ISSN 1330-3651
UDC/UDK 620.169.1:539.42

ESTIMATE OF A POWER DISTRIBUTOR LIFE SPAN BASED ON THE FRACTURE MECHANICS CRITERIA

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Preliminary notes

Dimensioning of pressure vessels can be done according to various criteria, the basic one being the safety against the fracture by splashing. In this paper two methods for this dimensioning procedure are presented. The first one is based on application of the classical mechanics while the second one uses the fracture mechanics principles. Both methods were applied for checking the exploitation properties and capability of a vapor distributor in a power plant. Based on the in-situ measured damages and calculations by both methods, it was concluded that the vapor distributor could be further used as a part of the boiler installation in the local power plant. The second criterion, based on the application of the fracture mechanics principles, provided more reliable results than the first one, based on the classical mechanics.

Keywords: *creep crack growth, critical crack length, critical stress intensity factor, fatigue life, fracture mechanics approach, pressure vessel, power distributor*

Procjena vijeka trajanja razvodnika snage temeljena na kriterijima mehanike loma

Prethodno priopćene

Dimenzioniranje posuda pod tlakom može se vršiti prema različitim kriterijima, od kojih je jedan od osnovnih sigurnost protiv loma. U ovom radu su u tom smislu prezentirane dvije metode. Prva se bazira na primjeni klasične mehanike dok druga koristi principe mehanike loma. Obje metode su primijenjene za provjeru eksploatacijskih svojstava razvodnika snage u energetskom postrojenju. Na bazi in-situ izmjerenih oštećenja i proračuna po obje metode, zaključeno je da se razvodnik snage može i dalje koristiti kao dio kotlovske instalacije u lokalnoj termoelektrani. Drugi kriterij, baziran na principima mehanike loma, dao je pouzdanije rezultate nego prvi, baziran na klasičnoj mehanici.

Ključne riječi: *kritična duljina pukotine, kritični faktor intenzivnosti naprezanja, posuda pod tlakom, pristup temeljen na mehanici loma, rast pukotine uslijed puzanja, razvodnik snage, zamorni vijek*

1 Introduction
Uvod

The fracture mechanics application has introduced significant changes into the engineering practice, [1-6]. Those changes were caused by transition from the classical design principle of the components, to the design based on the safety against fracture principle [1]. The classical design principle was the so-called "safe-life" principle, where the remaining life-span of the component, which operates in the fatigue conditions, was determined, while the second principle is the so-called "fail-safe" principle.

The knowledge of the fatigue crack growth principles made possible, with sufficient reliability, establishing of the remaining life span of structural components containing a crack [2-3]. Thus, one can estimate whether the component can operate until the next control, namely even the most responsible components are not being replaced before the cracks or similar flaws are not discovered during the regular checkups. The component is designed in such a way that in the case of an existing crack, its life span is larger than the period until the next control. The crack size is smaller than the minimal one that can be detected by the non-destructive test methods. The component's life span is the period of the crack growth, from the noticed size until the critical one for the brittle fracture.

The basic change fracture mechanics application introduced into the engineering practice is acceptance of inevitability of existence of cracks and similar flaws, as well as awareness that they influence the structural components' life span. This made it possible to mathematically express the relationships between the three variables: stress, the flaw size and the fracture toughness, namely, one variable could be calculated if the other two were already known. For example, if stress is known, based on the applied load and geometry of the structure, as well as the material fracture toughness, based on experiments, one can determine the critical flaw size. A frequent case that appears in practice is that the crack is detected; then, considering that the material fracture toughness is known, the critical stress could be determined or vice-versa, the minimal fracture toughness can be determined if the structural stress state were known. This concept can be applied already in the structural design phase, if one assumes existence of a crack, whose sizes are of the same order of magnitude as the nondestructive testing equipment sensitivity. Then one can calculate the allowable stress based on the known fracture toughness, or vice-versa.

