Thermomechanical CSM analysis of a superheater tube in transient state

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Abstract   The paper presents a thermomechanical computational solid mechanics analysis (CSM) of a pipe "double omega", used in the steam superheaters in circulating fluidized bed (CFB) boilers. The complex cross-section shape of the "double omega" tubes requires more precise analysis in order to prevent from failure as a result of the excessive temperature and thermal stresses. The results have been obtained using the finite volume method for transient state of superheater. The calculation was carried out for the section of pipe made of low-alloy steel.

Keywords: CFB boiler; Superheater; Omega tube; Transient state; Finite volume method; Computational solid mechanics

Nomenclature

c	–	specific heat, kJ/(kg K)
E	–	Young's modulus, GPa
h	–	heat transfer coefficient, W/(m^{2}K)
k	–	thermal conductivity, W/(m K)
p	–	pressure, MPa

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T –   temperature, °C
T_w –   wall temperature, °C
t –   time, s
x, y, z –   Cartesian coordinates, m
n –   normal direction, m

Greek symbols

β –   linear thermal expansion coefficient, 1/K
ν –   Poisson's ratio
ρ –   density, kg/dm^3
σ_{zz} –   longitudinal (axial) stress, MPa
σ_{eq} –   equivalent Huber stress, MPa

1   Introduction

Finite volume method (FVM) [1–2] is widely used in thermal and strength
analysis of steam boilers [3–4]. The article presents results of temperatures
and stress calculations for steam superheater cross "double omega", used
in circulating fluidized bed (CFB) boilers. Transient cooling process of
the pipe material through the unit change of inner wall temperature was
analyzed. This process can actually occur, when the temperature of steam
flow will need to reduce value using steam injection. The calculation results
were obtained using the computational package [5] based on the FVM.

2   Mathematical model of superheater

Thermal-stress calculations were carried out for steel 10CrMo910 which is
used for superheaters in CFB boilers. Material properties such as thermal
conductivity, specific heat and density used in calculations are temperature
dependent and are presented in Fig. 1.

The governing equations for the temperature distribution in the cross-
section of the omega tube is:

$$c\left(T_w\right)\rho\left(T_w\right)\frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x}\left[k(T_w)\frac{\partial T_w}{\partial x}\right] + \frac{\partial}{\partial y}\left[k(T_w)\frac{\partial T_w}{\partial y}\right]. \tag{1}$$

The initial temperature distribution $T_{w,0}(x,y)$ is non-uniform and results
from the steady-state calculation of the superheater

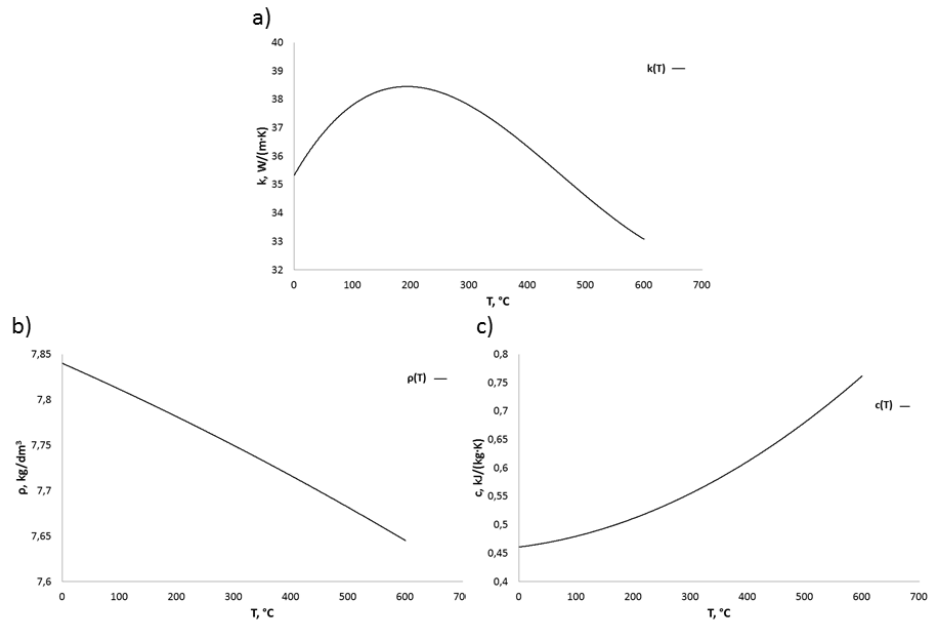$$T_w|_{t=0} = T_{w,0}(x,y) . \tag{2}$$

Figure 1. Properties of low-alloy steel 10CrMo910 as a function of temperature: a) – thermal conductivity, b) – density, c) – specific heat.

