A new procedure for optimum heating of pressure components with complex shape

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Abstract

Optimum fluid temperature changes can be determined using analytical or numerical methods. However, the calculated optimum temperature changes are difficult to follow in practice in the initial stage of heating. But it is possible to increase the fluid temperature step-wise to the minimum value and then heat the pressure component according to the determined optimum temperature changes. A method for determining time-optimum medium temperature changes is presented. The heating of the pressure elements will be conducted in such a way, that the circumferential stresses caused by pressure and fluid temperature variations at the edge of the opening, at the point of stress concentration, do not exceed the allowable values. The step wise temperature increase and the heating rate can be determined analytically using the least squared method.

Keywords: Heating optimization, Inverse problem, Pressure vessels, Thermal stresses.

1. Introduction

Rapid start – ups and shutdowns of the steam boilers cause excessive thermal stresses in thick walled pressure components. The boiler drums of the conventional power plants and feed water nozzles in the reactors of the nuclear power plants are among the critical pressure [3, 4, 10, 11], determining the heating and cooling rates during the start up and the shut down of the power unit. The lifetime of the pressure elements can be reduced significantly, if the heating and cooling rates are too high. The optimum fluid temperature changes can be determined with respect to the allowable rate of the temperature change [10] or taking into account the allowable thermal stress at the component wall [3, 8, 9, 10]. A method for determining the allowable temperature changes of the working medium during the heating and cooling of the thick-walled elements of the power steam boilers will be presented.

Figure 1: Longitudinal section of the boiler drum – downcomer junction

The allowable rate of the temperature change of the working medium will also be determined using the German boiler regulations –TRD 301 [11] or European Standard 12952-3 [4], which are based on a quasi-steady state, one dimensional temperature distribution in the pressure element. The stress concentration coefficient for stresses caused by pressure and thermal load at the point P\textsubscript{1} (Figure 1) is assumed to be in accordance with those regulations. It has to be noted, that only a few types of vessel-nozzle junctions have been considered in the
aforementioned regulations. In the proposed method, two points: P1 and P2 (Figure 1) are considered while determining the allowable temperature changes of the working medium and the stress concentration coefficients are determined using the three dimensional stress analysis, conducted with the use of the finite element method (FEM). At the point P1 the circumferential stresses, caused by the pressure, are greatest, while a large concentration of the circumferential thermal stresses were observed at the point P2. Complex shapes of the analyzed junctions can easily be considered in the analysis of the temperature and stress distribution using the FEM method. Both, the TRD 301 regulations and the EN 12952-3 standard [4] are too conservative, because they exclude rapid, step changes of the medium temperature at the beginning of the heating or cooling process. Thus, a new procedure for the determination of the optimum changes of the medium temperature will be presented [3]. At the beginning of the heating process of the pressure element, the medium temperature changes stepwise, e.g. by filling the pressure element at the ambient temperature, with boiling water. The value of the allowable step in temperature rise of the medium is determined in a simplified way, by dividing the maximum allowable values of stress by the maximum value of the, so called, “influence function”, which represents thermal circumferential stresses at the edge of the opening, caused by a sudden unit rise of the medium temperature. Further temperature changes are determined while assuming the quasi-steady temperature distribution in the thick walled element. This method of heating the thick walled elements is justified, as the maximum thermal stresses, caused by a sudden rise in the medium temperature occur after 60s to 120s, and later, the value of the thermal stress falls, and with time it reaches zero. A three dimensional stress analysis, using FEM was conducted, in order to prove, that the total maximum circumferential stresses, at the edge of the opening, during the optimum heating of the boiler drum – downcomer intersection do not exceed the allowable values. The method of determining the optimum temperature changes of the medium presented in this paper, allows the shortening of the boiler start up time, from the cold state, thus reducing the losses occurring during the start up process.

