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DETERMINING OF HOT WATER-PIPE EXPLOITATION TIME ON THE BASIS OF LIMITING STATES

WYZNACZANIE CZASU EKSPLOATACJI CIEPŁOCIĄGU NA PODSTAWIE IDENTYFIKACJI STANÓW GRANICZNYCH*

Methodology for determining the limiting time of the hot water-pipeline exploitation has been described in the present study. Pitting corrosion causing local reduction of the hot water-pipeline wall thickness was assumed as the basis of the limiting time determining. Three limiting states influencing the hot water-pipeline strength were taken into consideration in the executed analysis. It was estimated that the wall thickness distribution is consistent with normal distribution as well as that exceeding of the hot water-pipeline wall thickness limiting values within given probability level is a basis for the exploitation time determining.

Keywords: *hot water-pipeline, corrosion, limiting states, exploitation time.*

W artykule przedstawiono metodykę wyznaczania granicznego czasu eksploatacji rurociągu. Podstawą wyznaczenia tego czasu jest korozja wżerowa powodująca lokalne zmniejszanie grubości ścianek rurociągu. W analizie wzięto pod uwagę trzy stany graniczne decydujące o wytrzymałości rurociągu. Oszacowano, że rozkład grubości ścianek jest zgodny z rozkładem normalnym a przekroczenie granicznych wartości grubości ścianki rurociągu na zadanym poziomie prawdopodobieństwa jest podstawą do określenia czasu jego eksploatacji.

Słowa kluczowe: *ciepłociąg, korozja, stany graniczne, czas eksploatacji.*

1. Introduction

Occurrence of the corrosion in hot water-pipelines is the main cause of the exploitation properties reduction and with time the user is forced to make costly pipe replacements. Corrosion process inside hot water-pipeline is continuous and there are practically none possibilities to prevent the process.

In the worldwide literature there are many of positions concerning estimation of the gas transfer networks, which take under consideration the corrosion phenomena [2, 5]. Problems of the corrosion of hot water-pipelines are broadly discussed in [3, 4, 12]. The procedure presented in this paper is original and the authors focused their attention to the problems of the hot water-pipeline strength, with special attention paid to pitting corrosion phenomenon. Appearance of the corrosion pits has random character and the places of their occurrence are difficult to locate.

The authors have undertaken the difficult task of determining the hot water-pipeline exploitation time with respect to reaching the limiting times caused by exceeding permissible stresses within the pipe material resulting from development of corrosion pits.

Problems described in the present study concern a specific hot water-line exploited in one of Polish mines.

2. Characteristics of the corrosion process and determining the hot water-pipeline limiting states

Hot water-pipeline which is exposed to adverse impacts of water-based chemical environment and to appearance of variable loads (pressure pulsation), including random pulsation as a subject of progressive degradation, which takes place in result of the action of chemical compounds present in water, high temperature and time.

Occurring corrosion is considered as an electro-chemical process, which takes place in continuous manner and leads to deepening of the corrosion pits on the pipe wall [14]. These changes of the depth of the corrosive losses have character of quantitative changes (they can be measured). In consequence the limiting states of the hot water-pipeline walls are exceeded, what in turn results in break-down (qualitative change) or increased probability of the break-down occurrence.

Process of the corrosion pits deepening may be treated as random process consisting of successive phases related with change of the corrosion loses height and events leading to qualitative changes [6].

Periodical measurements of the wall thickness can be considered as controlled phases of the process development. After some time of the exploitation, the assumed critical states are exceeded, what is considered as events proving partial damages leading in consequence to break-down, which is in turn considered as the process failure (hot water-pipeline).

It can be characterized as a stochastic process $N(t)$ of integer-non-negative values and continuous time, both by the distribution of number of events taking place within time intervals having length corresponding to real process duration and distribution of the lengths of intervals between occurring events.

