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Effect of creep characteristics on pipeline durability

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Analysis and modelling

ABSTRACT

Purpose: The paper presents an assessment of durability of a steam pipeline operating above the threshold temperature. The durability calculations take into account the creep characteristics of the material.
Design/methodology/approach: The results of calculations of the degree of wear caused by the creep of a pipeline, made using numerical methods, are presented. The calculation model takes into consideration the basic geometric and material properties of the pipeline, its operating parameters, and the displacement of valve and turbine chambers which force an initial displacement of the pipeline in the cold state.
Findings: As a result of the calculations made, the effect of redistribution and relaxation of stresses induced by the initial guy wire tension has been found. This leads to a rapid loss of stresses, the consequence of which is enhanced durability of the investigated object.
Research limitations/implications: Due to the lack of data regarding objects operated for a long time, the calculations of their durability made under this study provide preliminary information on the expected further operational life of a specific structural element. The comprehensive evaluation of the life of an object should be supplemented by research on the material to enable determining the actual degree of material wear in the areas of the analyzed element subject to the highest effort.
Practical implications: To ensure operational safety of pipelines operated for a long time, a method is presented to evaluate their durability, which takes into account the effect of additional loads on the effort of the pipeline.
Originality/value: In the calculations of wear caused by creep, carried out in line with the EN-13480 standard, the criterion is the stress in the wall of a component under internal pressure. The paper presents the results of stress calculations while taking account of additional operational load, which has a significant influence on the degree of material wear.
Keywords: Pipeline durability; Material creep; Calculation model; Numerical methods; Stress relaxation

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1. Introduction

In the durability calculations of power engineering devices designed with taking into account the damage caused by creep, the criterion used for the evaluation of wear is the average reduced stress in the component wall [1-4]. In standardized calculation procedures, only the effect of internal pressure on the effort of the facility is taken into consideration. Due to the complexity of calculations, the durability assessment performed with the application of engineering methods usually omits the influence of additional loads having effect on the facility, such as: thermal elongation, thermal displacement of installation connections, the applied guy wires and their initial tension, the distribution of temperature on the surface and cross-section of a component, deadweight of the installation, interaction of shaped components and the real characteristics of installation suspensions and supports, etc. An additional influence on the distribution of stresses in the facility is connected with geometric and structural notches which cause a local concentration of stresses which, in turn, may determine the degree of damage caused by creep of the material from which the operated facility is made. It is possible to take into consideration the said factors which have a significant influence on the value and distribution of stresses in the facility by applying the finite element method in the calculations [5-7]. The operation of facilities at higher temperatures, in practice over 450-500°C, makes the materials of which they are made slowly deteriorate. Their structure changes and their strength properties decrease [8]. An external symptom of this phenomenon is a permanent deformation which increases over time. A consequence of deformation during operation is a redistribution of the stresses which are present in the facility.

The paper presents an assessment of the durability a steam pipeline operating at a temperature above the threshold temperature with the application of numerical methods. The calculations of stress distribution take account of the creep characteristics of the material at the operating temperature of the facility.

2. Scope of research

The paper presents the results of calculations made using numerical methods, regarding the degree of wear caused by the creep of a pipeline. The calculation model takes into consideration the basic geometric properties of the pipeline, its operating parameters, deadweight, thermal elongation and displacement of valve and turbine chambers which force a displacement of the pipeline connections in the cold state, and which limit the freedom of thermal deformation of the pipeline in the steady-state conditions of turbine operation.

The displacement value of the valve chamber ferrule in the cold state was determined on the basis of the measured displacements of the valve chamber lugs after a general overhaul of the power unit. The displacement of the pipeline connection to the turbine housing in the hot state was calculated with taking into account the dimensions of the turbine housing and the temperature difference between the cold and hot states of the power unit [5].

The model tests took into account the creep characteristics of steel 14CrMoV6-3 after the operating time of ca. 100.000 hours.

3. Object of research

The object of the research was an intermediate high-pressure pipeline connecting the valve chamber with the high-pressure part of the turbine. The pipeline is made of the 14CrMoV6-3 steel and the shaped element connecting the pipeline with the turbine is made of cast steel, 21CrMoV5-7. The pipeline is operated at a temperature of T=535°C and subjected to steam pressure of p=17.6 MPa. General view of the object of the research is shown in Fig. 1.