The heat conduction Eq. (1) is subject to the following boundary conditions (Fig. 2):

$$k_w \frac{\partial T_w}{\partial n}\bigg|_{A-B} = h_1\big(T_1 - T_w|_{A-B}\big) \ , \tag{3}$$

$$k_w \frac{\partial T_w}{\partial n}\bigg|_{B-C-D-E} = 0 \ , \tag{4}$$

$$k_w \frac{\partial T_w}{\partial n}\bigg|_{E-F} = h_2\big(T_2 - T_w|_{E-F}\big) \ , \tag{5}$$

$$k_w \frac{\partial T_w}{\partial n}\bigg|_{A-F} = 0 \ . \tag{6}$$

The cross section of a double omega tube with prescribed boundary conditions is shown in Fig. 2. Three-dimensional model of the superheater with a total tube length of 2.5 m was build for temperature and stress calculations. The number of cells in the superheater model is equal to 215,235.
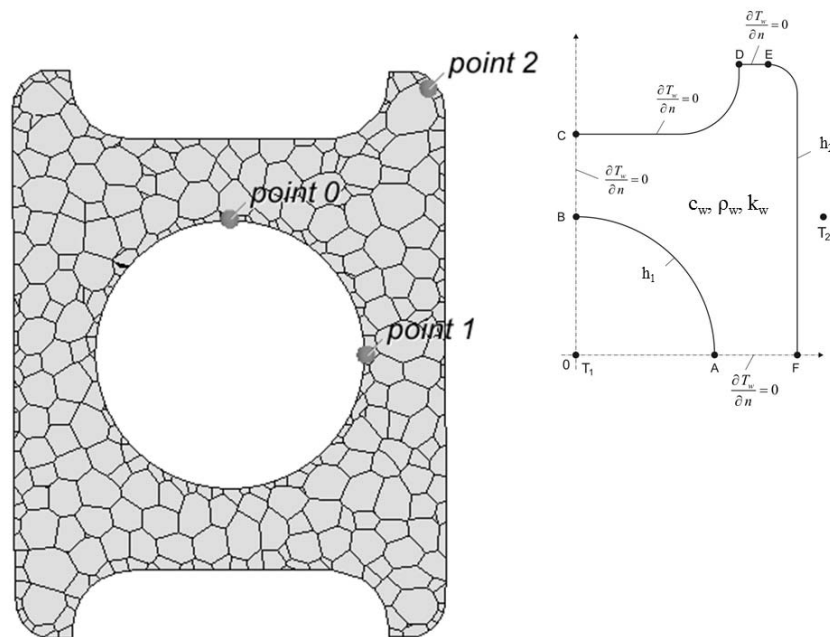
Figure 2. Division of the analyzed cross section into control volumes and the boundary
conditions with characteristic points at the boundary.

Figure 2 shows the division of tube cross section into cells (control volumes).
Characteristic points are also marked in the figure.

The analyzed cross section is located in the middle of the tube. The three-
dimensional modeling of the tube was carried out to eliminate the impact
of tube ends on the stress distribution in the analyzed cross-section. Elas-
tic thermal stresses were calculated using temperature dependent physical
properties (Fig. 3).

3   Numerical modeling

The main goal of computer simulations is to determine temperature and
thermal stress distributions in the tube during the transient operation of
the superheater. The influence of steam pressure flowing through the tube
on the stress distribution was studied.