In a case described in the present study, the electro-chemical corrosion after a certain period of the hot water-pipeline exploitation, depth of corrosion pits becomes a random variable of defined probability distribution. Taking under consideration limiting values of the hot water-pipeline wall thickness and increase of the depth of corrosion pits, we can determine percentage fraction of the corrosion pits,

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** which are dangerous for the hot water-pipeline exploitation, as well as we can assess distribution, which characterizes increasing in time probability of the failure occurrence. Assuming a particular permissible level of risk of the failure, we can determine the hot water-pipeline exploitation time.

Determining of the hot water-pipeline exploitation time is not possible without determining the hot water-pipeline strength. Resistance to failures will depend both on external loads and course of the corrosion process development.

Circumferential stresses σ are generated within light-wall pipelines exposed to action of external pressure p, which have the same value within the whole pipeline thickness h (in given cross-section) [7, 8].

$$s = \frac{r \cdot p}{h} \quad (1)$$

$$r = \frac{(D_Z + D_W)}{4}$$

where:
r – mean pipe radius,
D_z – outside pipe diameter,
D_w – inside pipe diameter.

Thin wall condition in form $\frac{h}{r} \leq 0{,}2$ is satisfied.

Strength analysis of the pipeline can be considered on the basis of required thicknesses of the pipeline wall, assuming critical strength K_r:
- yield stress $K_r = R_e$,
- immediate strength $K_r = R_m$,
- and fatigue strength limit $K_r = Z_{rj}$.

Using the formula (1) we can determine the wall thickness:

$$h = \frac{D_Z \cdot p}{2 \cdot K_r + p} \quad (2)$$

Thickness of the pipeline walls h with respect to assumed values of critical stress K_r is schematically shown in Fig. 1.

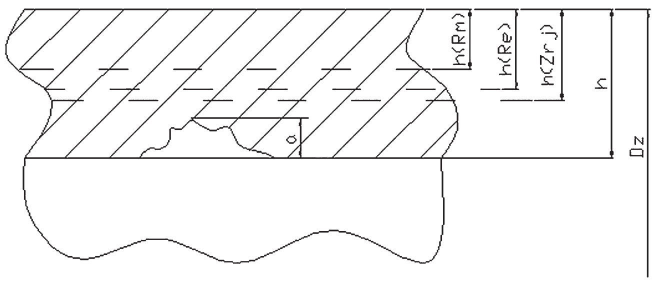


Fig. 1. Pipeline wall with example of corrosion pit and required limiting thicknesses

$h(R_m)$ – minimal permissible pipe thickness with respect to immediate strength,
$h(R_e)$ – minimal permissible pipe thickness with respect to yield stress,
$h(Z_{rj})$ – minimal permissible pipe thickness with respect to fatigue strength,
a – corrosion pit depth,
h – nominal pipe wall thickness.

3. The pipeline exploitation time calculation

One of the basic problems in the pipeline exploitation is related with assuring continuous and safe transport of the medium. In order to realize this task the user must control the pipeline condition, particularly consequent decrease of pipe strength, what can lead to the pipeline failure. Corrosion of the pipeline walls is one of factors influencing pipe weakening. If this process in continuous in time we can easily determine time, when we should undertaken suitable steps to avoid the pipeline failure.

The problem is much more complicated, if the pit corrosion occurs, as described in point 2. Change of the pipe wall thickness (and development of dip corrosion pits) is caused mostly by electro-chemical corrosion, resulting from high level of the water mineralization (presence of the great amounts of chlorides).

Beside uniform decrease of the wall thickness, some places with dip pits are observed, which can be considered as potential points of the failure occurrence – Fig. 1. Additional problem is related with the fact that the pits are usually scattered along the whole pipeline length, and they cannot be detected during the control. From the other side, control of the whole pipeline is often very costly and time-consuming, and sometimes simply impossible. Thus the user often faces the problem of determining the risk level of the pipeline exploitation, including time remaining until making decision preventing the failure, having incomplete information about the pipeline condition.

One possibility of calculation the mentioned values comprises use of probabilistic models describing wall thickness and corrosion pits distributions, including their changes in time.

