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A COMPARISON OF ALLOWABLE HEATING AND COOLING RATES BASED ON TRD REGULATIONS AND PN-EN 12952-3 CODE FOR T-PIPES OF 13HMF STEEL

PORÓWNANIE DOPUSZCZALNYCH SZYBKOŚCI NAGRZEWANIA I OCHŁADZANIA UZYSKANYCH W OPARCIU O PRZEPISY TRD I PN-EN 12952-3 DLA TRÓJNIKA ZE STALI 13HMF

Abstract

In this paper the calculation of allowable heating and cooling rates for pressurized elements of power plant unit are presented. The evaluation methodology are conducted according to two standards: TRD 301 and PN-EN 12952-3 code. The exemplary object is the T-pipe made of the steel 13HMF. The obtained results and related discussion are included.

Keywords: allowable rate heating and cooling, allowable stress, T-pipe

Streszczenie

W artykule przedstawiono obliczenia dopuszczalnych szybkości nagrzewania i ochładzania elementu ciśnieniowego bloku energetycznego w oparciu o przepisy TRD i PN-EN wykonane na przykładzie trójnika ze stali 13 HMF i omówiono przyczyny zaistniałych rozbieżności w wynikach.

Słowa kluczowe: dopuszczalna szybkość nagrzewania i ochładzania, naprężenia dopuszczalne, trójnik

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1. Introduction

The valid determination of the rates, which power plant pressurized elements may be heated and cooled, is very important because assuming invalid working parameters may lead to lesser durability of elements or their damage [4–6].

TRD 301 [2] regulations and PN-EN 12952-3 [1] code were utilized to evaluate allowable heating and cooling rates of power plant unit and subsequently a comparative analysis was conducted for T-pipe element (fig.1). The calculations were performed on the base of German TD 301 regulations (Technische Regeln für Dampfkessel) and simultaneously on the base of PN-EN 12952-3:2004/Ap1:2005 code. The mentioned T-pipe is typically utilized in fresh steam pipes and overheated steam pipes located in a unit of 360 MW power plant. It is made of ferritic 13HMF steel.

2. Geometrical dimensions and working conditions

Material properties of 13HMF steel may be read from strength tables for assigned temperature or evaluated from a linear interpolation. The basic strength properties of 13HMF steel are presented in the fig. 2.

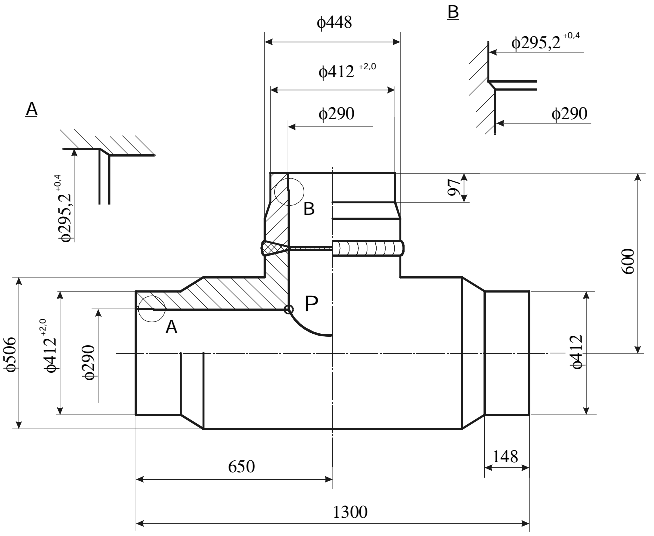

Fig. 1. T-pipe made from 13HMF steel

Rys. 1. Trójnik ze stali 13HMF

It may be accounted, while comparing TRD 301 regulations and PN-EN 12952-3 code, that they introduced different symbols for parameters. The basic parameters and their substitutes in TRD 301 and PN-EN 12952-3 code are presented in the paper [3]. For describing both cases of evaluating allowable heating and cooling rates in the mentioned article, the author involved parameters' symbol according to PN-EN 12952-3 code.

The T-pipe has following dimensions: $d_o = 506$ mm is an external diameter, $d_i = 290$ mm is an internal diameter, $d_{ob} = 448$ mm is an external diameter of a ramification, $d_{ib} = 290$ mm is an internal diameter of a ramification.