The initial temperature and stress distributions for the transient analy-
sis were obtained from calculations in steady state. The parameters in the
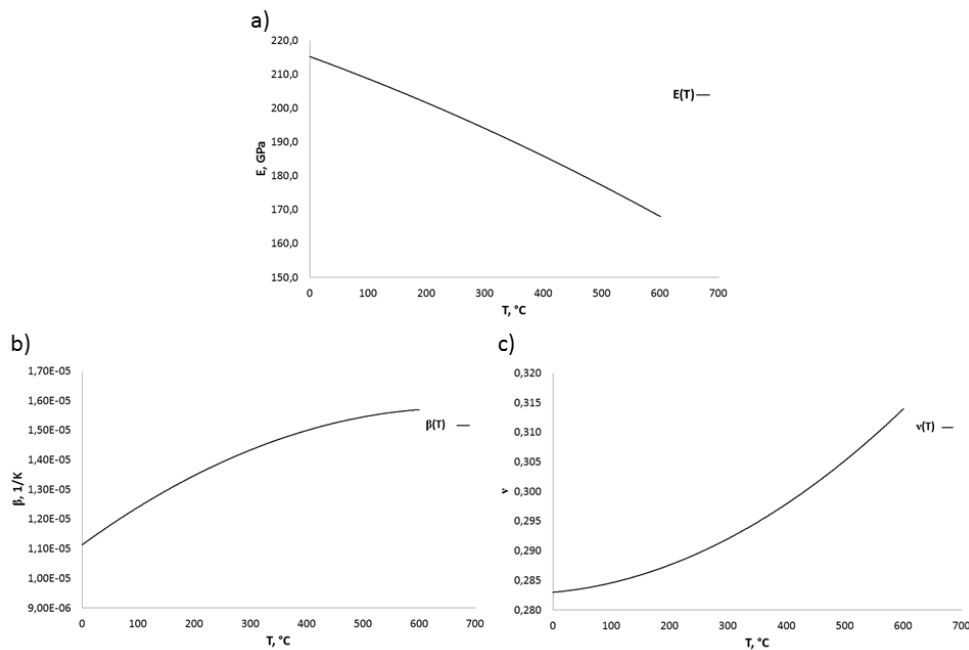boundary conditions used for the steady state analysis are: $T_1 = 495\,^\circ\mathrm{C}$,

Figure 3. Strength properties of 10CrMo910 steel as a function of temperature: a) – Young's modulus, b) – linear thermal expansion coefficient, c) – Poisson's ratio.

$h_1 = 3500$ W/(m²K), $T_2 = 850\,°$C, $h_2 = 200$ W/(m²K). There was a step change in steam temperature at $t > 0$ and this kind of tube cooling occurs during the injection cooling of the steam. The water is injected into the attemperator to cause the decrease of steam temperature. It was assumed that steam temperature decreases suddenly by 50 K.

The calculated temperature and stress distributions are presented in Figs. 4–7 for different times. Figure 4 shows steady-state temperature and stress distributions in the tube without internal pressure ($p = 0$ MPa). The Fig. 5 illustrates the influence of internal pressure on the distribution of longitudinal and equivalent stresses. If the pressure is present then tensile stresses in the region close to the internal tube surface are higher (Figs. 4c and 5c). The equivalent stresses are the highest at corners of the pressure-free tube (Fig. 4d). If the tube is loaded with pressure then the largest equivalent stresses occur near the inner surface of the tube. The equivalent stress at the tube corner is approximately equal to 60 MPa (Fig. 5d) while the creep rupture strength of 10CrMo910 steel at temperature $550\,°$C is
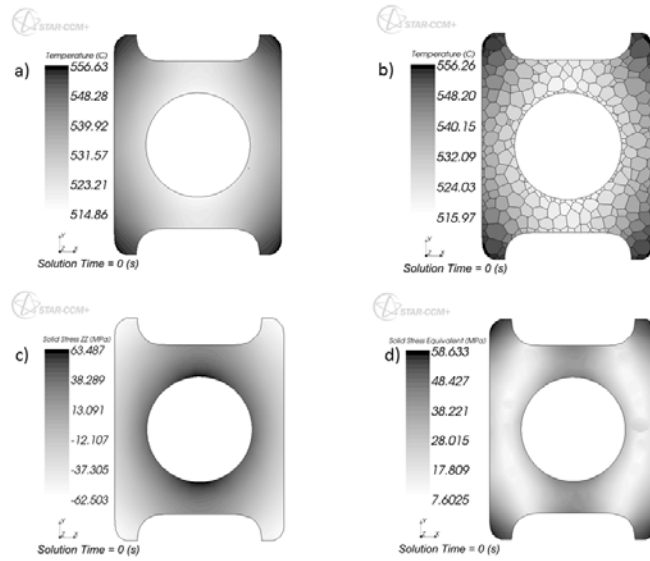
Figure 4. The distribution of temperature (a-b), longitudinal (axial) stress (c) and equiv-
alent stress (d) at the steady-state for $p = 0$ MPa (initial conditions for tran-
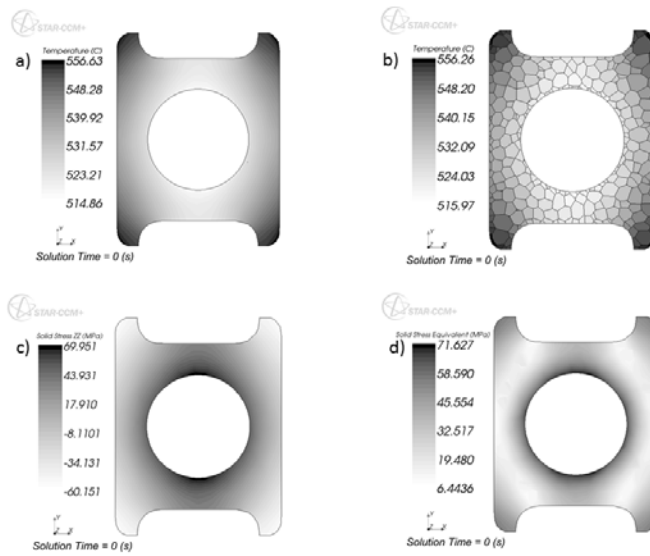sient analysis).