Determining of the distribution of remaining wall thicknesses (or corrosion pits depth) of the tested pipeline can be executed on the basis of the executed depth measurements results. Based on the compatibility tests we can match suitable probability distribution and determine its parameters. Than taking under consideration the exploitation conditions, parameters of transported medium and their variability in time, the required limiting wall thickness value should be determined with respect to assumed critical state, as shown in 2. Having distribution of the wall thicknesses and required limiting values we can determine probability of exceeding the assumed limiting value. Wall thicknesses for normal distribution of the pipeline are shown in Fig. 2.

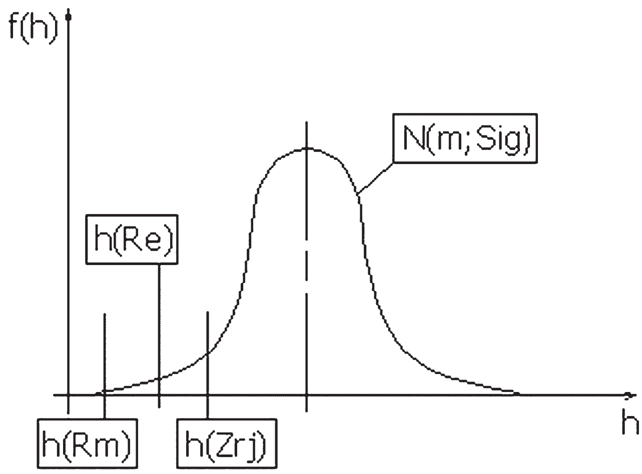


Fig. 2. Density function of the wall thicknesses distribution with required limiting thicknesses

Specified probability of exceeding the limiting value gives us information about the degree of failure risk in the moment when the wall thickness measurements were executed. However, designation of the time after which chosen critical state with assumed reliability level is reached, is also essential.

In connection with the ongoing corrosion process, determined distribution of the wall thicknesses will be gradually shifted. If you have the measurements of the wall thickness executed in various periods of the pipeline exploitation, their distributions and manner of the parameters change in time should be determined. If the executed analysis allows determining the distribution shifting manner, including character of these changes in time, we can on this basis make a prognosis of the distribution changes in time. Then using method of successive approximation we can determine time after which the wall thickness reaches limiting value on assumed probability level – Fig. 3.

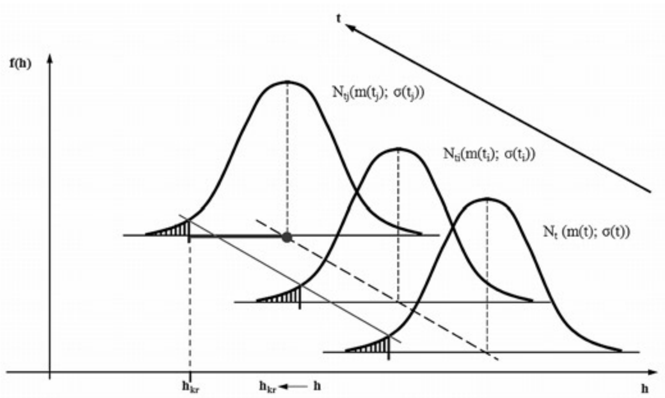


Fig. 3. Calculation of the time of limiting state on assumed probability level

4. Practical example

Weld-less R35 low carbon (P235GH) steel pipes of the diameter φ508x11 were used for the pipeline building, and basal requirements are defined in Polish standard No PN-80H-74219 [13]. The pipes were manufactured with use of the hot rolling technology, with beveled walls and calibrated endings.

Required minimal value of the pipe material yield stress in temperature of 473 [K] (200 [ºC]) should satisfy inequality $R_e \geq 185$ [MPa] where $R_m = 345$ [MPa].

Pressure of the transported medium is the basal load for the examined pipeline. Operational values of the transported medium determined on the basis of round-the-clock service oscillate within the range 1,4 ÷ 2,7 [MPa].

Exploitation of the pipeline is also threatened by variable stresses resulting from non-uniform pressure of the transported medium. Moreover, data collected from the round-the clock monitoring also prove its wavy course as well as stochastic values generating additional load impulses.

