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FORECASTING THE FAILURE OF A THERMAL PIPELINE ON THE BASIS OF RISK ASSESSMENT AND EXPLOITATION ANALYSIS

PROGNOZOWANIE USZKODZENIA CIEPŁOCIĄGU NA PODSTAWIE OCENY RYZYKA EKSPLOATACJI*

In this paper, a procedure for determining the utilisation period of a thermal pipeline, exploited in mining plants was presented. On the basis of analyses conducted in the real life situations, the pipeline failure, which could be caused by its bursting due to exceeding pipeline strength, was forecasted. The exploitation conditions of the thermal pipeline and factors contributing to its degradation were also analysed. Using the probability sampling method, the exploitation risk was assessed and the lifespan of the pipelines, after which the pipelines shall be replaced by new structures, were determined.

Keywords: *thermal pipeline, failure, pipeline resistance, exploitation risk, forecasting the failure.*

W artykule przedstawiono procedurę postępowania w wyznaczenia okresu użytkowania ciepłociągu eksploatowanego w zakładach górniczych. Na podstawie badań przeprowadzonych w warunkach rzeczywistej eksploatacji prognozowano awarię rurociągu, która może być spowodowana pęknięciem na skutek przekroczenia jego wytrzymałości. Opisano warunki eksploatacji ciepłociągu i czynniki wpływające na jego degradację. W ujęciu probabilistycznym oszacowano ryzyko eksploatacji i wyznaczono okres użytkowania, po którym powinna nastąpić wymiana rurociągów.

Słowa kluczowe: *ciepłociąg, uszkodzenie, wytrzymałość rurociągu, ryzyko eksploatacji, prognozowanie uszkodzenia.*

1. Introduction

Ensuring the failure free work of the analysed thermal pipeline is a priority for the enterprise, on site of which the pipeline is exploited. Even a short break in hot water supply can cause serious complications for the normal work of the plant and can cause significant financial losses. The assessment of the failure hazard is an important information, as it is possible to plan preventative actions in the exploitation systems, which will prevent the damage, which could otherwise occur in the near future.

Problems of reliability and maintenance risk of pipelines operations are presented in articles [5, 8, 9]. The existing literature mainly focuses on the influences of corrosion and ageing elements of the pipeline [3, 4, 6].

The important problem, associated with forecasting failures of the thermal pipeline is a preventive maintenance of the pipeline [13], and in the analysed case, it is an issue of building an additional, spare pipeline, which will be used instead of the existing one. The so far exploited thermal pipeline, after renovation, will be used as an additional pipeline in case of any failures and during the planned repair works.

Two thermal pipelines, mutually supplementing each other during the exploitation, guarantee high reliability of hot water supply.

In this paper, the authors presented the methodology for forecasting the pipeline failure and or determining the lifespan of a thermal pipeline in a real life situation.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

2. Structural – exploitation characteristics and identification of damage to the thermal pipeline

The analysed object – the pipeline – is used for transporting hot water, of the average temperature around 463 K. The values of work pressures of the transported water vary from 1,33 to 2,44 MPa within a 24 hour period and a maximum flow output reaches 700 t/h. The pipeline was built of seamless steel pipes, manufactured of a low carbon, R35 steel (P235GH)–PN-80/H-74219. The required minimum value of the yield point of the pipe material, at 473 K equals $R_{et} \geq 185$ MPa. The pipeline is protected with a thermal insulation of the thickness of 25 cm, comprising of a layer of glass wool mat, covered with a protective layer of tar paper and aluminium sheeting.