The phenomenon of creep, usually characterized by deformation and creep rate, is described by numerous equations [9-11], which include the functions of: time, stress, temperature, stress and time, stress, temperature and time.

For the purposes of a mathematical description of the creep characteristics of the pipeline material, the Bailey-Norton equation has been used, which depicts the relationship between deformation and stress, time and temperature in the following way:

$$\varepsilon_c = C_0 \cdot \sigma^{C_1} \cdot t^{C_2} \cdot e^{\frac{C_T}{T}} \tag{1}$$

where: σ – stress, Pa; t – real time, s; T – temperature, K; C_0, C_1, C_2, C_T – material constants.

The Bailey-Norton equation describes the course of the creep curve in the scope of stage I and II creep (Fig. 2).

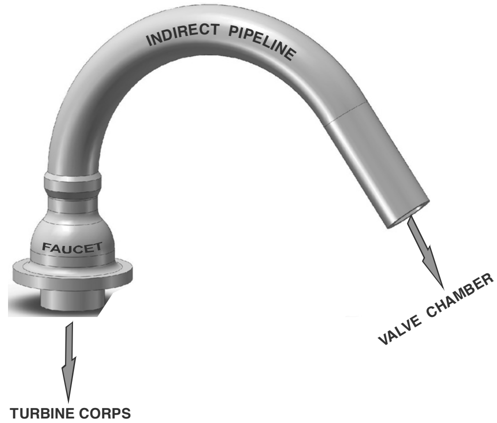

Fig. 1. General view of the research object: intermediate high-pressure pipeline

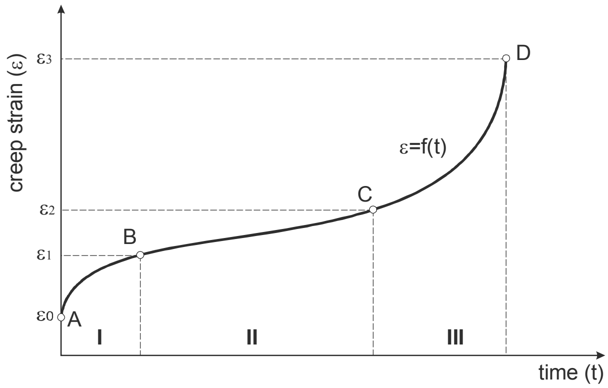

Fig. 2. The course of a typical creep curve. (I) – an unsteady process with a decreasing creep rate, (II) – a steady process with a constant creep rate, (III) – an unsteady process with an increasing creep rate

The values of the coefficients in the Bailey-Norton equation were calculated on the basis of experimentally determined creep characteristics of the 14CrMoV6-3 steel at a temperature of 535°C, which is presented in Fig. 3. The creep curve was sampled, obtaining thereby a numerical dependence between the deformation, stress and time. Next, by finding the logarithm of the creep equation, the linear dependence was found between the variables in the Bailey-Norton equation:

$$\ln(\varepsilon) = \ln(C_0 \cdot e^{\frac{C_T}{T}}) + C_1 \ln(\sigma) + C_2 \ln(t) \tag{2}$$

Using the method of linear regression of a multivariable function, the material constants were determined for the creep function (1) which was formulated as follows:

$$\varepsilon_c = 2.765 \cdot 10^{-27} \cdot \sigma^{2.755} \cdot t^{0.518} \tag{3}$$

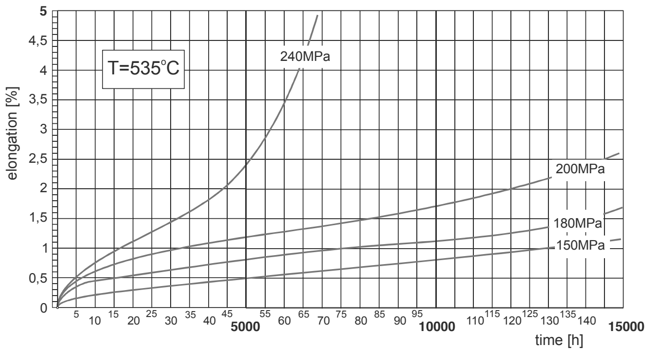

Fig. 3. Creep characteristics of the 14CrMoV6-3 steel [12]

The calculated correlation ratio (R) of the function approximating the Bailey-Norton equation is 0.9784 at 45 degrees of freedom.

