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MODELING OF STRESS STATE IN THICK WALLED PRESSURE ELEMENT BASED ON EUROPEAN STANDARDS AND PROPOSED CREEP EQUATION

MODELOWANIE STANU NAPRĘŻENIA W ELEMENCIE CIŚNIENIOWYM ZGODNIE Z EUROPEJSKIMI NORMAMI I ZAPROPONOWANYM RÓWNANIEM PEŁZANIA

Abstract

The elements subjected to high temperatures are exposed to phenomena such as the creep, where time-dependent properties of materials should be considered. Many devices of the steam boiler work in creep conditions, what limits the time of their work. The chosen thick-walled superheater header is exposed to a high temperature and pressure and therefore it should be designed according to the European Standards. In this article, the standard requirements for a component operating in creep conditions are presented, and the FEM analysis is performed. In the FEM analysis, the proposed creep equation is used based on the results obtained from experimental tests.

Keywords: *power boilers, creep, lifetime, FEM analysis*

Streszczenie

Elementy poddane wysokim temperaturom są narażone na zjawiska, takie jak pełzanie, gdzie czasowo zależne własności materiałowe powinny być uwzględnione. W kotłach parowych duża część urządzeń pracuje w warunkach pełzania, co ogranicza czas pracy tych części ciśnieniowych. Wybrana do analizy grubościenna komora wylotowa przegrzewacza pary jest narażona na działanie wysokiej temperatury oraz ciśnienia, dlatego też projektuje się ją zgodnie z Normami Europejskimi. W artykule zaprezentowano wymagania normowe dla komór pracujących w warunkach pełzania oraz przedstawiono analizę MES. W analizie MES wykorzystano zaproponowane równanie pełzania, bazując na wynikach eksperymentalnych.

Słowa kluczowe: *kotły energetyczne, pełzanie, żywotność, analiza MES*

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1. Introduction

A lot of pressure elements of power boilers are subjected to high temperatures, what determines the lifetime of these devices. The creep is the main phenomenon which limits the operation time of these devices.

A lot of failures in power boilers occur in cylindrical elements in stress concentration areas and these parts of components should be monitored.

The pressure parts of boilers are described in the European Directive 97/23/WE (PED) [1] and should be calculated according to the harmonized norms: EN 12952-3 [2] and EN13445-3 [3].

In this article, the European Norms requirements and FEM analysis for the superheater outlet header SH3 is presented. In the FEM analysis the proposed creep equation is used which is based on the results obtained from experimental tests.

2. Requirements of European Norms

Water-tube boiler pressure parts must be designed in accordance with the requirements of European Standard EN 12952-3. The wall thickness and other dimensions of pressure parts should be sufficient to withstand the calculation pressure at calculation temperature for the designed lifetime.

The calculations according to EN 12952-3 are based on the design by formulas (DBF). The DBF method may not be enough for complicated shapes of headers with nozzles, and for temperature and time dependent phenomena. This method can be supplemented by calculations based on the design by finite element analysis (DBA) – according to EN 13445-3.

2.1. Allowable stress

The stress in pressure elements must not exceed the allowable stress f_1 for elastic conditions [2]. This allowable stress (according to EN 12952) is a function the proof strength or the tensile strength at calculation temperature (equation 1), divided by the safety factor.

$$f_1 = \frac{K}{S_1} \tag{1}$$

where:

f_1 – the allowable stress for elastic condition, MPa,
K – the material strength value for the design conditions, MPa,
S_1 – the safety factor for the elastic conditions.

The allowable stress f_2 for the creep conditions is based on the temperature and time dependent properties of metals (equation 2). This property according to EN 12952 is the creep rupture strength $R_{m\,t\,Tc}$ for the specified lifetime.

$$f_2 = \frac{R_{m\,t\,Tc}}{S_2} \tag{2}$$

where:

f_2 – the allowable stress for the creep condition, MPa,
$R_{m\,t\,Tc}$ – creep rupture strength, MPa,
S_2 – the safety factor for the creep conditions,

subscript:

t – the lifetime [h],
T_c – the temperature for the creep conditions [°C],

The rupture strength should be defined based on the calculation temperature T_c and the assumed lifetime t. The lifetime for the analyzed boiler elements is t = 200 000 [h]. For this lifetime the safety factor is S = 1.25, and the allowable stress is $f_2 = R_{m200\,000\,Tc}/1.25$. For exceptional cases, when the data of the rupture strength is not available for t = 200 000 [h], then 100 000 [h] data may be used ($R_{m\,t\,Tc}$ for t = 100 000 [h]), and the safety factor is then equal to S = 1.5. For short duration time, the creep rupture strength may be reduced to 10 000 [h], and then the safety factor is S = 1.25. These safety factors for each time are presented in table 1.