The working conditions of the T-pipe are described by the following steam's parameters: $p_{\min} = 0$ MPa as a minimum pressure in a cycle, $p_{\max} = 18$ MPa as a maximum pressure in a cycle, $t_{\min} = 20°C$ as a minimum temperature in a cycle, $t_{\max} = 540°C$ as a maximum temperature in a cycle, $n = 2000$ required number of starting and stopping phases. The number of cycles prior to the appearance of cracks is calculated by the formula $n_{\max} = 5 \cdot n = 10000$. The value of working usage pressure p is taken to be the maximum working steam pressure medium which may appear in the unit. It is equal to $p = 18$ MPa.

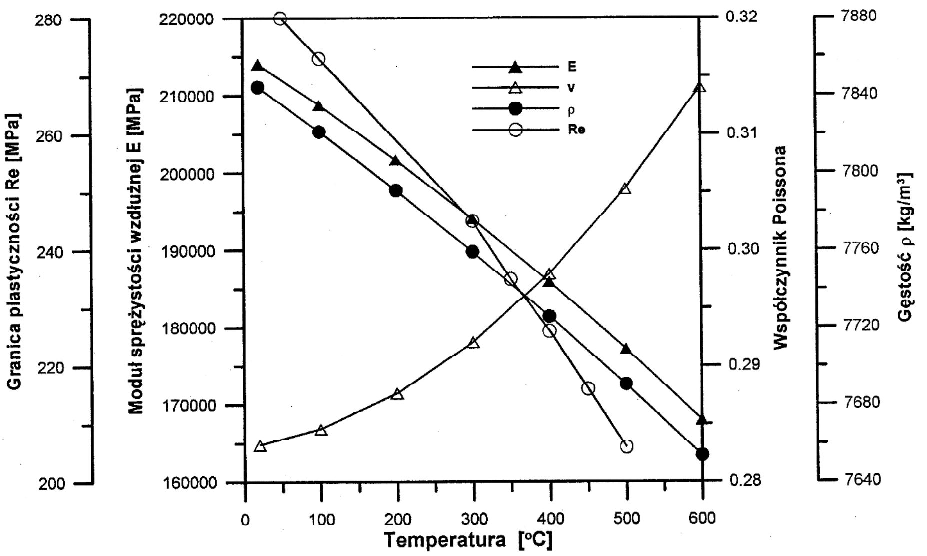

Fig. 2. The basic strength properties of 13HMF steel

Rys. 2. Podstawowe własności wytrzymałościowe stali 13HMF

For the mentioned element made of the 13HMF steel, the following material properties were determined: the minimum tensile strength $R_m = 430$ MPa, the Poisson's ratio $v = 0,3$. For the mentioned load cycle, the substitute reference temperature $t^* = 410°C$ was evaluated basing on the formula:

$$t^* = 0,75 \cdot t_{\max} + 0,5 \cdot t_{\min} \tag{1}$$

The following material properties were determined for that substitute temperature t^*: the elastic modulus $E_{t^*} = 1,841 \cdot 10^5$ MPa, minimum yield strength $R_{et^*} = 224$ MPa, linear coefficient of thermal expansion $\beta_{Lt^*} = 1,404 \cdot 10^{-5}$ K^{-1} and temperature equalization factor $D_{th} = 528$ mm^2/min.

3. Evaluation of allowable heating and cooling rates according to TRD regulations

The sediment is accumulated on the internal walls of the T-pipe during working life. Taking it into consideration, TRD 301 [2] regulations introduces formulas basing on the T-pipe dimensions for special factors which have to be determined and introduced into evaluation process. The factors are:

- a substituted wall thickness $e_{ms} = 124{,}2$ mm,
- a substituted internal diameter of the T-pipe $d_i = 257{,}6$ mm,
- an average diameter of the T-pipe $d_m = 381{,}8$ mm,
- a quotient of the external surface radius to the internal surface radius $u_0 = 1{,}964$.

Keeping determined geometrical parameters, the allowable amplitude of stress changes $2f_a$ were evaluated from the formula:

$$2f_a = A + B \cdot (n_{\max})^{\log(C)} \tag{2}$$

It is equal to $2f_a = 597{,}6$ MPa.

