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Piotr DZIERWA[1]

OPTIMUM HEATING OF BOILER DRUMS

In a paper, a method for determining time-optimum medium temperature changes is presented. The heating of the pressure elements will be conducted so that the circumferential stress caused by pressure and fluid temperature variations at the edge of the opening at the point of stress concentration, does not exceed the allowable value. In contrast to present standards, the stress distribution at two points at the edge of the hole is taken into consideration. Optimum fluid temperature changes are approximated by simple time functions. The temperature of medium at the beginning of the heating process was varied steeply and then the temperature was increased with a constant rate.

Keywords: thermal stresses, inverse heat conduction problem, pressure vessels, boiler standards

1. Introduction

The major limiting factor relevant to fast steam boiler start-ups are the maximum allowable thermal stresses in thick-walled components such as headers of superheaters and reheaters, boiler drum and T and Y shaped junctions in steam pipelines [1-2]. Optimization of heating and cooling of thick boiler components is the subject of many studies [3-5], since too rapid heating or cooling element causes high thermal stresses. The heating rates: v_{T1} for pressure p_1 and v_{T2} for pressure p_2 can be determined in accordance with the German TRD 301 boiler regulations [6], or the European Standard EN 12952-3 [7] from the following equation

$$\left| \alpha_m \left(p - p_o \right) \frac{d_{in} + s}{2s} + \alpha_T \frac{E\beta}{1-\nu} c\rho \frac{v_T s^2}{k} \phi_w \right| \le \left| \sigma_a \right| \tag{1}$$

The second term in eq. (1) represents a thermal circumferential stress at the hole edge at the point P_1 (Fig.1) assuming the quasi-steady state temperature distribution in the component. The quasi-steady distribution of temperature occurs in the wall of the component after heating the component for a long period of time at

[1] Piotr Dzierwa, Politechnika Krakowska, Al. Jana Pawła II 37, 31-864 Kraków, tel. 12 6283554, e-mail: pdzierwa@wp.pl

the constant rate [8]. Both standards do not allow for abrupt changes in fluid temperature which is their major drawback. Stress concentration coefficient α_p for internal pressure-caused stresses can be determined from approximate equations based on experimental results or by means of the Finite Element Method (FEM).

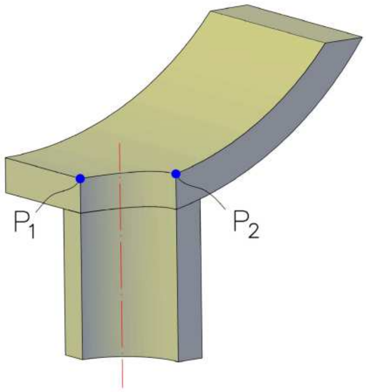

Fig. 1. Pressure vessel – connector junction; location of points P_1 and P_2

The coefficient ϕ_w depends only on the diameter ratio and can be determined from the following expression

$$\phi_w = \frac{1}{8}\frac{\left(\omega^2-1\right)\left(3\omega^2-1\right)-4\omega^4\ln\omega}{\left(\omega^2-1\right)\left(\omega-1\right)^2} \tag{2}$$

which was derived from the assumed quasi-steady state of the wall temperature distribution. Once v_{T1} for p_1 and v_{T2} for p_2 is determined according to TRD boiler regulations, the value of the allowable medium temperature change rate $v_T = dT_f/dt$ for arbitrary pressure $p_1 \le p \le p_2$ can be determined by means of the linear interpolation from the following formula

$$\frac{dT_f}{dt} = \frac{p_2 v_{T1} - p_1 v_{T2}}{p_2 - p_1} + \frac{v_{T2} - v_{T1}}{p_2 - p_1}\, p\left(T_f\right) \tag{3}$$