The methodology of fracture mechanics application depends on the available data, material behavior, environmental influences and structural loading. For the static load case, one should differentiate between the material behavior, which is described as linearly elastic, and the material behavior when the plasticity cannot be neglected. In the former case the linear elastic fracture mechanics (LEFM) is applied [7], while in the latter case, depending on the form of the material plastic flow, various forms of elastic-plastic fracture mechanics are used [8-10]. For the case of the dynamic material loading, special significance is attributed to the fatigue, as the typical mechanism of the crack growth under the action of the cyclic loading. Yet another mechanism of crack growth has to be taken into account at elevated temperature, i.e. creep, and its interaction with fatigue, as well [11-20]. The environmental influence can have the critical importance also due to elevated temperatures and/or corrosion.

In this paper two procedures of design were applied to estimate the life span of a power distributor. The measurements were performed and data obtained in the power plant "ZASTAVA-ENERGETICS", Kragujevac, Serbia.

2
Estimates of the life span of a pressure vessel
Procjena vijeka posude pod tlakom

Pressure vessels are manufactured in various geometrical shapes, sizes and are aimed for different purposes. They range from the small and simple reservoirs for air compressors up to extremely complex and large vessels in nuclear reactors.

The fundamental principle in designing the pressure vessels is to secure the corresponding safe limits, with respect to splashing fracture, when they are subjected to designed pressure. Experimental investigation performed pointed to the fact that the splashing pressure of vessels is closely related to tensile strength of materials. However, this is valid only in the case when the material properties depend on temperature only and not on time as well.

For the majority of carbon and low-alloyed steels, the allowable stresses correspond to about one quarter of the tensile strength. As the additional criterion the yield stress is added. This is done in order to prevent the large deformations of materials when their value is lower than the tensile strength. Based on these criteria, in an ideal case, the safety degree of 4 or higher could be expected, with respect to the splashing pressure of the vessel.

This limit could be increased or decreased due to the influence of various factors like the welded or other joints; breeches of pipes and other connections, which act as the stress concentrators; carriers and similar elements, which are welded to the pipe; cracks and other faults in the material, which can appear during manufacturing or during exploitation of the vessel.

In designing the pressure vessels, a relatively high safety degree is applied. However, the designed safety degree can be significantly decreased due to insufficient knowledge of all the operating conditions, inadequate quality control during manufacturing, or changes in operating conditions.

The sudden and unexpected brittle fracture, which can occur, represents a very serious and important problem in safety analysis and risks estimates. Such a fracture usually occurs either due to the reasons like the existing flaw, which can suddenly expand, or due to the interaction of an existing flaw and operating conditions influence.

2.1
Classical design method
Klasična metoda proračuna

The power distributor that was inspected in the "ZASTAVA-ENERGETICS" power plant was of a cylindrical shape and is presented in Fig. 1. Fig. 1a presents the photograph of the vessel while its scheme is presented in Fig. 1b.

To analyze the life span of this pressure vessel the thin walled cylinder subjected to internal pressure has been considered, Fig. 2. The cylinder is subjected to internal pressure p, it has the wall thickness t and diameter D. Due to the action of internal pressure the transversal and longitudinal stresses, $\sigma_{\theta\theta}$ and σ_{zz} appear whose values are defined by expressions ($\beta = 0°$)