2. Mathematical formulation of the method

Maximum circumferential stress at the stress concentration point P (Figure 1) – the location of which at the edge of the opening, is given by vector \( r_p \) – being the sum of pressure stresses \( \sigma_p \) and thermal stresses \( S(r_p, t) \), is as follows:

\[
\sigma_p = S(r_p, t) + \sigma_p(r_p, t)
\]

where thermal stress \( S(r_p, t) \), caused by the change of the medium temperature over time \( f(t) \) is determined using the Duhamel’s integral

\[
S(r_p, t) = S_0 + \int_0^t f(\theta) \frac{\partial u(r_p, t-\theta)}{\partial \theta} d\theta
\]

The \( u(r_p, t) \) function, also called the influence function, represents the thermal stress at time \( t \) at the selected point \( r \) of the pressure element, caused by a unit, stepwise increase of the medium temperature \( f(t) = 0 \) for \( t \leq 0 \) and \( f(t) = 1 \) for \( t > 0 \).

The initial value \( S_0 \) is constant and is independent of the location of \( r \). The influence function \( u(r, t) \) allows to determine thermal stress \( S(r_p, t) \) for any continuous change of the medium temperature \( f(t) \), using the Duhamel’s integral, defined by Eq. (2). The influence function \( u(r_p, t) \) at the points \( P_1 \) and \( P_2 \) describes the change of circumferential stresses at the edge of the opening, caused by a unit, stepwise increase of the temperature medium.

For the pressure element without internal pressure the optimum temperature changes are determined from the following equation

\[
S_0 + \int_0^t f(\theta) \frac{\partial u(r_p, t-\theta)}{\partial t} d\theta = y(t)
\]

This is an inverse problem, since we have to solve the Volterra integral Eq. (3) of the first kind. The so called future time steps, which were introduced to the analysis of the inverse problems by Beck [3, 9], will be used for the stabilisation of the solution to the inverse problem. In order to determine \( f(t) \), its real changes will be replaced by a step curve (Figure 2). The value of the medium temperature \( f_M \) will be determined from condition (3) at the \( t_{M+F} \) time point:

\[
S(r_p, t_{M+F}) - y(t_{M+F}) = 0
\]
Figure 2: Approximation of the real changes of the medium temperature \( f(t) \) using the step curve

It is assumed, that the determined value of \( f_{st} \) applies only for the \( t_{st,1} \leq t \leq t_{st} \) time interval.

Approximating the integral in Eq. (2) by the method of rectangles and solving Eq. (2) sequentially for \( f_{st} \) we obtain:

\[
f_i = \left( y(t_{F,i}) - S_i \right) / u_{F,i} \quad \text{for} \quad M = 1
\]

\[
f_{st} = \frac{y(t_{st,F}) - S_0 - \sum_{i=1}^{M} f_i \Delta u_{st,F-i}}{u_{F,i}}, \quad M = 2, 3, ... 
\]

where

\[
\Delta u_0 = u_1 - u_0 = u_1 \Delta u_{i+1} - u_i \quad \text{and} \quad u = \sum_{i=0}^{\infty} \Delta u_i
\]

Eq. (5) and Eq. (6) allow to determine \( f_1, f_2, f_3, \) etc. in a sequential way.

When the component is loaded by internal pressure, the total circumferential stresses at the points \( P_1 \) and \( P_2 \), caused by internal pressure and thermal load, can limit the rate of the medium temperature changes during the boiler start up and shut down process. The procedure for determining the optimum medium temperature \( f(t) = T_f(t) \), for this case is presented [9].

3. Comparison with the boiler regulations

The heating rates: \( v_{T1} \) for \( p_1 \) and \( v_{T2} \) for \( p_2 \) can be determined in accordance with the German TRD 301 boiler regulations [11], or the European Standard EN 12952-3 [4]. The rate of the allowable temperature change \( v_T = dT_f / dt \) for arbitrary pressure \( p_1 \leq p \leq p_2 \) can be determined from the following equation:

\[
dT_f / dt = v_T(p)
\]