The most important factor in assessing the technical condition of the pipeline and determining its damage due to exploitation is the change of the pipe wall thickness, being a result of pitting [3, 4, 10]. The analysed pipeline is also subjected to adverse influence of the chemical environment of the transported medium and, occurring simultaneously, impulse dynamic loads. The progressing degradation of the steel microstructure occurs as a result of the influence of the chemically aggressive compounds, stresses, high temperature and time. The basic cause of the changes in the thickness of the pipeline walls is the electrochemical corrosion, being a result of high mineralisation of used water. Additional cause of a quick oxidation of the pipe surfaces is high temperature of water, what furthers the corrosion. The presence of numerous chemical compounds, particulate suspended in the water and high temperature also contribute to an accelerated oxidation of the surface of the metal and, to a certain degree, to the abrasion of the surface of the pipeline [10]. The results of the conducted measurements of the thickness of the pipeline walls show, that corrosion pitting in some places is several millimetres deep. This leads to lowering the area of dangerous cross-sections of the pipeline and to increasing the summarised compound stresses. Another type of destructive effect of chemical corrosion are deep pitting on the surface of the metal. The local change in the thickness of the pipe wall result in pipeline deformation – proportional to the temperature difference. When applying the superposition principle for deformations caused by the exploitation stresses (pressure of the medium and its changes in time), it is also important to include deformations caused by thermal stresses. The changing load of the pipeline is also visible in high values of pipeline shift on erected supporting structures and towers. On the basis of observation, conducted over many years, the change of the pipeline shift on the supporting structures in all directions, *x*, *y*, *z,* was also proven.

This shift, reaching up to several dozen centimetres, lead to changes in the pipeline route, and in one case, it even led to the pipeline slipping of the supporting structure.

The pipeline deformations, caused by its shift on the supporting structures are particularly hazardous for weakened cross-sections.

3. Assessing the stresses in the selected sections of the pipeline

In thin wall pipes, subjected to an internal pressure p (the thin wall condition: $h/r \leq 0{,}2$ is fulfilled) circumferential stresses σ occur. Those stresses assume the same values for the entire thickness of the pipe (for the specific cross-section) [7]:

$$\sigma = \frac{r \cdot p}{h} \tag{1}$$

$$r = \frac{\left(D_Z + D_W\right)}{4} \tag{2}$$

where: h – thickness of the pipe wall (mm), r – average radius of the pipe (mm), D_z – external radius of the pipe (mm), D_w – internal radius of the pipe (mm), R – average radius if the pipe bend (mm).

For pressure changes, determined on the basis of analyses conducted over many years, the following values were determined: $p_{śr} = 1{,}75795$ MPa, $p_{min} = 1{,}33457$ MPa, $p_{max} = 2{,}44297$ MPa and for pipe thickness (φ508x11) in selected measuring points, the run of the changes of the circumferential stress σ were determined.

Circumferential stresses (caused by the internal pipe pressure) along the circumference of the pipe change in places, where the pipeline course changes from a straight section to a bent section.

Average circumferential stress in the wall, on the internal side of the bend of a curved pipeline equals:

$$\sigma_{wew} = \frac{\sigma \cdot \left(R - 0{,}5 \cdot r\right)}{\left(R - r\right)} \tag{3}$$

and on the external side of the bend equals:

$$\sigma_{zew} = \frac{\sigma \cdot \left(R + 0{,}5 \cdot r\right)}{\left(R + r\right)} \tag{4}$$

For the φ508x11 pipe and for the average bending radius $R = 750$ mm the following stress values were obtained:

$$\sigma_{wew} = 1{,}247 \cdot \sigma \tag{5}$$

$$\sigma_{zew} = 0{,}876 \cdot \sigma \tag{6}$$

Circumferential stress along the straight section of the pipe (φ508x11) for the cited pressure changes equals:

$$\sigma = \frac{248{,}5 \cdot p}{11} \tag{7}$$

Taking into consideration the registered pressure values, the following was obtained:

$$\sigma_{min} = 30{,}1493 \text{ MPa}, \sigma_{śr} = 39{,}7139 \text{ MPa}, \sigma_{max} = 55{,}1891 \text{ MPa}$$

Taking into consideration the formula for calculating the average circumferential stress on the internal side of the bend of the curved pipeline, the following was obtained:

$$\sigma_{wew,\,min} = 37{,}5962 \text{ MPa}, \sigma_{wew,\,śr} = 49{,}5225 \text{ MPa},$$
$$\sigma_{wew,\,max} = 68{,}8208 \text{ MPa}$$

Impulse (dynamic) effect of the pressure can double the pipeline shift on the supporting structures [2] as compared to the effects of the static pressure. As a result, the pipeline shifts on the supporting structures and its fixing (supports) become unstabilised. A justified, engineering solution to the problem is, in this case, the change of the construction and the methods of suspending and supporting the compensator.