$$\sigma_{\theta\theta} = \frac{p \cdot D}{t} \quad (1)$$

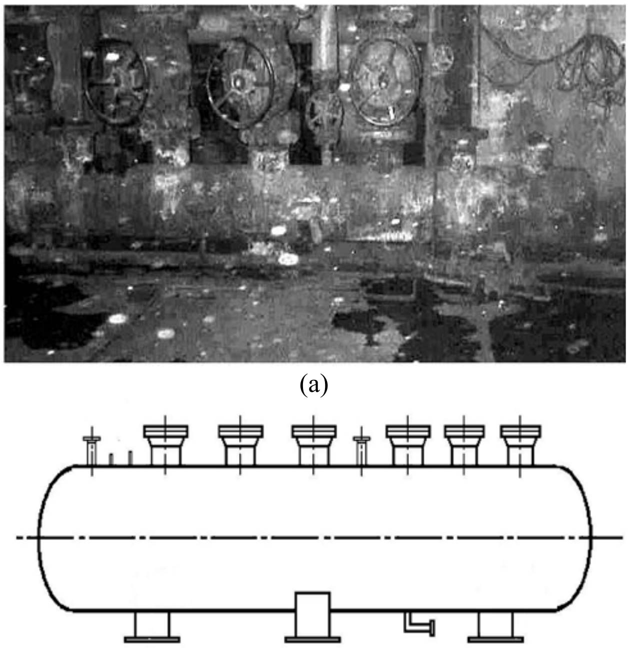

Figure 1 *The power distributor RP7: (a) photograph; (b) sketch*
Slika 1. *Razvodnik snage RP7: (a) slika; (b) skica*

and ($\beta = 90°$)

$$\sigma_{zz} = \frac{p \cdot D}{2 \cdot t}, \quad (2)$$

respectively.

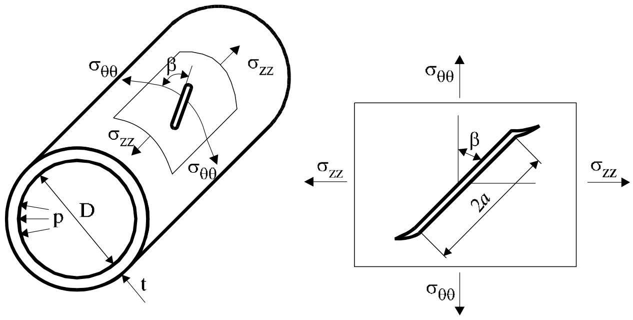

Figure 2 *The cracked thin-walled cylinder subjected to internal pressure*
Slika 2. *Napuknuti tankostjeni cilindar izložen unutarnjem tlaku*

The critical value of the cylinder wall thickness for the longitudinal crack, calculated based on the stress expression (1) is

$$t_{\mathrm{cr,\,l}} = \frac{p \cdot D}{R_{\mathrm{p0,2}}}, \quad (3)$$

while the critical value of the cylinder wall thickness for the transverse crack, calculated based on the stress expression (2) is

$$t_{\mathrm{cr,\,t}} = \frac{p \cdot D}{2 \cdot R_{\mathrm{p0,2}}}, \quad (4)$$

with $R_{\mathrm{p0,2}}$ being so-called technical yield stress value.

2.2
Fracture mechanics approach
Pristup mehanike loma

Within the fracture mechanics framework, the material is not considered as continuous, but as a solid body with a flaw. The most dangerous faults are of the thin cracks shape with particularly sharp tips. These flaws are the source of the stress concentration of different degrees. In this analysis it is assumed that the typical flaw in the pipe is a crack of the length $2a$ at angle β with respect to the transversal direction, Fig. 2. The material's strength, with respect to unstable growth of such a crack, is determined by the critical value of the stress intensity factor, K_{Ic}. The critical crack length can be determined from the expression

$$K_{\mathrm{Ic}} = \frac{p \cdot D}{2 \cdot t}\sqrt{\pi \cdot a_{\mathrm{cr}} \cdot (1+\sin^2\beta)} \tag{5}$$

i.e.,

$$a_{\mathrm{cr}} = \frac{4 \cdot K_{\mathrm{Ic}}^2 \cdot t^2}{\pi \cdot p^2 \cdot D^2 \cdot (1+\sin^2\beta)}. \tag{6}$$