Table 1

Safety factor as a function of mean creep strength related to time

Time [h]	Safety factor S_2
200 000	1.25
100 000	1.5
10 000	1.25

2.2. Creep design check

According to EN 12952-3 the required wall thickness is estimated based on the simple calculation (the DBF method). For pressure and temperature load cases, the stress in the cylindrical header is equal (equation 3):

$$\sigma_1 = p_c \cdot \left(\frac{1}{2} + \frac{d_{is}}{2 \cdot e \cdot v} \right) \tag{3}$$

where:

σ_1 – he hoop stress in a cylindrical element, MPa,
d_{is} – the inside diameter of a header, MPa,
e – the thickness of a cylindrical header, mm,
v – the efficiency factor for adjacent branches or isolated openings.

The stress σ_1 must be less or equal to the allowable stress f for the creep load case and elastic load case (equation 4):

$$\sigma_1 \leq f = \min(f_1, f_2) \tag{4}$$

where:

f – allowable stress for all load cases, MPa,
σ_1 – the hoop stress in a cylindrical element, MPa,
f_1 – the design stress for an elastic condition, MPa,
f_2 – the design stress for the creep condition, MPa.

Equation 3 using efficiency factor v gives conservative results. The factor v estimation method is described in detail in EN 12952-3. For this reason the FEM analysis (the DBA method) is often used [4]. Requirements and assumptions for this analysis can be found in EN 13445-3. According to EN 13445-3 (for FEM analysis) if the creep checks are required, the two design checks should be considered:

- Creep Rupture Design Check (CR),
- Excessive Creep Strain Design Check (ECS).

The Creep Rupture Design (CR) needs to be checked whether the stress does not exceed design material strength parameters RM divided by partial safety factor γ_R. These material parameters depend on the kind of material and monitoring lifetime (table 2). For load cases without monitoring strength parameter RM is equal to the creep rupture strength $R_{m\,t\,Tc}$, and the safety factor is $\gamma_R = 1.25$. For the CR method one should take into account the following conditions:

- linear-elastic ideal-plastic constitutive law (if the design creep constitutive law is not reached),
- von Mises' yield condition and associated flow rule.

Table 2

RM and γ_R for CR load cases without monitoring

Material	RM	γ_R
Steel	$R_{m\,t\,Tc}$	$1.25 \text{ if } \frac{R_{m\,t\,Tc}}{R_{p1.0\,t\,Tc}} '' 1.5 \quad \textit{otherwise} \quad \frac{1}{1.2} \cdot \frac{R_{m\,t\,Tc}}{R_{p1.0\,t\,Tc}} \leq 1.5$

For Excessive Creep Strain (ECS) in only one condition to meet:

- in each point of the structure, the accumulated equivalent structural creep strain, must not exceed 5%.

This rule can be used, if the design creep's constitutive law is reached.

3. Numerical example

For a thick-walled pressure element in the numerical example has been chosen the outlet header of superheater. It is the part of a power boiler. Its geometry is presented in Fig. 1.

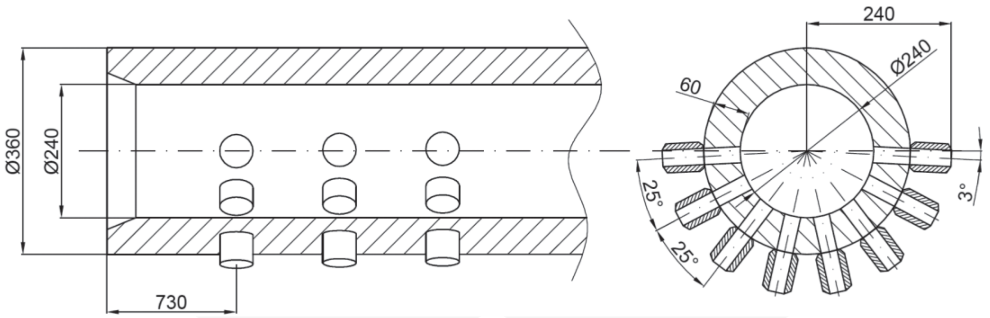

Fig. 1. The outlet header SH3 dimensions

Its outside and inside diameters equal respectively 360 mm and 240 mm. The tubes connected to the header has the diameter of 52 mm and the thickness of 10mm. The outlet header is made of P91 steel. The calculation parameters are: pressure *P* = 284 [bar], and temperature *T* = 569 [°C].