If the allowable range of stress changes at the reference temperature $2f_a$ is greater than or equal to doubled minimum yield strength at the reference temperature:

$$2f_a \geq 2 \cdot R_{et^*} \tag{3}$$

then reduced allowable range of stress changes $2f_{va}^*$ is determined from the fomula:

$$2f_{va}^* = \sqrt{2 \cdot R_{et^*} \cdot 2f_a} \tag{4}$$

The allowable range of stress changes at the reference temperature is equal to $2f_a = 597{,}6$ MPa. It means that it is greater than $2 \cdot R_{et^*}$ which is equal to 448 MPa. On that cause, it was assigned $2f_{va}^* = 517{,}4$ MPa.

The next step was an evaluation of stresses. The stress of a cylinder element induced by a working pressure p_0 are equal to $f_{\mathrm{tang},\, p0} = 88{,}5$ MPa. It was evaluated from the formula:

$$f_{\mathrm{tang}\ p} = \alpha_m(p) \cdot p \cdot \frac{d_m}{2 \cdot e_{ms}} \tag{5}$$

The stress concentration factor α_m involved in the expression (5) is evaluated from the formula:

$$\alpha_m(p) = \alpha_{m0} \cdot f_4 + 2 \cdot f_u(p) \tag{6}$$

where:

α_{m0} – theoretical stress concentration factor.

The factor $f_u(p)$ dependent on the ovality is assumed to be equal to 0 on the cause of the assumption of the ovality $U = 0$. The value of the factor f_4 for the processed surfaces is taken from codes as $f_4 = 1$. The theoretical stress concentration factor α_{m0} is assigned to $\alpha_{m0} = 3{,}2$ as recommended in codes. In the general, it leads to $\alpha_m(p)$ equal to $\alpha_m(p) = 3{,}2$.

The stresses $f_{\tan g\, p,\max}$ appearing in the element and induced by the maximum pressure $p_{\max}$ are evaluated from the formula (5) with pressure p substituted by the maximum pressure $p_{\max}$. It leads to $f_{\tan g\, p,\max} = 88{,}5$ MPa. Analogically, the stress $f_{\tan g\, p,\min}$ induced by the minimum pressure $p_{\min}$ was evaluated. It is equal to $f_{\tan g\, p,\min} = 0$ MPa.

For the evaluation of the minimum stresses in the cycle, it was assumed that:

$$f_{\tan g,\,\min} = f_{\tan g\; p,\,\min} + \frac{f_{\tan g\; p,\,\max} - f_{\tan g\; p,\,\min} - 2\cdot f_{va}^{*}}{1-g} \tag{7}$$

where:

$f_{\tan g\, p,\min}$ – is the element stress induced by the minimum pressure,
$f_{\tan g\, p,\max}$ – is the element stress induced by the maximum pressure,
$2f_{va}^{*}$ – is the reduced allowable range of stress changes,
g – is absolute quotient of the cooling rate at the beginning of the stopping phase to the heating rate at the beginning of the starting phase.

For the same rates of starting and stopping, the value of g is assumed to be equal to $g = 1{,}0$. In the conclusion, it leads to the minimum stress in the cycle equal to $f_{\tan g,\min} = -214{,}5$ MPa.

The maximum stress in the cycle is evaluated from the formula:

$$f_{\tan g,\,\max} = 2 f_{va}^{*} + f_{\tan g,\,\min} \tag{8}$$

It is equal to $f_{\tan g,\max} = 303{,}0$ MPa.

Keeping determined maximum and minimum allowable stresses, the allowable temperature differences were evaluated and finally the allowable heating and cooling rates were determined. The allowable temperature difference (a difference between element internal surface temperature and an average temperature of the wall) was evaluated on the base of formulas for four cases: the beginning of the starting phase, the end of the starting phase, the beginning of the stopping phase, the end of the stopping phase.

At the beginning of the starting phase, the allowable temperature difference was evaluated from the formula:

$$\Delta_{t1} = \frac{0{,}35}{\beta_{Lt^{*}} \cdot E_{t^{*}}} \cdot \left(f_{\tan g,\,\min} - f_{\tan g\; p,\,\min}\right) \tag{9}$$

At the end of the starting phase, the allowable temperature difference was evaluated from the formula:

$$\Delta_{t1'} = \frac{0{,}35}{\beta_{Lt^{*}} \cdot E_{t^{*}}} \cdot \left(f_{\tan g,\,\min} - f_{\tan g\; p,\,\max}\right) \tag{10}$$

At the beginning of the stopping phase, the allowable temperature difference was evaluated from the formula:

$$\Delta_{t1} = \frac{0{,}35}{\beta_{Lt^{*}} \cdot E_{t^{*}}} \cdot \left(f_{\tan g,\,\max} - f_{\tan g\, p,\,\max}\right) \tag{11}$$

At the end of the stopping phase, the allowable temperature difference was evaluated from the formula:

$$\Delta_{t1'} = \frac{0,35}{\beta_{Lt^*} \cdot E_{t^*}} \cdot (f_{\tan g,\, \max} - f_{\tan g,\, \min}) \tag{12}$$

The differences are equal to: $\Delta_{t1} = -29{,}04$ K, $\Delta_{t1'} = -41{,}03$ K, $\Delta_{t2} = 29{,}04$ K, $\Delta t_{2'} = -41{,}03$ K.