The rate of the temperature change \( v_T \) in equation (20) for any \( p \) in the interval \( p_1 \leq p \leq p_2 \) is obtained from the linear interpolation between \( (p_1, v_{T1}) \) and \( (p_2, v_{T2}) \):

\[
v_T = \frac{p_2 v_{T1} - p_1 v_{T2}}{p_2 - p_1} + \frac{v_{T2} - v_{T1}}{p_2 - p_1} p(T_f)
\]

When the fluid in the pressure component is a saturated steam, saturated water or steam-water mixture, then the fluid pressure depends on the saturation temperature \( p = \left[ (T + a)/b \right]^c \)

where the symbols \( p \) and \( T \) denote the saturation pressure in MPa and temperature in °C respectively. The constants are: \( a = 20.81045 \), \( b = 200.40565 \), \( c = 4.564173 \).

The uniform initial condition was assumed: \( T(t = 0) = T_0 \), where \( T_0 \) is the constant temperature.

The allowable rates of fluid temperature changes \( v_{T1} \) and \( v_{T2} \) are determined from the condition that the sum of
circumferential stresses caused by pressure and thermal loads are equal to the allowable stress $\sigma_a$

$$\alpha_s \left( p - p_o \right) \frac{D + H}{2H} + \alpha_s \frac{E \beta}{1 - \nu} \frac{c \rho}{k} v_j H^2 \phi_{nw} = \sigma_a \quad (11)$$

where the symbol $\phi_{nw}$ denotes

$$\phi_{nw} = \frac{1}{8} \left( \omega^2 - 1 \right) \left( \frac{3 \omega^2 - 1}{(\omega^2 - 1)^2} - 4 \omega^3 \ln \omega \right) \quad (12)$$

The allowable temperature rate $v_{T1}$ at the beginning of the process is calculated from Eq.(11) for $p = p_1$ and $\sigma = \sigma_a$. The allowable temperature rate $v_{T2}$ at the end of the process is calculated from Eq.(11) for $p = p_2$ and $\sigma = \sigma_a$.

4. Determination of the optimum fluid temperature changes by solving the parametric least squares problem

Optimum changes of the fluid temperature $T_f$ during heating of the pressure component, are very difficult to carry out in practice for the initial stage of the heating process. However, optimum fluid temperature changes can be approximated by a ramp function consisting of a step increase in fluid temperature $T_s$ followed by the temperature increase with a constant rate $v_T$ (Figure 3). As an example, the optimum fluid temperature changes $T_f(t)$ during slab heating will be determined. It is worth mentioning that cylindrical or spherical vessels can be considered as a thick plate (slab) if the inner radii of vessels are large. The thermal stress at the point $0 \leq x \leq L$ should be equal to the allowable stress :

$$\sigma_T(x, t) = \sigma_a(t) \quad (13)$$

where the thermal stress $\sigma_T$ is given by:

$$\sigma_T = \frac{E \beta}{1 - \nu} \left[ T(t) - T(x, t) \right] \quad (14)$$

The allowable stress $\sigma_a$ may depend on time. The mean temperature $\bar{T}(t)$ over the slab thickness is defined as:

$$\bar{T}(t) = \frac{1}{L} \int_0^L T(x, t) dx \quad (15)$$

The problem of optimum heating or cooling will be solved under the assumption that physical properties of the component material and the heat transfer coefficient are constant.

The mathematical formulation of the problem is

$$c \rho \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}, \quad t > 0, \quad (16)$$

$$T(x, 0) = T_0, \quad 0 \leq x \leq L \quad (17)$$

$$\frac{\partial T}{\partial x} \bigg|_{x=0} = 0, \quad t > 0, \quad (18)$$

$$k \frac{\partial T}{\partial x} \bigg|_{x=L} = h \left[ T_f(t) - T \bigg|_{x=L} \right], \quad t > 0 \quad (19)$$