Initial condition has the form $T(t = 0) = T_0$. TRD regulations assume that the thermal stress concentration coefficient, on the edge of a hole, is constant and is equal to $\alpha_T = 2$. From stress calculations conducted by means of FEM, however, one can deduce that the value of this coefficient in the quasi-steady state is not constant and depends, to a large extent, on the value of heat transfer coefficient h at the inner surface of a construction element. The European Standard EN 12952-3 has been improved by introducing a variable stress concentration factor α_T. The factor α_T depends on the heat transfer coefficient h at the vessel inner surface. The determination of allowable temperature change rates of a fluid in a quasi-steady state can be rendered more accurate when α_T is determined from FEM stress analysis. When the fluid in the pressure component is saturated steam, saturated water or steam-water mixture, then the fluid pressure depends on the saturation temperature. The paper presents a new method of determining the optimum fluid temperature changes during heating and cooling of thick walled pressure vessels weakened by holes. Optimum temperature curve is determined from the condition that the total circumferential stress, caused by the thermal load and pressure, at the edge of the hole at the point P_2 (Fig. 1) is equal to the allowable stress. Current standards limit the boiler heating rate taking into account the stress at the point P_1, because at this point there is the greatest concentration of the circumferential stress caused by pressure. However, during pressure vessel heating, the stresses due to pressure are tensile while the stresses from the thermal load are compressive and they compensate each other. At the same heating rate of the pressure element during boiler start-up, total circumferential or equivalent stress at the point P_1 is smaller than the corresponding stress at the point P_2. This is due to much lower concentration of stress from pressure at the point P_2. In determining the optimum heating rate or the optimum time changes of fluid temperature in the vessel when with temperature increases the pressure, one must take into account the point P_2.

2. Mathematical formulation of the problem

The previous optimization analysis shows [4-5] that the optimum fluid temperature changes $T_f(t)$ obtained from the solution of the Volterra integral equation of the first kind, can be well approximated by (Fig. 2a)

$$T_f = T_0 + a + b\,t + c/t \tag{4}$$

At first, the optimum fluid temperature changes are approximated by the function $T_f\,(t)$ (Fig. 2b)

$$T_f = T_0 + a + b\,t \tag{5}$$

which can easily be carried out in practice. The symbols in Eq. (5) stand for: a – initial stepwise temperature increase, b – constant rate of fluid temperature changes. The optimum values of parameters a, b and c appearing in the function (4) or the parameters a and b in the function (5) will be determined from the condition

$$\sigma_\varphi\left(\mathbf{r}_{P_2}, t_i\right) \cong \sigma_a, \quad i = 1, \ldots, n_t \tag{6}$$

The parameters a and b will be determined by the method of least squares. The sum of squared differences of the calculated circumferential stress: $\sigma_\varphi = S + \sigma_p$ and allowable stresses σ_a at the point P_2 for the selected n_t time points should be minimum

$$\sum_{i=1}^{n_t}\left[\int_0^{t_i} T_f(\theta)\frac{\partial u\left(\mathbf{r}_{P_2}, t-\theta\right)}{\partial t}d\theta + \alpha_m\left(p - p_o\right)\frac{d_{in}+s}{2s} - \sigma_a\right]^2 = \min \tag{7}$$

Fluid temperature T_f (θ) in the sum (7) was assumed as a function (4) or (5). Problem of seeking a minimum of function (3) is a parametric least squares problem. Parameters $x_1 = a$, $x_2 = b$, $x_3 = c$ in the function (4), or parameters $x_1 = a$ and $x_2 = b$ in the function (5) are to be searched. Parameter values at which the sum of squares (7) is a minimum have been determined by the Levenberg - Marquardt method [9].