For the formulas simplicity, a factor V was introduced into formulas evaluating allowable heating and cooling rates:

$$V = \frac{D_{th}}{\gamma_{\text{cyl}} \cdot e_{ms}{}^{2}} \tag{13}$$

where:

D_{th} – is the temperature equalization factor at the reference temperature,
γ_{cyl} – is the shape factor.

The shape factor γ_{cyl} is evaluated from the formula:

$$\gamma_{\text{cyl}} = \frac{1}{8} \cdot \frac{(u_o{}^2 - 1) \cdot (3 \cdot u_o{}^2 - 1) - 4 \cdot u_o\, 4 \cdot \ln(u_o)}{(u_o{}^2 - 1) \cdot (u_o{}^2 - 1)^2} \tag{14}$$

and it is equal to $\gamma_{cyl} = -0{,}469$. It leads to V equal to $V = -0{,}073$ min^{-1}. Finally, the allowable heating and cooling rates for the element may be evaluated from the formula (20) by exchanging the variable Δ_t with particular allowable temperature differences:

$$v_{t1} = V \cdot \Delta_t \tag{15}$$

It leads to the following allowable heating and cooling rates: at the beginning of the starting phase $v_{t1} = 2{,}12$ K/min, at the end of the starting phase $v_{t1'} = 2{,}99$ K/min, at the beginning of the stopping phase $v_{t2} = -2{,}12$ K/min, at the end of the stopping phase $v_{t2'} = -2{,}99$ K/min.

4. Evaluating of the allowable heating and cooling rates on the base of PN-EN 12952-3 code

In the beginning of the allowable heating and cooling rates for elements, the additional geometrical parameters need to be determined. They are: an average diameter of the T-pipe which is equal to $d_{ms} = 381{,}8$ mm, an average diameter of the ramification which is equal to $d_{mb} = 357{,}1$ mm, a T-pipe wall thickness which is equal to $e_{ms} = 124{,}2$ mm, a ramification wall thickness which is equal to $e_{mb} = 90{,}85$ mm, a quotient of the average ramification diameter to the T-pipe diameter which is equal to $z = 0{,}94$.

The next steps are an evaluation – as recommended by PN-EN 12952-3 code – of stresses induced by a pressure and the minimum and maximum stress in the cycle. The stress $f_{\text{tang},\, p0}$ induced by a working pressure p_0 is equal to $f_{\text{tang},\, p0} = 97{,}88$ MPa. It is evaluated from the formula (5) with the stress concentration factor equal to $\alpha_m = 3{,}538$. The value of α_m is evaluated from the formula:

$$\alpha_m = 2{,}2 + e^{A} \cdot \zeta^{B} \tag{16}$$

The stress $f_{\mathrm{tang}\,p,\max}$ appearing in the element and induced by the maximum pressure $p_{\max}$ is evaluated from the formula (5) with a pressure exchanged with the maximum pressure $p_{\max}$. It is equal to $f_{\mathrm{tang}\,p,\max} = 97{,}88$ MPa. Analogically, the stress $f_{\mathrm{tang}\,p,\min}$ induced by the minimum pressure $p_{\min}$ was evaluated. It is equal to $f_{\mathrm{tang}\,p,\min} = 0$ MPa. The minimum stress in the cycle is evaluated from the formula:

$$f_{\tan g,\,\min} = f_{\tan g,\,p\min} + g_s \cdot (f_{\tan g,\,p\max} - f_{\tan g,\,p\min} - \Delta f_v) \tag{17}$$

where:

Δfv – is the amplitude of the reference stress which is equal to 509,5 MPa.