The boundary condition of the third kind is given at the exposed surface. The time varying fluid temperature $T_f(t)$ in Eq. (19) is unknown and will be determined from the condition (13).
The solution of the direct heat conduction problem, which is defined by the heat conduction equation (16), initial condition (17), boundary conditions (18) and (19) is as follows:

\[
T(x,t) = T_s + (T_0 - T_s) F(x,t) + v_t t - v_f F_1(x,t)
\]  
(20)

where

\[
F(x,t) = \sum_{\mu_n} \frac{2 \sin^2 \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} \exp \left( -\frac{\mu_n^2 \alpha t}{L^2} \right)
\]  
(21)

\[
F_1(x,t) = \frac{L^2}{\alpha Bi} \left( \frac{1}{3} - \sum_{\mu_n} \frac{2 \sin^2 \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} \cos \frac{x}{L} \exp \left( -\frac{\mu_n^2 \alpha t}{L^2} \right) \right)
\]  
(22)

where: \( \alpha = \frac{k}{c \rho} \) is thermal diffusivity, \( \mu_n \) are the positive roots of the transcendental equation \( \mu_n \tan \mu_n = Bi \), and \( Bi = \frac{h L}{k} \) is the Biot number.

Substituting expression (20) into Eq. (15) gives

\[
T(x,t) = T_s + (T_0 - T_s) F(x,t) + v_t t - v_f F_1(x,t)
\]  
(23)

where \( F(t) \) and \( F_1(t) \) are given by:

\[
F(t) = \sum_{\mu_n} \frac{2 \sin^2 \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} \exp \left( -\mu_n^2 Fo \right)
\]  
(24)

\[
F_1(t) = \frac{L^2}{\alpha Bi} \left( \frac{1}{3} - \sum_{\mu_n} \frac{2 \sin^2 \mu_n}{\mu_n + \sin \mu_n \cos \mu_n} \cos \frac{x}{L} \exp \left( -\mu_n^2 \frac{\alpha t}{L^2} \right) \right)
\]  
(25)

Taking into account Eqs. (20) and (23), Eq. (14) can be expressed in the form:

\[
\sigma_r(x_t, T_t) \approx \sigma_{x_t}^E, \quad i = 1, ..., n_i
\]  
(26)

In the optimization problem, the unknown parameters \( T_s \) and \( v_f \) are to be adjust to satisfy approximately the following system of equations

\[
\sigma_r(x_t, T_t) \approx \sigma_{x_t}^E, \quad i = 1, ..., n_i
\]  
(27)
where $\sigma_T$ is given by Eq. (26).

The least squares method is used to estimate parameters $T_s$ and $v_T$. The parameters $T_s$ and $v_T$ are computed by minimizing the sum of squares of the differences between values given by the model (26) and the allowable stress $\bar{\sigma}$:

$$S_e = \sum_{i=1}^{n} \left[ \frac{E\beta}{1-v} \left( (T_i - T_s) \left[ F_i(t_i) - F(x_T,t_i) \right] - v_T \left[ \bar{F}_i(t_i) - F_i(x_T,t_i) \right] \right) \right]^2 = \min$$

(28)

It is necessary to find the values of $T_s$ and $v_T$, for which the two partial derivatives are simultaneously zero:

$$\frac{\partial S_e}{\partial T_s} = 0, \quad \frac{\partial S_e}{\partial v_T} = 0.$$  

(29)

Finding derivatives (29) gives a set of linear equations in the unknowns $T_s$ and $v_T$, which has the following solution

$$T_s = \frac{b a_{22} - b_s a_{12}}{a_{1s} a_{22} - a_{12} a_{2s}}$$  

(30)

$$v_T = \frac{b a_{2s} - b_s a_{1s}}{a_{1s} a_{2s} - a_{1s} a_{2s}}$$  

(31)

where

$$F_N(x_T,t_i) = \bar{F}(t_i) - F(x_T,t_i)$$

(32)

$$F_{1N}(x_T,t_i) = \bar{F}_i(t_i) - F_i(x_T,t_i)$$

(33)

$$a_{11} = \sum_{i=1}^{n} F^2_N(x_T,t_i)$$

(34)

$$a_{12} = \sum_{i=1}^{n} F_{1N}(x_T,t_i) F_N(x_T,t_i)$$

(35)

$$b_1 = T_s \sum_{i=1}^{n} F^2_N(x_T,t_i) - \sum_{i=1}^{n} \bar{\sigma}_e(t_i) F_N(x_T,t_i)$$

