable rates [4] should be considered as indicative only because they were established assuming a quasi-steady state of the temperature field that arises in a pressure element as it is heated and cooled at a constant rate. Considering substantial time-dependent changes in basic parameters, such as the fluid pressure and temperature or the working medium mass flow, the quasi-steady state is very seldom in practice.

The control system quality is dependent on the accuracy of the measurement of stresses in selected elements of the power unit. A direct measurement of thermal stresses by means of strain gauges is most often impossible and for this reason they are determined using an indirect method – by measuring temperature. In many power units thermal stresses are found based on temperature measurements in the center of the wall thickness and close to the inner surface [5]. It is assumed that the thermal stress is directly proportional to the measured temperature difference. However, this stress control method is very inaccurate and in many cases – totally wrong. A satisfactory stress assessment is only achieved in cylindrical and flat elements if the transient-state temperature field is one-dimensional along the wall thickness, which is very seldom the case. Unfortunately, in this situation too, this manner is inaccurate [6], which results from the adopted assumption that the internal surface temperature is in fact often the temperature value measured 5–10 mm from the internal surface. The temperature measured in the center of the wall thickness is not the wall average temperature, either. This happens only if the temperature distribution along the wall thickness is linear, which again is very seldom.

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The monitoring system should calculate the transient-state temperature and stress distribution in a selected component. Once all boundary conditions are specified, the problem may be solved for both homogeneous and non-homogeneous materials [7].

In the case of the power unit elements, an unknown boundary condition usually occurs on the internal surface of components which are in contact with the fluid. In order to define this convection boundary condition, it is necessary to determine the heat transfer coefficient and the temperature of the fluid in the boundary layer close to the element internal surface. The measurement of the two quantities is very difficult because they vary not only over time but also in space. However, they can be calculated analyzing the phenomena that take place in the flowing fluid numerically, using the balance finite difference or Finite Element Method [8,9]. The whole area where the fluid is contained has to be discretized. Then the mass, momentum and energy balance equations have to be written. Depending on the flow nature, it may also be necessary to introduce a suitable turbulence model. The calculations are more difficult in the case of two-phase flows that involve boiling or condensation processes.

Another way to determine the distribution of temperatures and stresses is finding a solution to the inverse problem of heat conduction in the device under analysis. Inverse methods allow determination of the entire time- and space-dependent temperature distribution in an element based on measured temperature histories in selected spatial points [10,11]. The solution can be found even though some thermal boundary conditions remain unknown. The temperature distribution reconstructed in this manner makes it possible to calculate stresses in the analyzed elements as accurately as possible.

Inverse methods are also used in literature to determine residual stresses induced by shot peening in round bars [12] or estimate thermal parameters and the friction coefficient during the warm flat rolling process [13].

The aim of this work is to present an inverse method intended for stress estimation in pressure components of power boilers. The proposed algorithm has to reconstruct the time- and space-dependent temperature, strain and stress distribution in some cross sections of thick-walled cylindrical elements without information concerning the thermal boundary conditions on inner surfaces. The strain and stress caused by steam pressure may also be considered if the steam pressure transient is measured inside the pressure component. The results obtained by means of the proposed method will be compared with exact and measured values.

2. Formulation of the method

If the temperature in a cylindrical component chosen part does not vary along the generatrix but changes along the circumference, and on the wall thickness, the unsteady-state temperature distribution is two-dimensional. The transient-state temperature may be written as $T(r, \phi, t)$.

The equation governing the transient-state heat conduction problem is expressed as follows:

$$c(T)\rho(T)\frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q} \tag{1}$$

where $\mathbf{q}$ is the heat flux vector. Fourier's law for an isotropic material takes the form

$$\mathbf{q} = -k\nabla T \tag{2}$$

All material properties (c – specific heat, ρ – density, k – thermal conductivity) are assumed as known functions of temperature. The control volume Finite Element Method is used to solve problems that occur in elements with a complex geometry [14]. Eq. (1) is integrated over general control volume V with bounding surface S:

$$\int_V c(T)\rho(T)\frac{\partial T}{\partial t}dV = -\int_V \nabla \cdot \mathbf{q}dV \tag{3}$$

By applying the mean value theorem for integrals on the left and the divergence theorem on the right, the following equation is obtained:

$$Vc(\overline{T})\rho(\overline{T})\frac{d\overline{T}}{dt} = -\int_S \mathbf{q}\cdot\mathbf{n}\ dS \tag{4}$$

where the bar indicates an average value in volume V and $\mathbf{n}$ is a normal unit surface vector directed to the outside of the control volume.