The minimum stress in the cycle is equal to ftang, min = –205,80 MPa. The maximum stress in the cycle is evaluated from the formula:

$$f_{\mathrm{tang},\,\max} = f_{\mathrm{tang},\,\min} + \Delta f_v \tag{18}$$

The stress concentration factor α_t involved in the previous equation is equal to $\alpha_t = 0{,}911$ and it is evaluated from the formula:

$$\alpha_t = \left\{ \left[2 - \frac{h + 2700}{h + 1700} \cdot z + \frac{h}{h + 1700} \cdot (\exp(-7 \cdot z) - 1 \right]^2 + 0{,}81 \cdot z^2 \right\}^{\frac{1}{2}} \tag{19}$$

where:

h – is the heat penetration factor which is equal 1000 W/m^{2}K for a steam,

z – is a quotient of the average ramification diameter to the average T-pipe body diameter.

At the beginning of the starting phase, the allowable temperature difference is determined from the formula:

$$(p = p_{\min}): \quad \Delta t_1 = \frac{(f_{\tan g,\,\min} - \Delta f_{\tan g,\,p\min})}{\frac{\alpha_t \cdot \beta_{Lt}{}^{*} \cdot E_t{}^{*}}{1-\nu}} \tag{20}$$

At the end of the starting phase, the allowable temperature difference is determined from the formula:

$$(p = p_{\max}): \quad \Delta t_1^{'} = \frac{(f_{\tan g,\,\min} - \Delta f_{\tan g,\,p\max})}{\frac{\alpha_t \cdot \beta_{Lt}{}^{*} \cdot E_t{}^{*}}{1-\nu}} \tag{21}$$

At the beginning of the stopping phase, the allowable temperature difference is determined from the formula:

$$(p = p_{\max}): \quad \Delta t_2 = \frac{(f_{\tan g,\max} - \Delta f_{\tan g,p\max})}{\frac{\alpha_t \cdot \beta_{Lt}{}^* \cdot E_t{}^*}{1-\nu}} \tag{22}$$

At the end of the stopping phase, the allowable temperature difference is determined from the formula:

$$(p = p_{\min}): \quad \Delta t_2^{'} = \frac{(f_{\tan g,\max} - \Delta f_{\tan g,p\min})}{\frac{\alpha_t \cdot \beta_{Lt}{}^* \cdot E_t{}^*}{1-\nu}} \tag{23}$$

The allowable temperature differences are equal to: $\Delta t_1 = -61{,}17$ K, $\Delta t_{1'} = -90{,}27$ K, $\Delta t_2 = 61{,}17$ K, $\Delta t_{2'} = 90{,}27$ K.

On the base of allowable temperature differences, the allowable heating and cooling rates were calculated from the formula:

$$v_t = \Delta t \cdot \frac{D_{th}}{\text{cyl} \cdot e_{ms}^2} \tag{24}$$

The shape factor γ_{cyl} involved in the equation above is evaluated from the formula (14) and it is equal to $\gamma_{\text{cyl}} = -0{,}469$.

The allowable heating rates at the beginning of the starting phase is evaluated from expression (24) with Δt substituted by Δt_1. It is equal to $v_{t1} = 4{,}46$ K/min. The allowable heating rate at the end of the starting phase is evaluated from the expression (24) with Δt substituted by $\Delta t_{1'}$. It is equal to $v_{t1} = 6{,}59$ K/min. The allowable cooling rate at the beginning of the stopping phase is evaluated from the expression (24) with Δt substituted by Δt_2. It is equal to $v_{t1} = -4{,}46$ K/min. The cooling rate at the end of the stopping phase is evaluated from the expression (24). It is equal to $v_{t1} = -6{,}59$ K/min.

5. Conclusions

The allowable heating and cooling rates for pressurized elements of power plant unit were evaluated on the base of two methods and two, substantially different results were obtained. It is caused by differences between regulations of TRD and PN-EN 12952-3 code. One of the important differences is the stress concentration factor. In the case of TRD regulations, the factor is equal to 1,5 or 2. In the case of 12952-3 code, the factor is evaluated from the formula (19). The methodology for stress calculations are also different in TRD 301 and PN-EN 12952-3. The PN-EN code introduces correction factor related to temperature influence. The factor does not appear in TRD 301.

The next difference appears in the calculation of the allowable temperature differences. The equality between TRD 301 and PN-EN 12952-3 may appear only if the expression:

$$\frac{\alpha_t}{1-\nu} = 0{,}35 \tag{25}$$

is satisfied. The PN-EN code recommends to verify results by numerical methods for more precise values.

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