(36)

$$a_{21} = a_{12}$$

(37)

$$a_{22} = \sum_{i=1}^{n} F^2_{1N}(x_T,t_i)$$

(38)

$$b_2 = T_s \sum_{i=1}^{n} F_N(x_T,t_i) F_{1N}(x_T,t_i) - \sum_{i=1}^{n} \bar{\sigma}_e(t_i) F_{1N}(x_T,t_i)$$

(39)

The symbol $F^*_e(t_i)$ denotes

$$\bar{\sigma}_e(t_i) = \frac{\bar{\sigma}(t_i) - (1-v) \bar{\sigma}_e(t_i)}{E \beta}$$

(40)

Since the time points $t_i$ are equally distributed with the time step $\Delta t$, the time points $t_i$ are given by

$$t_i = i \Delta t, \quad i = 1, \ldots, n_t$$

(41)
The values of $T_s$ and $v_T$ can also be determined by the modified Levenberg-Marquardt method [5, 6] using the subroutine BCLSF from the IMSL mathematical library [1]. The same results were obtained using Eqs. (29) and (30) as well as the Levenberg-Marquardt method.

5. A new procedure for determining allowable temperature rates during heating and cooling of thick-walled boiler components

In the case of components, loaded with pressure, the optimum medium temperature can be obtained in a similar way. Initially the medium temperature may change stepwise and later the medium temperature changes can be conducted at a rate calculated according to the TRD 301 regulations or to the EN 12952-3 standard. Taking into account that TRD 301 regulations and the EN 12952-3 standard do not permit stepwise fluid temperature changes and the optimum fluid temperature changes resulting from the proposed method, a new procedure for optimum heating and cooling of pressure components will be proposed. The developed procedure has an advantage over the present boiler regulations, since the pressure components can be heated or cooled much faster which results in a large reduction of heat loss.

The procedure for determining the rate of the allowable medium temperature changes is as follows:

**Heating** – calculations will be conducted for the points $P_1$ and $P_2$ situated at the edge of the opening (Figure 1)

- Determine the stress concentration coefficients at the edge of the opening: $\alpha_p$ for the stresses caused by pressure and $\alpha_T$ for the thermal stresses,
- Determine the allowable values of stresses during the start-up process $\bar{\sigma}_s$, according to the EN 12952-3 standard, taking into account that the stress values $\bar{\sigma}_s$ are different for $P_1$ and $P_2$,
- Determine the allowable heating rates according to the EN 12952-3 standard: $v_T1$ for the initial pressure $p_1$ and $v_T2$ for the final pressure $p_2$,
- Determine, the minimum value of the influence function $u_{min}$ and time $t_{min}$ for which the function reaches the minimum, for the assumed value of the heat transfer coefficient,
- Calculate the initial stepwise rise in the medium temperature, using the formula

$$\Delta T_0 = \left[ \bar{\sigma}_s - \alpha_p (p_1 - p_0) \frac{D + H}{2H} \right] u_{min}$$

(42)

- Reduce the allowable value of the stepwise rise of the medium temperature by $v_T1 t_{min}$; the allowable value of the stepwise rise of the medium temperature is then: $\Delta T_0 = \Delta T_0 - v_T1 t_{min}$,
- Determine the optimum medium temperature $T_f(t)$ from Eq. (8) solving it by the Runge-Kutta method and taking into consideration the initial condition stating that the initial medium temperature is: $T_f(t=0) = T_0 + \Delta T_0$, where $T_0$ is the initial temperature of the component at time $t = 0$,
- Having determined the optimum temperature changes and heating times with respect to stresses at the points $P_1$ and $P_2$, the heating process which last longer will be assumed to be optimum.