3.1. Mechanical properties and creep equation

Steel P91 is often used for components of steam boilers because of high heat resistance and the improved properties in creep conditions. The mechanical and physical properties of P91 steel are presented in the Figure 2 [6].

The creep equation for P91 is built on the base of the uniaxial homogeneous stress states realized in standard material testing [7]. The load and the temperature are kept constant during the test and the axial engineering strain ε is plotted versus time *t*.

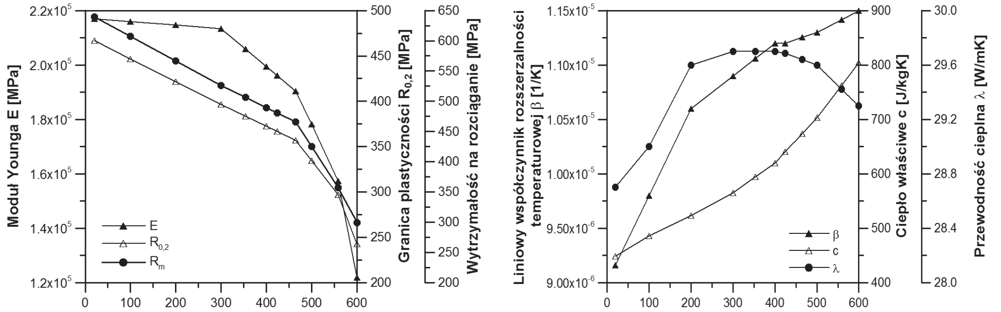

Fig. 2. The mechanical and physical properties of steel P91

Experimental data is interpolated using the modified Garofalo creep equation [8]. Coefficients in this equation describe physical magnitudes. This model describes well the first and the second stage of creep, but also takes the third stage of this phenomenon into account.

3.2. Finite Element Model

The numerical model of the header was built in ANSYS [9] and is presented in Fig. 3. The mesh of model consists of 8-node "brick" elements, which are described by linear shape functions.

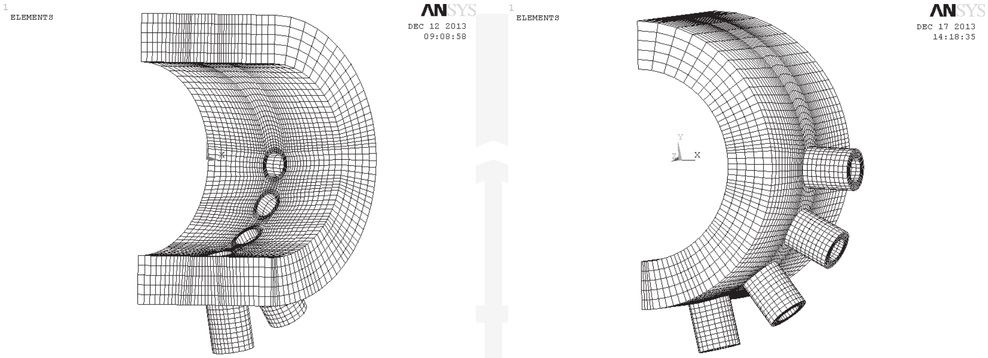

Fig. 3. Discretization of the outlet header SH3

The analyzed model is constrained to provide symmetry conditions and to prevent rigid movement of the body.

3.3. Results of FEM analysis

As the result of internal pressure P = 284 [bar] loading and temperature increase from 20[°C] to 569[°C] the stress concentration occurs on the inner surface in the opening for the nozzle. Fig. 4 presents the equivalent stress (HMH) distribution at the time t = 0 [h]. The maximum equivalent stress equals 207 [MPa]. This stress is lower than yield point, hence the plastic strain doesn't occur.

The distribution of equivalent strain (HMH) for time t = 0 [h] is shown in Fig. 5. The maximum equivalent strain equals ε = 0,13% and is located in the stress concentration point.