2.3
Life span estimates
Procjena vijeka razvodnika

One of the major contributions of the fracture mechanics to estimate the constructive parts elements is the application of the crack growth criterion. The unstable crack growth occurs when the stress intensity factor K_I becomes higher than the experimentally determined material characteristics K_{Ic}. The crack growth equation gives the relationship between the crack length increase Δa and increase of the load cycles number ΔN. In the sixties of the last century Paris established that the variation of the stress intensity factor could describe the sub-critical crack growth in the fatigue loading conditions in the same manner as the stress intensity factor described the critical or the fast fracture [8]. He established that the crack growth speed was a linear function of the stress intensity factor variation in the logarithmic diagram, i.e.:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot \Delta K^m, \tag{7a}$$

$$K = \sigma \cdot \sqrt{\pi \cdot a};\ \Delta K = \Delta\sigma \cdot \left(\sqrt{\pi \cdot a}\right) Y(a) \tag{7b}$$

where: a is the critical crack length, which varies from the initial to the critical value that leads to fracture, N is the load cycles number, C and m are the material constants and ΔK is the stress intensity factor increment (i.e., the difference between the stress intensity factor values at maximal and minimal loads). For the majority of materials the value of m varies between 2 and 7.

Based on equation (7a) it becomes possible to obtain the quantitative predictions of the remaining life span for the crack of a certain length. By substituting equation (7b) into equation (7a) one obtains:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot (\Delta\sigma \cdot Y \cdot \sqrt{\pi \cdot a})^m. \tag{8}$$

By integration of equation (8) with respect to the crack length and solving for the number of load cycles that leads to fracture N_f, one obtains:

$$N_{\mathrm{f}} = \frac{2}{C \cdot Y^m \cdot (\Delta\sigma)^m \cdot \pi^{\frac{m}{2}} \cdot (m-2)} \cdot \left(a_{\mathrm{i}}^{1-\frac{m}{2}} - a_{\mathrm{cr}}^{1-\frac{m}{2}} \right), \tag{9}$$

where a_i and a_{cr} are the initial and the critical crack lengths, respectively, while C and Y are the material constants.

2.4
Creep crack growth
Rast pukotine puzanjem

Temperature over 450 °C has significant influence on crack growth, not only by an increasing effect, but also by introducing a new mechanism of crack growth – creep [2, 5]. In the case of stationary creep, the crack growth rate can be estimated by using an exponential equation:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \mathfrak{D} \cdot C^{*\Phi}, \tag{10}$$

where $\mathfrak{D}$ and Φ stand for material constant, and C^* is fracture mechanics parameter. For the pressure vessel components, parameter C^* can be evaluated as follows [10]:

$$C^* = \sigma \cdot \dot{\varepsilon} \cdot \left(\frac{K}{\sigma}\right)^2, \tag{11}$$

where $\dot{\varepsilon}$ stands for creep strain rate, σ is applied stress and K stress intensity factor. If $\dot{\varepsilon}$ is expressed according to the Norton's creep law:

$$\dot{\varepsilon} = A \cdot \sigma^n, \tag{12}$$

where A and n stand for material constants, eqn. (11) can be written as follows:

$$C^* = A \cdot \sigma^{n-1} \cdot K^2. \tag{13}$$

For the problem considered in this paper, the applied stress is:

$$\sigma = \frac{p}{\dfrac{1}{R_{\mathrm{e}} - a} \cdot \dfrac{a}{\sqrt{1 + 1{,}61 \cdot \dfrac{c^2}{(R_{\mathrm{e}} - a) \cdot a}}} + \ln\left(\dfrac{R_{\mathrm{e}} - a}{R_{\mathrm{i}}}\right)}, \tag{14}$$

where a is crack depth, c half crack length, R_i and R_e – inner and outer pipe radius.