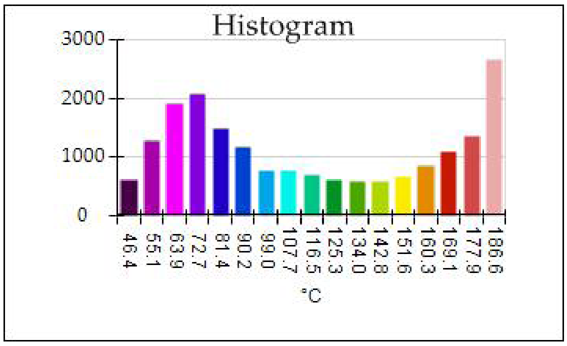
Assuming experimental relation for steel between fatigue limit Z_{rj} and immediate strength R_m ($Z_{rj} \approx 0{,}5\ R_m$), needed wall thicknesses were obtained:

$$h(R_e) = 3{,}7 \text{ [mm]},\ h(R_m) = 2{,}0 \text{ [mm]},\ h(Z_{rj}) = 3{,}9 \text{ [mm]}.$$

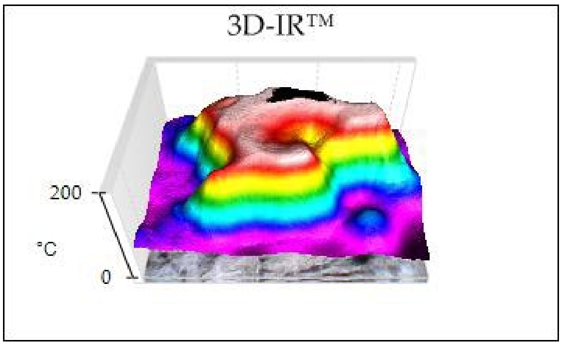
Moreover, taking under consideration dynamic action of the pressure with factor 2 [1] in comparison to static pressure ($p_{dyn} = 2p_{stat}$) we obtain the following wall thicknesses:

$$h(R_e) = 7{,}3 \text{ [mm]},\ h(R_m) = 3{,}9 \text{ [mm]},\ h(Z_{rj}) = 7{,}8 \text{ [mm]}.$$

In case of hot-water pipeline, measurements of the wall thicknesses were repeated three times during the pipeline exploitation. Wall thickness measurements were executed with use of ultrasonic thickness gauge (type DM-4DL, head DA 317). Moreover, thermovision measurements (camera type Ti25), were executed in the same points. The computer-processed results of these measurements are shown in Figure 4.

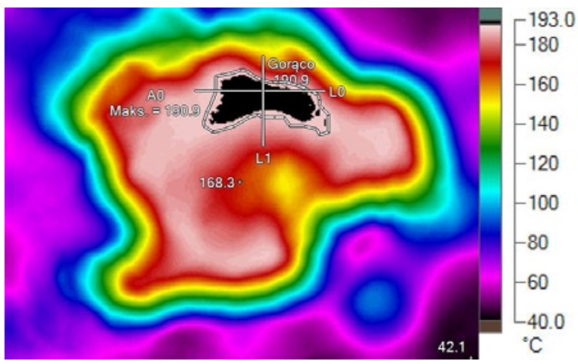


a)



b)

c)



d)

Fig. 4. Example of the thermovision measurement [11], a) image within visible range, b) image in infrared, c) histogram of given temperature value, d) three-dimensional temperature distribution on tested surface

On the basis of measurement results and calculated limiting values of the wall thickness, actual reliability level, i.e. probability of reaching limiting state resulting from possible material fatigue, as well as time after which the reliability drops to assumed limiting value amounting for 0,98, should be determined. Assumed high value of required reliability results from a significant risk of the pipeline exploitation.

The executed compatibility tests (Shapiro-Wilk test) proved that measurements of the wall thickness executed in 6, 8 and 17-th year of exploitation are characterized with normal probability distributions, which can be described consequently as: N6(12,33; 0,9), N8(11,86; 1,46), N17(10,53; 1,13). On the basis of most recent results of the wall thickness measurements executed in 17-th year of exploitation (in the year 2010), described with normal distribution N17(10,53; 1,13), probability of reaching limiting states and reliability levels corresponding to these states, have been determined. Results are shown in Table 1.