4. Calculation results of stress distribution in the pipeline with taking into account the creep

Model tests were conducted while taking into account in the calculations the measured value of the displacement which was used during the overhaul works for the purpose of connecting the pipeline with the valve chamber ferrule. In the hot state of the installation, we took into consideration the displacement of the pipeline end forced by the thermal expansion of the turbine housing. It was assumed in the calculations that the pipeline was subject to a steam pressure of 17.6 MPa, whereas the steam pressure in the bell was 4.3 MPa.

A model of the research object indicating the displacement values of intermediate pipeline connections is presented in Fig. 4.

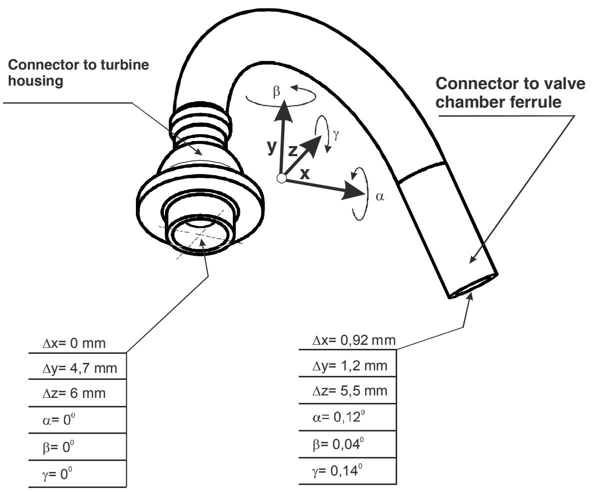

Fig. 4. Displacement values of pipeline connections in the cold and hot states

The calculations were conducted with the application of the finite element method with the time step of 1000 seconds within a time interval corresponding to 31.536.000 seconds of continuous operation of the pipeline (1 year service).

The calculation results of reduced stress distribution in the selected moments of pipeline operation are shown in Figs. 5-7.

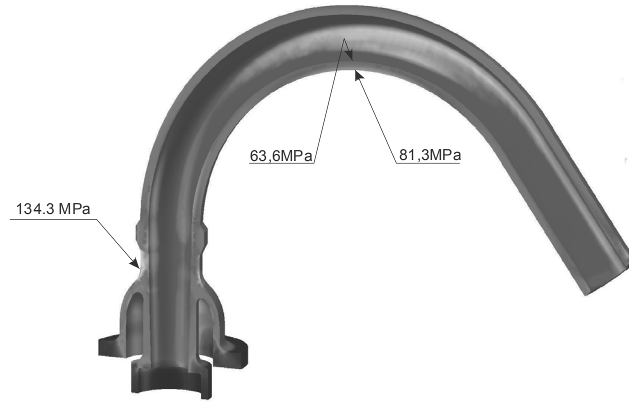

Fig. 5. Reduced stress distribution in the pipeline before start-up of the power unit

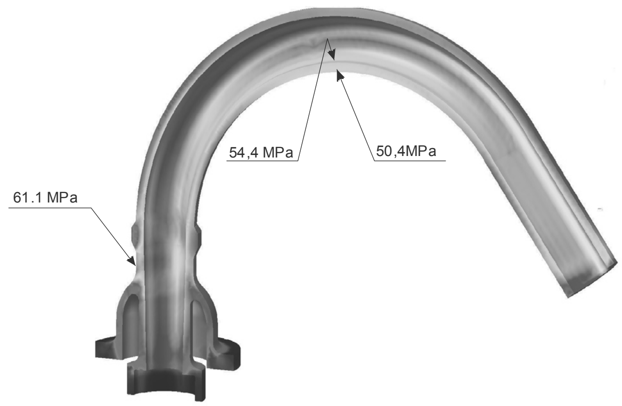

Fig. 6. Reduced stress distribution in the pipeline after the time of t=100 hours after the start-up of the power unit

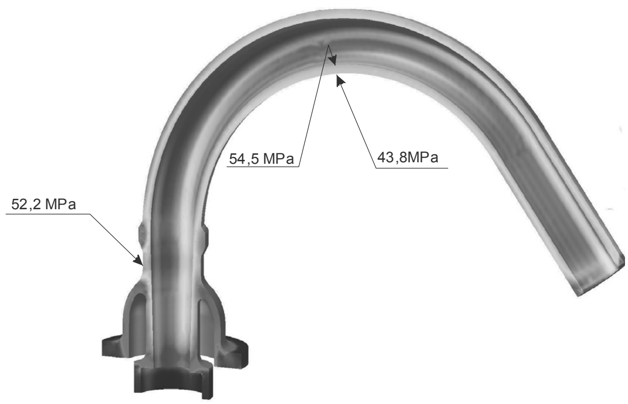

Fig. 7. Reduced stress distribution in the pipeline after the time of t=500 hours after the start-up of the power unit