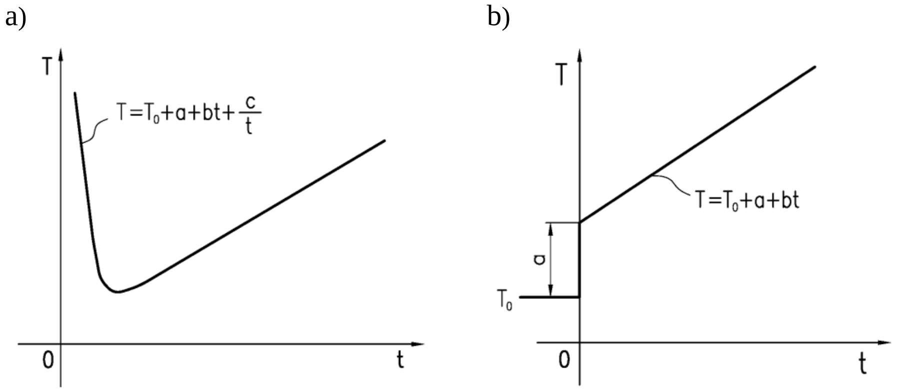

Fig. 2. Functions using for approximation of optimum time changes of fluid temperature; a) function defined by eq. (4), b) function defined by eq. (5)

3. Results of calculations

Optimum fluid temperature changes during warm-up of the boiler drum with an inner diameter d_{in} = 1700 mm and wall thickness s = 90 mm were determined. The inner diameter of the downcomer is d_{wo} = 90 mm and wall thickness s_o = 6 mm. The following properties of steel were adopted for the calculation: k = 42 W/(m·K); c = 538.5 J/(kg·K); ρ = 7800 kg/m^3; $E = 1.96\cdot 10^{11}$ N/m^2; $\beta = 1.32\cdot 10^{-5}$ 1/K, and ν = 0.3. The heat transfer coefficient on the inner surface of the drum and downcomer is: h = 1000 W/(m^2·K). Allowable stress is: σ_a = -138.7 MPa. The allowable stress σ_a for the boiler start-up was determined assuming 2000 boiler start-ups from a cold state [6]. The outer surface of the drum and downcomer are thermally insulated. Stress concentration factor for the circumferential stress caused by the pressure at the point P_2 was determined by finite element method (FEM) and is: α_m = 0.51.

Optimum fluid temperature changes were estimated using the influence function for the heat transfer coefficient, h = 1000 W/(m$^2 \cdot$K). The course of circumferential stress at the point P_2 as a function of time, which is required to apply the method of Levenberg - Marquardt, was determined using the FEM. The optimum fluid temperature changes have been determined for the pressureless state p_n = 0 MPa and for design operation pressure p_n = 10.87 MPa. The optimum fluid temperature changes described by function (4) are presented in Figure 3a. Figure 3b depicts the optimum fluid temperature changes approximated by the function (5). The initial jump of the temperature is 48.6 K for gauge pressure p_n = 0 MPa, and 51.2 K for p_n = 10.87 MPa. The analysis of the results illustrated in figures 3a and 3b indicates that the drum pressure has little effect on the optimum time changes of the fluid temperature. This is due to small value of the stress concentration coefficient at the point P_2 for the stress caused by the pressure, which is only α_m = 0.51.

a) b)