Also a result of an impulse load [2] along the length of the pipeline or crosswise to the course of the pipeline, is a double increase of circumferential stress, as compared to to the effects of the static pressure.

The properties of the materials show a significant dispersion of experimental data, obtained while analysing its mechanical properties. This dispersion is also present when analysing the fatigue strength and static strength, e.g. the yield point R_e or immediate strength R_m, thus the resistance of the material can be considered to be a random variable. The coefficients of variation υ_R characterising the dispersion of the mechanical properties can be obtained from statistical analyses, according to Warszyński [12] , for steel $\upsilon_R = 0{,}05 \div 0{,}1$ and it is an indicator of the material quality, which depends on the manufacturing and further treatment conditions.

The average value of $R_{e,\,śr}$ and the minimum value of $R_{e,\,min}$ of the yield point can be estimated with the use of the following formula:

$$R_{e,\min} = R_{e,sr} \cdot \left(1 - u \cdot v_R\right) \tag{8}$$

where the value of u is assumed: $u = 2 \div 3$, that is the value, ensuring, with the probability exceeding 0,98, that the resistance will be greater than $R_{e,\,min}$. Utilising the afore recommendations and formulas, the distribution parameters of the yield point R_e were determined in the following chapters.

4. Assessment of the probability of damage the pipeline

The analysed thermal pipeline is exploited in difficult and variable external conditions. Both, the pressure and the temperature of the transported medium change in time. In addition, the transported medium can be characterised by its chemical composition, which, in conjunction with high temperature, causes a fast progressing corrosion of the thermal pipeline walls. Receding thickness of the pipeline walls and the dynamic character of the load are a factor contributing to a constant risk of exceeding the ultimate limit state and the damage occurring.

Probability of damage of the thermal pipeline can be determined with the use of the results of the measurements of the wall thickness of the thermal pipeline and the results of the registered changes of the thermal load (pressure and temperature).

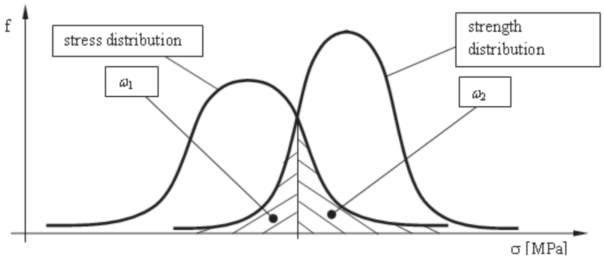

Fig. 1. Strength and stress distribution [11]

The approximated estimation of the probability of the damage of the structure can be determined using the Strielecki method. The probability of damage P is determined on the basis of load distribution and the structure strength (Fig. 1) and it is expressed with the dependency [1]:

$$\omega_1 \cdot \omega_2 < P < \omega_1 + \omega_2 - \omega_1 \cdot \omega_2 \tag{9}$$

where: ω_1 and ω_2 – areas under the strength density distribution curve and the load induced, stress distribution curve were presented in Fig. 1.

On the basis of the strength data of the material, of which the pipeline was made (data included in paragraphs 2 and 3), the distribution of its yield point was described – by a normal distribution N (264; 39,5). The stress distribution was determined on the basis of the measured wall thickness and the registered pressure changes. The probability of pipeline damage, determined with the use of the Strielecki method, for the average wall thickness and for the worst measured point, in various years of pipeline exploitation, were presented in table 1. Due to the small values of the probability of pipeline damage, those values were expressed as a percentage.

The determined above probability of damage, for both: the average wall thickness and the worst measured point, only gives the point assessment. However, much more hazardous points, where the wall thicknesses can be lower, can also occur in the analysed section of the pipeline.