5. Determining the characteristics of stress redistribution in the pipeline induced by material creep

The material creep during operation of a power unit causes relaxation and redistribution of stresses in the pipeline. In the pictures showing the calculation results for the stress distribution in the pipeline, two points were selected which were characterized by the highest values of reduced stress. Further analyses focused on the point situated on the inner surface of the curve and on the point situated on the outer surface of the pipe bell. The location of the points of the pipeline for which the relaxation characteristics were determined is shown in Fig. 8.

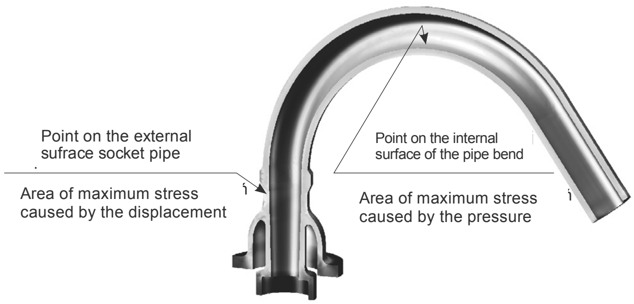

Fig. 8. Location of the points of maximum stresses in the pipeline

The characteristics of redistribution and relaxation of stresses prepared on the basis of the numerical calculations are presented in Figs. 9 and 10. In the case of the curve, the stresses stabilize at a level of 54.5 MPa after ca. 100 hours of operation. Fig. 10 shows a part of the characteristics until the time of stress stabilization.

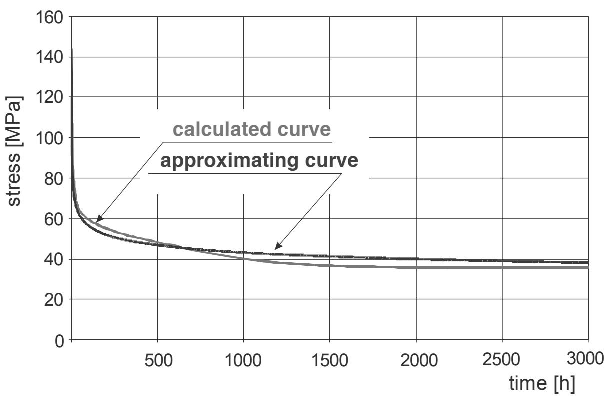

Fig. 9. Characteristics of stress redistribution on the outer surface of the bell

The characteristics presented in Fig. 9 and 10 were approximated with exponential curves in the form: $y = Ax^b$. For the bell, the interdependence between the stress value and the operating time $\sigma_{b(ell)} = f(t)$ is presented in the equation:

$$\sigma_b = 95.5t^{-0.1} \text{ for } (0 \le t \le 8760 \text{ h}) \; [R^2=0.9805] \tag{4}$$

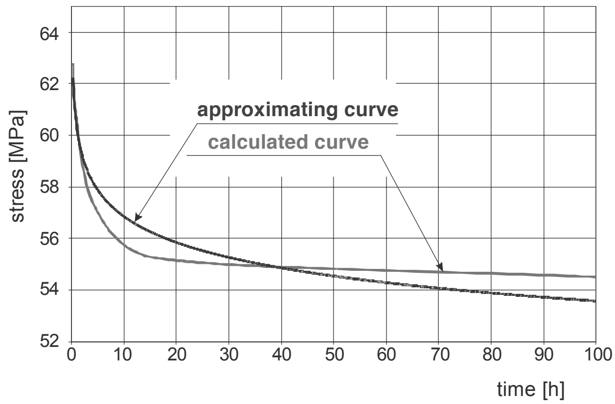

Fig. 10. Characteristics of stress redistribution in the point on the inner surface of the pipeline curve

The equation describing the variability of stress in time on the inner surface of the curve $\sigma_{c(urve)} = f(t)$ has the following form:

$$\sigma_c = 60.3t^{-0.03} \text{ for } (0 \le t \le 100 \text{ h}) \; [R^2=0.8486] \tag{5}$$

where: t – time, h; σ – stress, MPa.