**Cooling** – the calculations are only carried out for the point $P_1$

- Determine the stress concentration coefficients at the edge of the opening: $\alpha_p$ for the stresses caused by pressure and $\alpha_T$ for the thermal stresses,
- Determine the allowable values of stresses during the cooling process $\bar{\sigma}_s$, according to the EN 12952-3 standard,
- Determine the allowable cooling rates according to the EN 12952-3 standard: $v_T1$ for the initial pressure $p_1$ and $v_T2$ for the final pressure $p_2$,
- Determine, the maximum value of the influence function $u_{max} = - u_{min}$, and time $t_{max}$ for which the function reaches the maximum, for the assumed value of the heat transfer coefficient,
- Calculate the initial value of the stepwise rise in the medium temperature, using the formula

$$\Delta T_0' = \left[ \bar{\sigma}_s - \alpha_p (p_1 - p_0) \frac{D + H}{2H} \right] u_{max}$$

(43)

- Assume that $\Delta T_0 = \Delta T_0'$; there is no need to reduce the temperature stepwise change, since the reduction of stresses caused by pressure is greater than the rise in stresses caused by temperature changes. The reason for this is the small temperature drop during pressure decreasing for higher values of saturation pressure.
- Determine the optimum medium temperature $T_f(t)$ from Eq. (8) solving it by the Runge-Kutta method and taking into consideration the initial condition stating that the initial medium temperature is: $T_f(t=0) = T_0 - \Delta T_0$, where $T_0$ is the initial temperature of the component at time $t = 0$.

Such temperature changes can be conducted in real life.
6. Examples of calculation

Firstly, the optimum medium temperature changes over time, during the heating of a plate, of the thickness \( H = 0.1 \) m will be determined. The edges of the infinitely large plate can expand freely, but they cannot bend. The following data was assumed for the calculations: the thermal conductivity: \( k = 42 \) W/(m·K), the specific heat: \( c = 483.1 \) J/(kg·K), the density: \( \rho = 7782 \) kg/m\(^3\), The Young modulus is \( E = 1.966 \times 10^{11} \) N/m\(^2\), the linear thermal expansion coefficient \( \beta = 1.32 \times 10^{-5} \) 1/K and the Poisson ratio \( \nu = 0.29 \). The heat transfer coefficient at the surface of the heated plate equals: \( h = 2000 \) W/(m\(^2\)·K). The other surface of the plate is thermally insulated. The allowable compressive stress on the heated surface of the plate is: \( \sigma_r = -109.06 \) MPa. At the start time, the plate temperature is even and equals 0° C. The time changes of the influence function for various heat transfer coefficients are presented in Figure 4.

![Figure 4: Plot of the influence function for the 0.1 m thick plate](image)

The time point, at which the influence function reaches the maximum absolute value, depends on the heat transfer coefficient. The greater the value of the heat transfer coefficient, the earlier will the absolute maximum value of the stress occur. The maximum absolute value of the influence function also increases with the increase of the value of the \( h \) coefficient. The optimum changes of the medium temperature were determined using formulas (5-6) and (30-31) (Figure 5). From the analysis of the results presented in Figure 5 can be seen, that it is impossible to achieve the optimum medium temperature at the beginning of the heating process, because this temperature is very high. Thus, the optimum temperature was approximated, using a ramp function consisting of the step temperature rise at time \( t = 0 \) and a linear temperature increase for time \( t > 0 \). The value of the initial medium temperature jump and the rate of the linear medium temperature rise were determined using the least squares methods, in such a way that assures that the integral over time from the square of the difference between the actual stress and the allowable stress on the heated surface of the plate is minimised. In the least squares method, the number of time points is: \( n_t = 100 \) and time step \( \Delta t \) is equal to 30 or 60 s (Figure 5b). In the estimated optimum medium temperature \( T_{ramp} = 54.94 + 0.0998 \) \( t \) time \( t \) is expressed in seconds. This optimum ramp heating can easily be conducted in power plants. The step increase of the medium temperature by 54.94 K can also be achieved without difficulty in real life by flooding the component with water at a temperature higher by 54.94 K than the initial temperature of the component. In the second example, optimum water temperature changes will be determined with respect to total stress at the points P1 and P2 on the edge of the boiler drum-downcomer intersection. The following boiler drum dimensions were assumed for the calculation: \( D = 1.7 \) m, \( d = 0.09 \) m, \( H = 0.09 \) m and \( h = 0.006 \) m (Figure 1). Also, the following properties of steel were assumed: \( k = 42 \) W/(m·K), \( c = 538.5 \) J/(kg·K), \( \rho = 7800 \) kg/m\(^3\); \( E = 1 \).
The heat transfer coefficient on the inner surface of the drum and downcomer is \( h = 1000 \text{W/(m}^2\text{K)} \). The outer surfaces of the boiler drum-downcomer intersection are thermally insulated. The stress distribution analysis was done for the elastic state. The stress concentration coefficients are: \( \alpha_p = 2.65 \) at the point P1 and \( \alpha_p = 0.51 \) at the point P2, respectively. Since the diameter and wall thickness of the downcomer tube is much smaller than the diameter and wall thickness of the boiler drum, the intersection resembles a plate with a hole subjected to biaxial stretching stresses with 2:1 ratio. For a plate with such a load, the stress concentration coefficient is 2.5 at the point P1 and 0.5 at the point P2.