Thus, another method of making a risk assessment was proposed. According to this method, the wall thickness distribution, of thicknesses measured at a certain date, shall be determined and referred to the determined minimum wall thickness of the thermal pipeline. On the basis of the strength condition:

$$\sigma = \frac{r \cdot p}{h} \le R_{e,\min} \tag{10}$$

Thus it can be noted as:

$$h_{\min} = \frac{D_Z \cdot p}{2 \cdot R_{e,\min} + p} \tag{11}$$

Taking into consideration the maximum measured pressure in the pipeline, and its dynamic properties, the h_{min}=6,64 mm was determined. Next, the distribution of the wall thicknesses, measured at certain dates, was determined and the probability, that in the system, the value equal to or lower than h_{min} will occur, was established (Fig. 2). This probability determines the possibility of wall thickness equal to or lower than the minimum required thickness occurring in the analysed section of the pipeline. It was assumed, that this is also a risk of a damage to the pipeline occurring.

The determined values of probability of damage, determined with the use of the described method were presented in table 2.

Tab. 1. Probability of damage of the thermal pipeline, determined with the use of the Strielecki method [11]

	Average from the measurements			The worst point		
Year, the measurements were taken	1999	2001	2010	1999	2001	2010
Consecutive year the pipeline was exploited	6	8	17	6	8	17
ω_1	0,002476	0,003127	0,007031	0,00195	0,01895	0,04033
ω_2	0,001656	0,002314	0,005385	0,00119	0,01743	0,04704
Probability of pipeline damage P [%] >	0,00041	0,000723	0,00379	0,00023	0,033	0,19

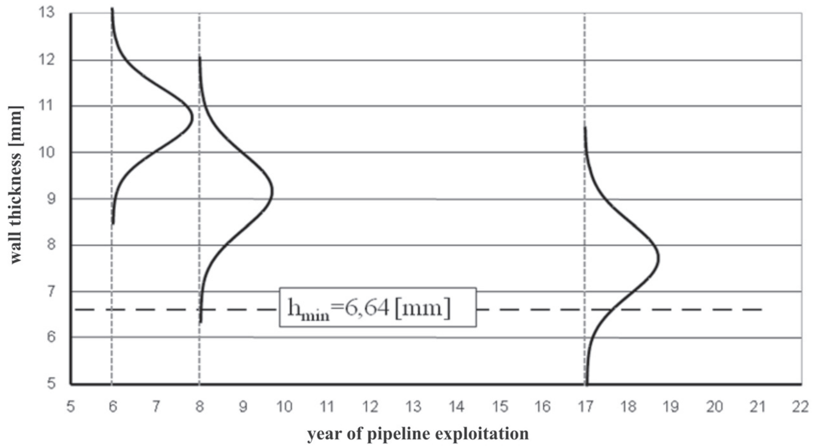

Fig. 2. Distribution of wall thickness of the thermal pipeline, measured at different dates

Tab. 2. Probability of damage of the thermal pipeline [11]

Year, the measurements were taken	1999	2001	2010
Consecutive year the pipeline was exploited	6	8	17
Wall thickness distribution	N(12,8; 0,9)	N(8,85; 1,46)	N(7,5; 1,13)
Probability of pipeline damage P	P≈0	P=0,065	P=0,223

The probabilities of the pipeline failure, calculated with the use of the proposed method are much greater than those, calculated with the use of the Strielecki method. This is due to the fact that in accordance to the specified wall thickness distribution, it is also possible, that the walls are thinner than it was determined by conducting measurements in selected points. This approach better represents the analysed, real life segment of the thermal pipeline, on which, only a minimal percent of its actual surface was analysed when taking the measurements.

5. Forecasting the failure of the thermal pipeline

The probability of failure of the thermal pipeline, as explained in Section 4, was determined for this point on the pipeline, in which the wall thinning achieved maximum values. This point was marked with number 21 (Fig. 3) and was regarded as the most hazardous. The measurements of the pipeline wall thickness were taken in 16 different points, marked in Fig. 3 with numbers from 21 to 46. In four cases, the thinning of the pipeline wall could be regarded as hazardous, due to the lowering of the pipeline strength and in those places, the pipeline failure can occur in a near future. Those particularly hazardous spots add to 25% of all measurements taken on the pipeline.