2.5
Cumulative damage
Kumulativno oštećenje

Standard classification of damage growth, based on fatigue crack initiation and growth, is even more complicated in the case of creep and its interaction with fatigue. Combination of local crack growth and creep makes the assessment of the remaining life very complicated. In the simplest case, one can assume for the total crack growth rate:

$$\frac{\mathrm{d}a}{\mathrm{d}N}=\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\text{fatigue}}+\left(\frac{1}{f}\frac{\mathrm{d}a}{\mathrm{d}t}\right)_{\text{creep}}. \tag{15}$$

Besides eqn. (15) there are several methods for total crack growth rate evaluation, the Palmgren-Miner rule being most often used. This rule is based on linear superposition of damage at each load level with expected number of cycles N_i. Thus, the damage due to i-th load level can be expressed as:

$$\mathfrak{D}_i=\frac{1}{N_i}, \tag{16}$$

whereas after n_i cycle damage is:

$$n_i\mathfrak{D}_i=\frac{n_i}{N_i}. \tag{17}$$

Total damage due to total loading is:

$$\sum n_i\mathfrak{D}_i=\sum\frac{n_i}{N_i}. \tag{18}$$

Failure occurs when:

$$\sum n_i\mathfrak{D}_i=C, \tag{19}$$

where C is empirical constant between 0,7 and 2,2, typically C=1, [1]. By using equations (18) and (19), one finally gets:

$$\sum\frac{n_i}{N_i}\geq C. \tag{20}$$

3 The power distributor calculations
Proračun razdjelnika pare

Results of testing done on a power distributor RP7, Fig. 1, which was operating in the "ZASTAVA-ENERGETICS" power plant, are presented. The task was to give the expert opinion on its exploitation readiness, taking into account previously recorded damages. The power distributor RP7 was in exploitation for 20 years and on its wall, at the lowest point, damages appeared in the form of erosion cracks, Fig. 3. Those cracks resulted from the action of water and corrosion during exploitation itself and from an incomplete emptying of the distributor during periods when it was not in operation. The data acquired by the in-situ measurements of the distributor are presented in Tab. 1.

The replicas of the damages were taken in the line of the left hand side end and the right hand side end of the connectors – flanges, Fig. 3. The replica appearances are presented in Fig. 4. By measuring the replicas' sizes, the data were obtained, as presented in Tab. 2.

Based on previously presented calculations in Section 2 and data obtained by measurements of the damages (replicas), the calculations were performed of the critical wall thicknesses and the remaining life span of the distributor.

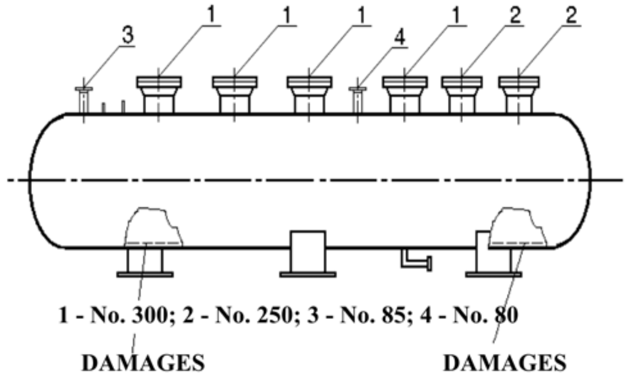

Figure 3 *The power distributor sketch showing places of erosion cracks*
Slika 3. *Slika razdjelnika pare s mjestima pukotina uslijed erozije*

Table 1 *The in-situ measurements data on the power distributor RP7*
Tablica 1. *Podaci in-situ mjerenja na razdjelniku snage RP7*

Nominal interior pressure	p = 3,8 MPa
Operating temperature	450 °C
Pipe diameter	D = 452 mm
Distributor material	16Mo3, EN 10028/2
Length (without bottom)	5600 mm
Interior cover diameter	508 mm
Cover wall thickness	30 mm
Bottom wall thickness	20 mm
Yield stress	$R_{p0,2}$ = 320 MPa
Critical stress intensity factor	$K_{Ic}=170\ \mathrm{MPa}\sqrt{\mathrm{m}}$

(a) (b)

Figure 4 *Formed replicas of the largest damages at the bottom of the boiler RP7; (a) The top view: Upper row - Damages at the left hand side end of flange; Lower row - Damages at the right hand side end of flange; (b) The side view*
Slika 4*. Kopije najvećih oštećenja na dnu kotla RP7; (a) Pogled odozgo: Gornji red - Oštećenja na lijevom kraju prirubnice; Donji red - Oštećenja na desnom kraju prirubnice; (b) Pogled sa strane*