Numerical simulation of outlet header's work for 200 000 [h] is possible by using the chosen creep equation. Distribution of the equivalent stress (HMH) in time t = 200 000 [h] is shown in Fig. 6. The maximum equivalent stress equals 84 [MPa] and this stress decline is the result of the creep strain increase.

The maximum equivalent creep strain (HMH) after 200 000 [h] is 0.66%, and this is the main portion of the equivalent maximum total strain, which reaches about 0.71% (Fig. 7).

The conducted analysis of all creep strain components at the stress concentration point showed that this concentration is mainly caused by the circumferential strain.

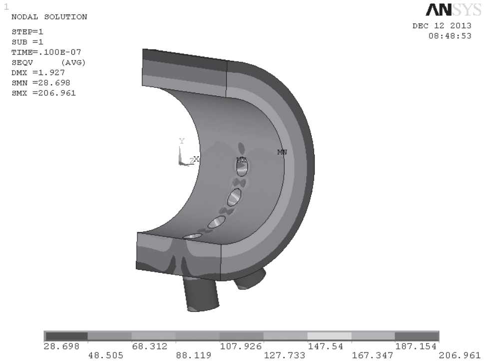

Fig. 4. Distribution of equivalent stress (HMH) for time *t* = 0 [h]

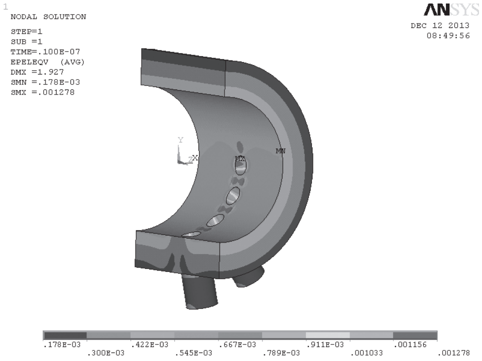

Fig. 5. Distribution of equivalent strain (HMH) for time *t* = 0 [h]

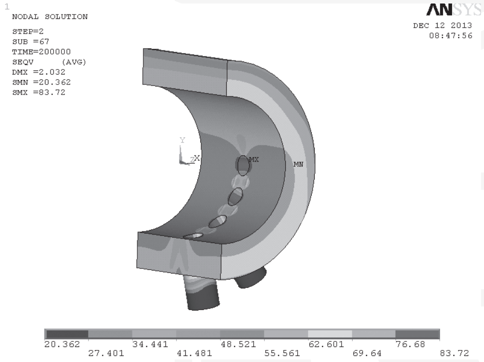

Fig. 6. Distribution of equivalent stress (HMH) for time *t* = 200 000 [h]

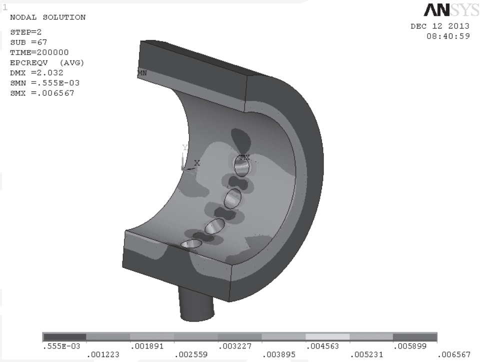

Fig. 7. Distribution of equivalent strain (HMH) for time *t* = 200 000 [h]

Assuming the value of the safety factor according to EN 13445-3 $\gamma_R = 1.25$ the allowable stress at 200 000 [h] equals $RM/\gamma_R = 122.5/1.25 = 98$ [MPa]. This means that the first condition for creep analysis according to EN 13445-2 is reached. The maximum equivalent strain calculated in the FEM analysis using the creep equation is less than 5%, which means that the second condition according to EN 13445-3 is obtained.

4. Conclusions

The strength analysis of the outlet header working under the creep conditions was described in this article. The analysis of thick walled element was based on the European standards and the proposed creep equation. Numerical analysis in ANSYS showed that equivalent stress (HMH) for 200 000 [h] is less than allowable stress 98 [MPa]. The maximum equivalent stress equals 84 [MPa] and this stress decline from 207 [MPa] at the time 0 [h] is the result of the creep strain increase. The results of the presented analysis showed that the main part of the equivalent strain is circumferential strain.

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