A precise assessment of the technical condition of the pipeline is not possible due to the fact, that the pipeline is thermally insulated. Considering, that the taken measurements are representative, it can be assumed that if the research was conducted, more points, being a potential centre of pipeline failures would be found.

A precise assessment of the technical condition of the pipeline is not possible due to the fact, that the pipeline is thermally insulated. It can be assumed that by continuing the measurements, the ratio of the particularly hazardous areas to the general number of measured points will remain unchanged.

Damage of a pipeline is a serious threat to the normal functioning of the enterprise, thus all feasible technical initiatives, preventing the pipeline failure, are undertaken. Taking into consideration diminishing with time strength of the pipeline, the erection of a second thermal pipeline, supplanting the existing one, is considered. This can lead to erecting two pipelines, mutually supplementing each other and guaranteeing high reliability of hot water supply.

The problem of determining, when the further exploitation of the pipeline can be so risky, that the construction of the second line will become necessary, becomes more and more important. Taking into consideration the divagations presented in Section 4, it was assessed, that for the weakest point on the pipeline (point no: 21) the damage will occur after 20 years of exploitation [11].

This conclusion was confirmed by the distribution of the failure frequency after 17 years of pipeline exploitation, as presented in figure 2, where around 22% of the values of the density function can exceed the thickness border value h_{min} = 6,64 mm.

An additional criterion, determining the necessity of replacing the thermal pipeline are the economic reasons. The expected value of the failure occurring can be calculated on the basis of the renewal function:

$$N(t) = \int \left(1 + N(t - x)\right) dF(x) \qquad (12)$$

where: $N(t)$ – renewal function, t-x – remaining exploitation time after the first failure, t – exploitation time, $F(x)$ – distribution of a random variable, being the pipeline exploitation time.

Pipeline failure generates the necessity of conducting repair works, the costs of which can be estimated. The first pipeline failure, being a result of corrosive processes shall be a signal that the subsequent failures can occur in a near future and in various zones of the thermal pipeline. This is also a signal that the pipeline strength was also lowered and the time has come to consider replacing the pipeline.

By continuing the use of the pipeline, threatened by failures, one can generate profit, which can be calculated. For the analysed case, the ratio of the profit from pipeline exploitation to financial losses, considering the repair costs was 90 to 1. Taking into consideration this ratio, the probability of generating profit and the risk of incurring losses were presented in figure 4. The point, in which the curves crossed determined the time, after which further pipeline exploitation became unprofitable. For the analysed case, this time period was 20 years.

The probability of generating profit and incurring losses after 16 years of pipeline exploitation was presented in figure 4. This section shows the exploitation period before and after the first pipeline failure occurred. The probability of this failure was calculated on the basis of the value of the renewal function. This is a sensitive period in the pipeline exploitation period; signalling the necessity of pipeline replacement.

The determination of the exploitation period of the thermal pipeline was conducted with the use of the probability sampling method. The worst possible cases were considered and the presented version is the pessimistic assessment. The applied, significant safety margin was determined by the fact that building a new thermal pipeline is a complicated and a costly technical – economical venture, which cannot be completed in a short period of time.