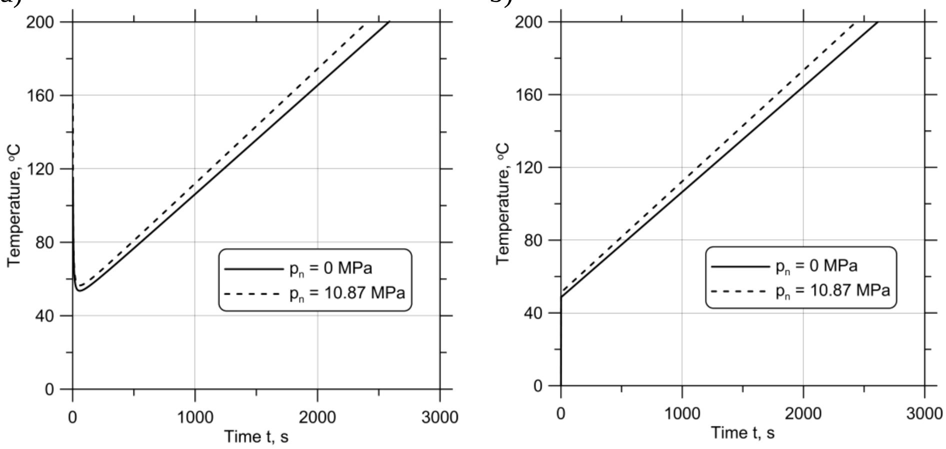

Fig. 3. Optimum time changes of water temperature $T_f(t)$ in the drum; a) approximated by function defined by eq. (4), b) approximated by function defined by eq. (5)

Plots of summary circumferential stress during the optimum heating process at the edge of the hole at points P_1 and P_2 as a function of time are presented in Figures 4 and 5. During the start-up the total circumferential stress at the point P_1 caused by thermal load and the pressure is lower than at the point P_2. Small excesses over the allowable stresses at the point P_2 result from the assumed forms of the functions given by equation (4) or (5). In the case of function (4) the total stress at the point P_2 is very close to the allowable stress.

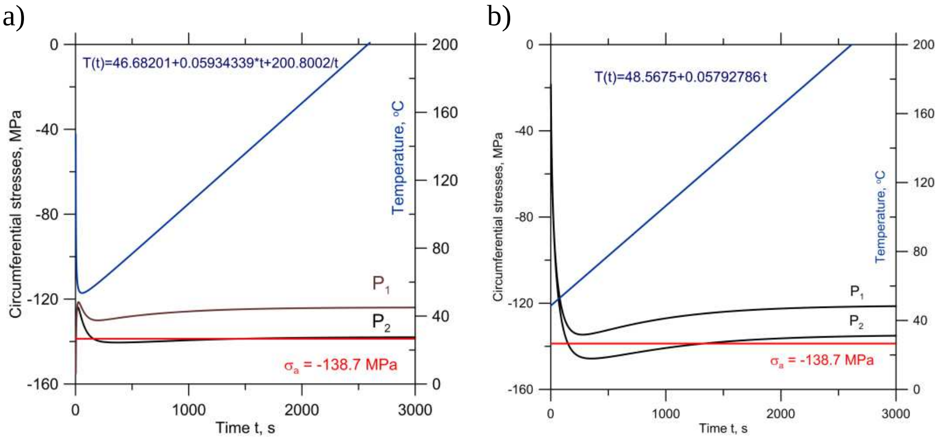

Fig. 4. Total circumferential stress due to pressure and thermal load at points P_1 and P_2 during optimum drum heating for p_n = 0 MPa; a) $T_f(t)$ approximated by function defined by eq. (4), b) approximated by function defined by eq. (5)

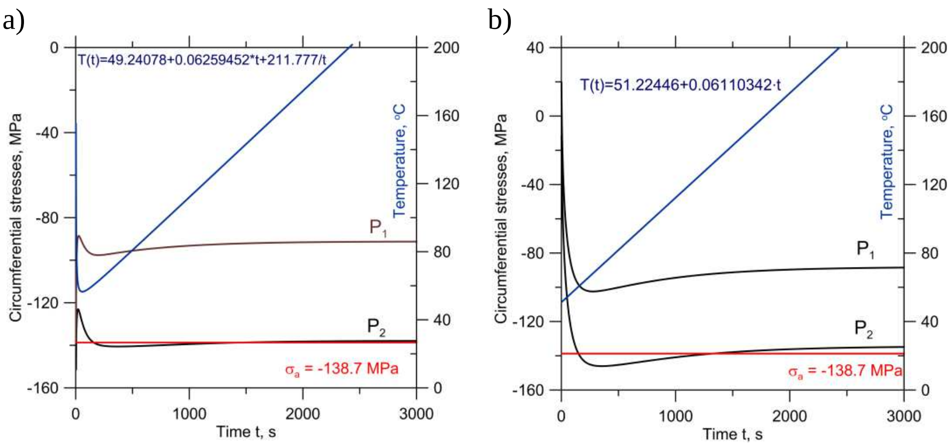

Fig.5. Total circumferential stress due to pressure and thermal load at points P_1 and P_2 during optimum drum heating for p_n = 10.87 MPa; a) $T_f(t)$ approximated by function defined by eq. (4), b) approximated by function defined by eq. (5)