Figure 5. The distribution of temperature (a-b), longitudinal (axial) stress (c) and equiv-
alent stress (d) at the steady-state for $p = 16$ MPa (initial conditions for tran-
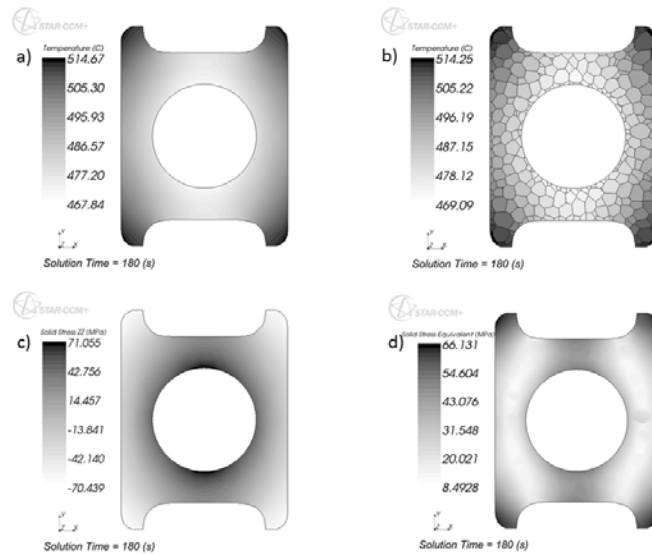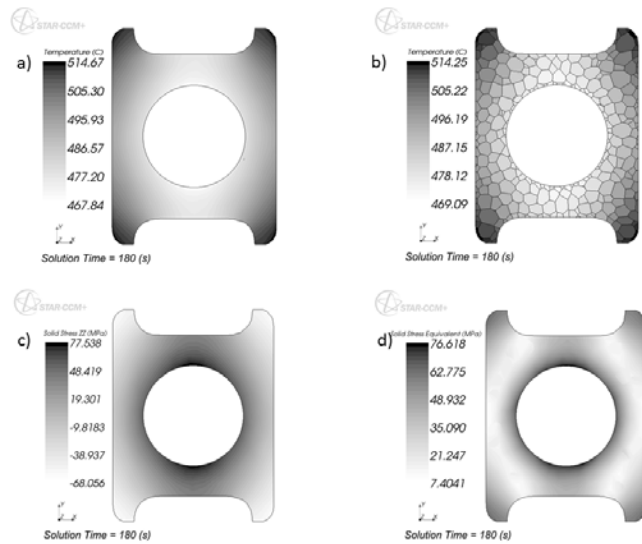sient analysis).

Figure 6. The distribution of temperature (a-b), longitudinal (axial) stress (c) and equivalent stress (d) to the final state ($t = 180$ s) after the step changes of temperature on the steam side ($T_1 = 495\,^{\circ}$C $> T_2 = 445\,^{\circ}$C).

Figure 7. The distribution of temperature (a-b), longitudinal (axial) stress (c) and equivalent stress (d) to the final state ($t = 180$ s) after the step changes of temperature on the steam side (with pressure $p = 16$ MPa).

73 MPa. Both the temperature and equivalent stress are close to the allowable limits. Transient temperature and stress distributions for $p = 0$ MPa and $p = 16$ MPa at time 180 s are presented in Figs. 6 and 7, respectively.