The cross section of a typical cylindrical component may be divided into control volumes, as presented in Fig. 1 [11]. Assuming that the component outer surface is perfectly insulated and an unknown boundary condition occurs on the inner surface, the inverse problem may be solved starting with a heat balance equation for the control volume associated with node $i=40$.

If the thermal capacity of any control volume is concentrated in its characteristic point "i", the heat balance Eq. (4) for node $i=40$ takes the following form (see Appendix A for details):

$$\frac{dT_i}{dt} = \frac{4a_i}{(r_7^2 - r_6^2)\cdot\Delta\varphi}\left[\frac{k_{i+1}+k_i}{2k_i}\cdot\frac{0.5\cdot\Delta r}{r_7\cdot\Delta\varphi}(T_{i+1}-T_i) + \frac{k_{i-13}+k_i}{2k_i}\cdot\frac{r_6\cdot 0.5\cdot\Delta\varphi}{\Delta r}(T_{i-13}-T_i)\right] \tag{5}$$

where $i=40$, $k_i = k(T_i)$, $c_i = c(T_i)$, $a_i = \frac{k_i}{c_i\cdot\rho_i}$.

Heat balance equations for control volumes $i=41$–51 have the form

$$\frac{dT_i}{dt} = \frac{2a_i}{(r_7^2 - r_6^2)\cdot\Delta\varphi}\left[\frac{k_{i-1}+k_i}{2k_i}\cdot\frac{0.5\cdot\Delta r}{r_7\cdot\Delta\varphi}(T_{i-1}-T_i) + \frac{k_{i-13}+k_i}{2k_i}\cdot\frac{r_6\cdot\Delta\varphi}{\Delta r}(T_{i-13}-T_i) + \frac{k_{i+1}+k_i}{2k_i}\cdot\frac{0.5\cdot\Delta r}{r_7\cdot\Delta\varphi}(T_{i+1}-T_i)\right] \tag{6}$$

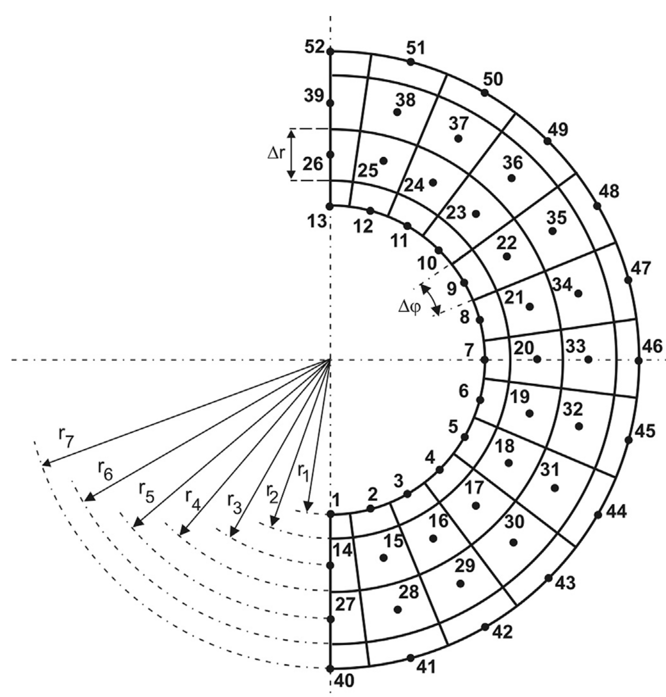

Fig. 1. Division of a cylindrical component cross section into control volumes.