Table 2 *Damage dimensions at critical points*
Slika 2. *Dimenzije oštećenja na kritičnim točkama*

Damage dimensions	The deepest damage / mm	The longest damage / mm
Depth	2,0	1,2
Surface width	3,0	2,5
Length	22,0	26,0

3.1 Calculations of the critical wall thickness
Proračun kritične debljine stijenke

These calculations are done based on application of the classical mechanics principles. The critical value of the pipe wall thickness for the longitudinal crack, according to equation (3) is:

$$t_{\mathrm{cr},1} = \frac{p \cdot D}{R_{\mathrm{p}0,2}} = \frac{3{,}8 \cdot 452}{320} \approx 5{,}4 \text{ mm.} \tag{21}$$

The critical value of the pipe wall thickness for the longitudinal crack, according to equation (4) is:

$$t_{\mathrm{cr,t}} = \frac{p \cdot D}{2 \cdot R_{\mathrm{p}0,2}} = \frac{3{,}8 \cdot 452}{2 \cdot 320} \approx 2{,}7 \text{ mm.} \tag{22}$$

According to the presented calculations, the calculated critical value of the pipe wall is 2,7 mm for the fracture in the transverse direction, while for the fracture in the longitudinal direction it is 5,4 mm. If the fracture is not purely transverse (the "mixed" fracture), the critical value of the pipe wall would be between 2,7 and 5,4 mm.

3.2. Calculations of the critical crack length
Proračun kritične duljine pukotine

These calculations are done based on the application of the fracture mechanics approach. The critical length of the transverse crack, obtained from equation (6) for $\beta = 0\,°$ is:

$$\begin{aligned} a_{\mathrm{cr,t}} &= \frac{4 \cdot K_{\mathrm{Ic}}^2 \cdot t_{\mathrm{cr,1}}^2}{\pi \cdot p^2 \cdot D^2 \cdot (1 + \sin^2 \beta)} = \\ &= \frac{4 \cdot 170^2 \cdot 5{,}4^2 \cdot 10^3}{\pi \cdot 3{,}8^2 \cdot 452^2 \cdot 1} = 363{,}7 \text{ mm,} \end{aligned} \tag{23}$$

while the critical length of the longitudinal crack, obtained from equation (6) for $\beta = 90°$ is:

$$\begin{aligned} a_{\mathrm{cr,1}} &= \frac{4 \cdot K_{\mathrm{Ic}}^2 \cdot t_{\mathrm{cr,t}}^2}{\pi \cdot p^2 \cdot D^2 \cdot (1 + \sin^2 \beta)} = \\ &= \frac{4 \cdot 170^2 \cdot 2{,}7^2 \cdot 10^3}{\pi \cdot 3{,}8^2 \cdot 452^2 \cdot 2} = 45{,}5 \text{ mm.} \end{aligned} \tag{24}$$

According to the presented calculations, the critical crack length for the longitudinal crack is 45,5 mm. That value of defect causes the catastrophic fracture if the pipe wall thickness is less than 2,7 mm. If at some point, the pipe wall thickness surpasses the value of 2,7 mm, the crack growth will be stopped.

If the fracture is not purely transverse or longitudinal, the critical value of the crack length should be taken in the range between 45,5 mm and 363,7 mm.