Only at the beginning of the heating total stresses are slightly smaller than the allowable stress. When the optimum fluid temperature is prescribed by the ramp function (5), then the allowable stress is exceeded a little more at the beginning of the heating process (Figs. 4b and 5b). This is due to too simple form of the function (5) approximating the optimum temperature changes. However, the process of optimum fluid temperature changes, which is characterized by an initial temperature jump above the initial temperature of the pressure element and further increasing the temperature with a constant rate, is easy to implement in practice. The initial temperature jump is easy to conduct in practice by flooding the vessel with a hot water. Heating the drum with a constant rate can also be easily performed in practice. In the case of the drum boiler water temperature in the evaporator can be raised with a constant rate controlling the flow of the fuel mass supplied to the combustion chamber. From a mathematical point of view, it is possible to find a better form of the function approximating the optimum fluid temperature changes, it is however difficult to carry out in practice.

4. Conclusions

The method for optimizing the start-up process presented in the paper can be used to determine the optimum fluid temperature during heating steam boiler drums in fossil power plants and pressure vessels of nuclear reactors. In contrast to present standards, two points at the edge of the opening are taken into consideration. Because of the high thermal circumferential stress occurring at the point P_2 at the opening edge that is not sufficiently compensated by the tensile circumferential stress caused by the pressure, the circumferential stress at this point is critical for optimum heating of the pressure vessel. The compressive thermal stress at the point P_2 is compensated to a small extent by the tensile stress due to the pressure since the circumferential stress from the pressure at the point P_2 is almost five times smaller compared to the corresponding stress at the point P_1. The optimum temperature and pressure changes during heating of the pressure vessel should be determined with respect to the total circumferential stress at the point P_2, and not, as in the existing standards due to the stress at the point P_1. Optimum fluid temperature changes are assumed in the form of simple time functions. For practical reasons the optimum temperature in the ramp form is preferred. It is possible to increase the fluid temperature stepwise at the beginning of the heating process and then the fluid temperature can be increased with a constant rate. The rapid jump in the drum water temperature at the beginning of the boiler start-up may be obtained by filling the drum with hot water. By the stepwise increase in fluid temperature, heating time of the pressure vessel is shorter than heating time resulting from the calculations according to EN 12952-3 European Standard.

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OPTYMALNE NAGRZEWANIE KOTŁÓW WALCZAKOWYCH

Streszczenie

W pracy przedstawiono sposób wyznaczania optymalnych zmian temperatury czynnika. Nagrzewanie elementów ciśnieniowych jest prowadzone w taki sposób, aby obwodowe naprężenie na krawędzi otworu w punkcie koncentracji wywołane ciśnieniem i zmianami temperatury czynnika, nie przekraczały wartości dopuszczalnej. W przeciwieństwie do aktualnych norm, analizowany jest rozkład naprężeń w dwóch punktach na krawędzi otworu. Optymalne zmiany temperatury płynu przybliżane są w formie prostych funkcji czasu. Temperatura czynnika na początku procesu nagrzewania zmienienia się skokowo a następnie wzrasta ze stałą prędkością. Temperatura czynnika na początku procesu nagrzewania zmienienia się skokowo, a następnie wzrasta ze stałą prędkością.

Słowa kluczowe: naprężenia cieplne, odwrotny problem przewodzenia ciepła, naczynia ciśnieniowe, przepisy kotłowe

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