Temperature histories at the characteristic points after sudden decrease in steam temperature are displayed in Fig. 8. Steady-state temperature distribution forms in the tube after about 100 s.
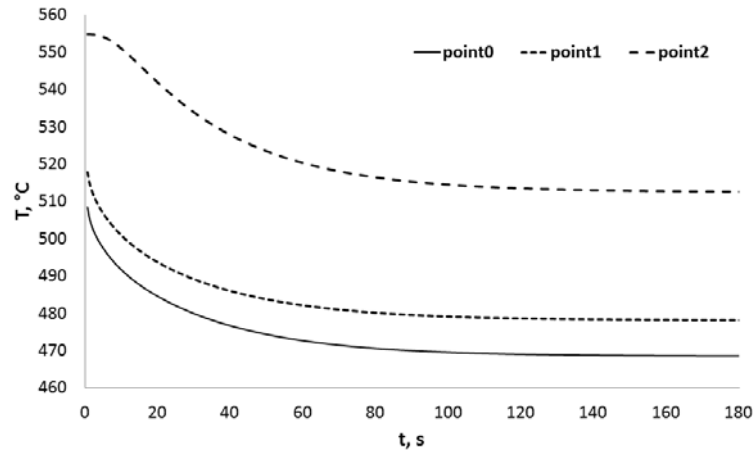

Figure 8. Temperature change in control points caused by the step change of temperature on the inner side of superheater. The results are identical for the case with temperature like also temperature and pressure.

Temperature differences over the tube cross-section are larger in transient state in comparison to the stresses under steady-state conditions, so the transient stresses are higher. Plots of the longitudinal and equivalent transient stresses as a function of time, are depicted in Figs. 9 and 10. In the first diagrams of Figs. 9 and 10 only thermal stresses are shown without consideration of pressure. The second plots in Figs. 9 and 10 present stresses caused by the thermal load and pressure. Since the tube temperature is highest at the corners then axial stresses are compressive. If the tube is loaded with pressure then absolute axial stresses at the corners are smaller since the longitudinal stresses due to pressure are tensile. Both longitudinal and equivalent stresses reach their absolute maximum at time about 10–15 s (Figs. 9–10).

Inspection of the results shown in Figs. 6–7 and 9–10 reveals that abrupt decrease of steam temperature caused by injection of cool water results in significant increase in thermal stresses.
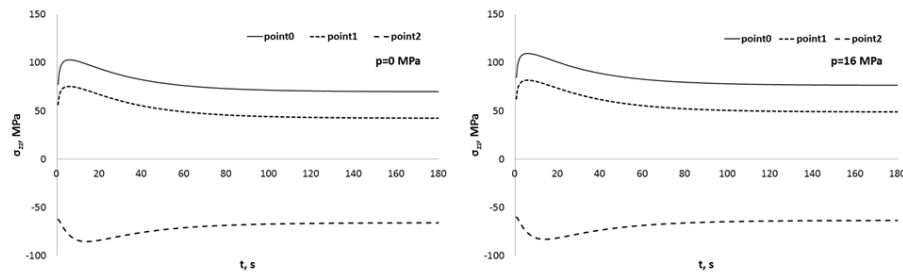
Figure 9. Longitudinal stress change in control points caused by the step change of temperature on the inner side of superheater.
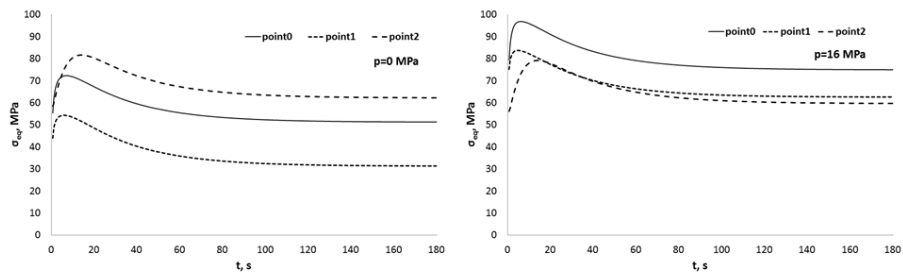

Figure 10. Equivalent stress change in control points caused by the step change of temperature on the inner side of superheater.

4 Conclusions

The results obtained from the temperature and stress analysis based on the finite volume method demonstrate that double omega superheater tubes work in adverse conditions. High gas corrosion failures may occur at the tube corners because of high metal temperatures. Also the stresses at the corners are high. The water injection to cool the superheated steam produces high transient thermal stresses at the tube wall. The maximum values of stresses occur during the first 20 seconds. The superheater tube needs about 100 seconds to attain steady state after the step change in steam temperature. The paper demonstrates that the simulation based on finite volume method makes it possible to asses properly thermal and strength working conditions in superheaters of large steam boilers.

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