3.3 Calculations of the remaining life span
Proračun preostalog vijeka razvodnika

Considering that the largest recorded damage was of 2 mm depth, the lower limit for integration of equation (9), i.e. the initial crack length, will be a_i=0,002. The upper limit, i.e. the critical crack length will be a_{cr}=0,02 since that is the distributor wall thickness. Based on equation (1), with addition of the internal pressure, which acts on the crack surfaces, one will have the stress variation of $\Delta\sigma$=46,8 MPa. It is assumed that the operating conditions are regular. The constants are: Y=1,41, C=0,76×10^{-10} and m=4. By substituting these values into equation (9) one obtains the remaining number of cycles as:

$$\begin{aligned} N_{\mathrm{f}} &= \frac{2}{0{,}76 \cdot 10^{-10} \cdot 1{,}41^4 \cdot 46{,}8^4 \cdot \pi^2 \cdot 2} \cdot \left(\frac{1}{0{,}002} - \frac{1}{0{,}02} \right) = \\ &= 31663 \text{ cycles.} \end{aligned} \tag{25}$$

If 1 cycle = 1 day (daily emptying down to the zero working pressure), it means that the remaining life span of the tested vapor distributor is 86,75 years.

3.4 Calculation of creep crack growth
Proračun rasta pukotine uslijed puzanja

For the material used in this investigation creep parameters at 450 °C are as follows: $\mathfrak{D}$=1,44 (units correspond to the crack growth in rate mm/h and C^* in MPa/h), A=1,38×10^{-10} (units correspond to the strain rate in 1/h and σ in MPa), Φ =0,6 and n=7,38. Other quantities used for calculation are: R_e=246 mm, R_i=226 mm, a=2 mm, c=11 mm, K=170 MPa$\sqrt{\mathrm{m}}$ and p=3,8 MPa. Using eqns (10)-(14) one gets:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = 1{,}161 \times 10^{-4} \text{ mm/h.} \tag{26}$$

Having in mind that the wall thickness at damage location is 20 mm, the remaining creep life of distributor is 125 800 hours, i.e. over 43 years.

3.5 Calculation of cumulative damage
Proračun kumulativnog oštećenja

Using eqns (15), (8) and (20), as well as adopted value for cycle frequency f=0,125 Hz one gets:

$$\begin{aligned} \frac{\mathrm{d}a}{\mathrm{d}N} &= 6{,}3165 \times 10^{-4} + 9{,}288 \times 10^{-4} = \\ &= 1{,}56 \times 10^{-3} \text{ mm/cycle.} \end{aligned} \tag{27}$$

Having in mind that the wall thickness at damage location is 20 mm remaining, for 1 cycle per 1 day the remaining fatigue life is 35,1 years.

Taking into account eqns (20), (25), (26) and design working hours (100 000) one gets:

$$\frac{31\,663}{100\,000} + \frac{15\,695}{100\,000} = 0{,}32 + 0{,}16 = 0{,}48 \le 1. \tag{28}$$

meaning that in the design period the distributor will not fail.

4 Conclusions
Zaključci

From the theoretical point of view, one can notice that the fracture mechanics approach provided more reliable conclusions about the state of the considered pressure vessel. The classical mechanics approach results for the wall thickness critical limits were well within the safety region. Those equations do not take into account the flaws, namely the sources of stress concentration, which can cause catastrophic fracture even before the wall thickness is reduced to its critical value. From the theoretical standpoint, the appearance of the longitudinal cracks is more probable than the appearance of the transverse cracks. The reason for this lies in the fact that the value of critical stress for the transverse cracks is twice the corresponding value for the longitudinal cracks.

The observed damages' lengths were more critical than the depths. Thus, one can conclude that, if the checks of the vapor distributor had been performed only by the classical mechanics principles, the damages' depth into the wall thickness could have grown until the prescribed critical value. However, the critical crack length would have been reached long before that. The consequence would have been the catastrophic failure of the vessel with immense damage to the plant as a whole and with strong possibility of casualties.

Results of investigations, conducted on site, point to the unfavorable action of corrosion and erosive action of water, causing damage to the bottom part of the vapor distributor. However, none of the analyzed damages has reached such extent that the distributor cover thickness would be less than the critical value, as the performed calculations show. According to all previously stated, the conclusion was that the vapor distributor RP7 could be used, as is, as a part of the boiler installation.

Since there was a high probability that the noticed damages were going to increase their magnitude during further exploitation, it was suggested that the mandatory regular periodical inspections of the considered distributor be performed and the necessary reparatory measures applied.

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