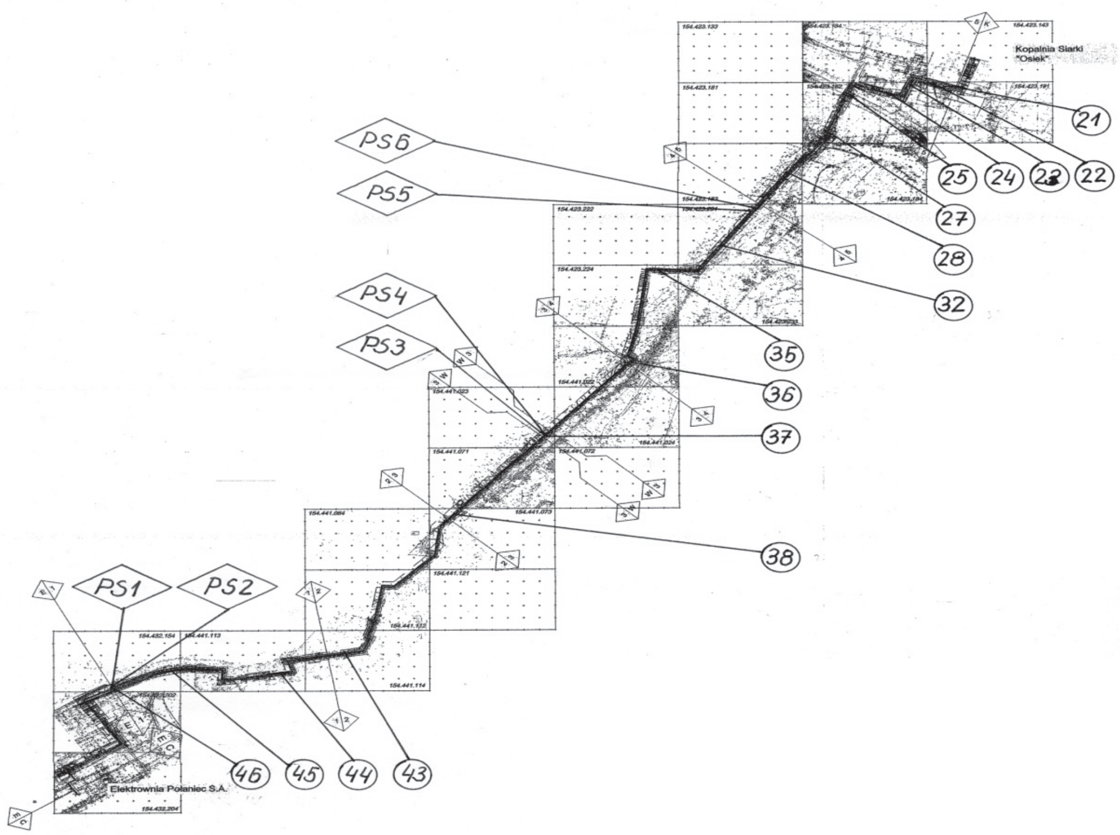

Fig. 3. Location of measurement points – spots in which the thickness of the pipeline wall was measured and location of spots in which thermo vision measurements were taken on the hot water (21, ..., 46 – exact points in which the measurements were taken)

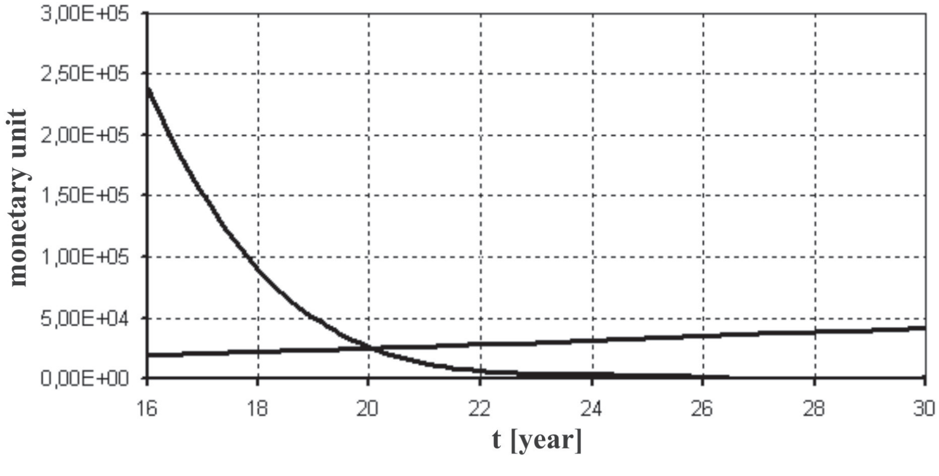

Fig. 4. Determining the exploitation period of the thermal pipeline

6. Conclusions

In exploitation processes, determination of the devices and installation exploitation period is an important managerial issue. Unjustified lengthening of the exploitation period will most often lead to significant losses and ecological hazard. Making such decision is never easy.

The proposal of employing the methods of assessing reliability of devices and installations presented in this article is a universal one and it can be used for solving this types of problems in various branches of the machine industry.

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