Table. 1. The pipeline reliability in the 17-th year of exploitation

	Limiting state with respect to:		
	occurrence of the material fatigue Z_{rj}	yield stress R_e	strength limit R_m
Reliability in 17-th year of exploitation	0,9921	0,9979	1

It should also be noted that mean change of the pipe wall in time has almost perfectly linear character, with factor R2=0,9933, what is shown in Fig. 5.

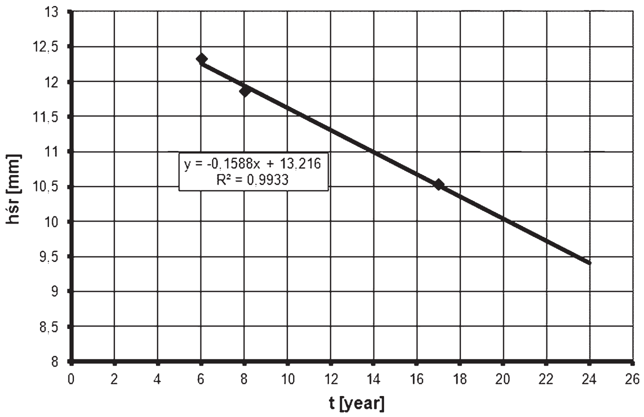


Fig. 5. Change in time of the pipe wall thickness $h_{śr}$ for tested pipeline

Determining the equation of time changes of the pipe wall thickness, which has a form:

$$h_{sr} = -0{,}1588\ t + 13{,}216\ ; \qquad (3)$$

forecasted mean values of the pipe wall thickness within slidable normal distribution for consecutive exploitation years have been calculated. Then assuming the mean invariable standard deviation in forecasted distribution, reliability levels have been determined and time after which the limiting value is reached, has been calculated (Fig. 3). The results are gathered in Table 2.

Table. 2. Reliability of the pipeline in consecutive exploitation years

Exploitation year	Forecasted $h_{śr}$	Probability of not achieving the limiting state with respect to:		
		occurrence of the material fatigue Z_{rj}	limit of yield stress R_e	limit of the strength R_m
18	10,36	0,9863	0,9958	1
18,5	10,28	0,9837	0,9949	
19	10,20	0,9807	0,9938	
19,5	10,12	0,9772	0,9925	
20	10,04	0,9733	0,9909	
20,5	9,96	0,9687	0,9891	
21	9,88	0,9635	0,9869	
21,5	9,80	0,9576	0,9844	
22	9,72	0,9510	0,9815	
22,5	9,64	0,9436	0,9782	

The obtained results prove that between 19,5 and 22,5-th exploitation year the pipe failure risk is relatively high because it exceeds value of 2% , and within this range the pipeline strength is located between limits resulting from material fatigue and plasticity. This exploitation period should be taken as a limit of safe exploitation and suitable time for the pipeline replacement. The result obtained are similar to the results of the strength tests described in works [9, 10].

Further tests aimed at better accommodation of the pipeline to real conditions indicate that the distribution of the pipeline operation until the limiting state with probability of 0,02 is reached, is compatible with the normal distribution N(28,9; 9,6). The obtained preliminary results require further verification and they will be presented in the next study.

5. Summary

Determination of the hot water-pipeline exploitation time is important for the potential user with respect to assure the production continuity. Each unexpected failure is accompanied with big economic losses and affects the production stability. Over time, the number of failures increases and the term of the pipeline replacement and the deadline for the exchange is approached.. Increasing number of the corrosion pits is a potential thread to the pipeline condition and the user is obliged to answer the question in which moment the activities aimed at the pipeline replacement into the new one should be undertaken.

The authors of the present study proposed one of possible manners of the problem solution and the described concept should be useful for users of pipelines, in which electro-chemical corrosion is a dominant process of deterioration of the object condition.

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