The thermal stress concentration coefficients in quasi-steady state are \( \alpha_T = 1.86 \) at the point P1 and \( \alpha_T = 2.074 \) at the point P2, respectively. Numerical model has been used for the determination of the influence function at points P1 and P2. FEM analysis was carried out by means of the ANSYS software. The maximum absolute value of the function \( u(r,t) \) is larger at the point P1 in comparison with its value at the point P1. Since total compressive stresses at the point P2 reach a larger value, the optimum medium temperature change rate with regard to circumferential stresses at point P2 is smaller than the temperature change rate at point P1. Furthermore, the temperature jump at the beginning of the process is smaller at the point P2. If stresses at the point P2 affect the course of heating and cooling, the start-up operation is longer, while shut-down lasts shorter in contrast to durations obtained by means of the approach, when P1 is the criterion point. Next, the changes of total stresses, in conjunction with determined optimum temperatures, was determined by means of the 3D FEM analysis to check that total stresses do not exceed the allowable stresses. From the analysis of the results, one can see that allowable stresses are exceeded at the point P2 (Figure 6c), when the optimum medium temperature is determined with respect to total stresses at point P1. If the optimum heating and cooling of a boiler drum is carried out with respect to total stresses at the point P2, the maximum stresses on the edge of a hole at the points P1 and P2 are smaller than the allowable stresses (Figure 7c). It is advantageous when the boiler drum is heated with respect to stresses at the point P2, since the allowable stresses both at the point P1 and P2 are not exceeded and the lifetime of the pressure component is longer.

Figure 5: Optimum medium temperature during the heating process of a thick walled plate; (a) – optimum temperature, (b) – comparison of thermal stresses during optimum heating with the allowable value,

Figure 6: Optimum medium temperature (a) and pressure (b) of the saturated water and total circumferential stresses (c) at the points P1 and P2 when optimum medium temperature changes are determined from the condition that the total circumferential stress at the point P1 is equal to the allowable stress \( \bar{\sigma}_u \).
Figure 7: Optimum medium temperature (a) and pressure (b) of the saturated water and total circumferential stresses (c) at the points P₁ and P₂ when optimum medium temperature changes are determined from the condition that the total circumferential stress at the point P₂ is equal to the allowable stress $\sigma_a$.

7. Conclusions
The presented method of determining the allowable changes of the medium temperatures during the boiler start-up and shut-down processes can be used in real life. It allows a significant reduction in the boiler start-up time, thus reducing the start-up costs – as at the beginning of the start-up process the pressure element can be filled with hot water. In this paper the procedures for determining the optimum temperature changes during the heating and cooling processes of the boiler drum or other boiler elements were presented. The proposed method can also be used when the pressure of the medium changes independently of the medium temperature. The present standards should be extended to take into consideration not only the point P₁ but also the P₂ on the hole edge, when allowable fluid temperature changes are determined.

References