6. Calculating the wear resulting from pipeline creep with taking into account the stress relaxation

The fact of taking into account the creep characteristics in the calculations of pipeline effort leads to continuous changes in the stress value over time. For the changing operating conditions, the appropriate fraction of damage caused by creep $\Delta\omega_i$ for each range of variable load conditions is calculated by dividing the operating time $t_{\sigma i}$ of the range by the theoretical durability T_{zi} corresponding to the load conditions in such a range of operation (Fig. 11). The degree of total creep wear in different operating conditions can be determined by applying the hypothesis of linear accumulation of damage by adding the values of $\Delta\omega_i$ for all the ranges of changes in the load from dependence [13].

$$\omega_p = \sum_i \Delta\omega_i = \sum_i \frac{t_{\sigma i}}{T_{zi}} \tag{6}$$

where: $t_{\sigma i}$ – operating time corresponding to stress σ_i, T_{zi} – calculated operating time corresponding to stress σ_i.

Taking into consideration the continuous changes of stress during the operation of the pipeline, the discrete diagram of changes in the load conditions was replaced with a diagram of continuous changes in the operating conditions, as shown in Fig. 12. The total creep wear in the conditions of continuous load changes has the following form:

$$\omega_p = \int_0^t \frac{dt}{T_z} \tag{7}$$

where: T_z – calculated operating time corresponding to stress σ_i within the time t_i of the object operation.

The creep resistance function was determined assuming linear characteristics of the pipeline material in a logarithmic coordinate system.

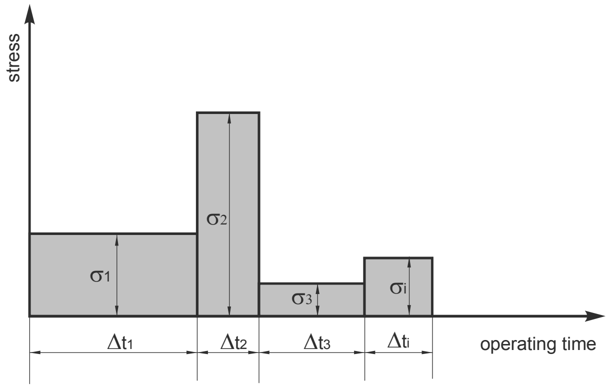

Fig. 11. Diagram of unsteady operating conditions of the object with a discrete load change

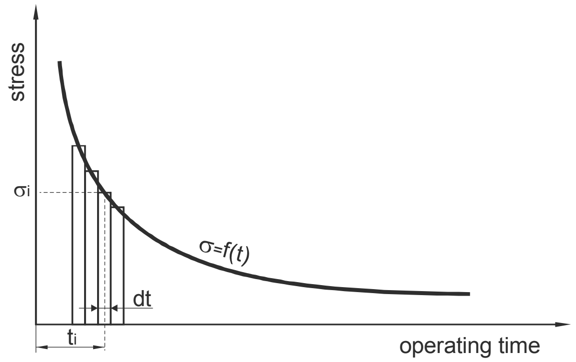

Fig. 12. Diagram of unsteady operating conditions of the object with continuous changes of stress

After taking into account the average time value of creep resistance of the 14CrMoV6-3 steel for 100.000 and 200.000 hours, which were respectively:

$$R_{z(100000h)535^{o}C} = 87.5\,MPa$$

$$R_{z(200000h)535^{o}C} = 73.2\,MPa$$

The equation of the characteristics of the intermediate pipeline material at a temperature of 535°C is as follows:

$$R_z = 10^{-0.259\cdot \lg(T_z)+3.238}, \quad (8)$$

or after transformation:

$$T_z = 10^{\frac{\lg(R_z)-3.238}{-0.259}} \quad (9)$$

In the case of stress relaxation in the computational scheme as a result of creep, the value of the calculated operation time, T_z, depends on the continuously changing stress according to the equation:

$$T_z = 10^{\frac{\lg[\sigma(t)]-3.238}{-0.259}} \quad (10)$$

After taking into account the relaxation characteristics (eq. 4, 5) in the above equation, the creep wear for the curve is presented by the formula:

$$\omega_{pc} = \int_0^t \frac{dt}{f_c(t)}, \quad \text{where: } f_c(t) = 10^{\frac{\lg(60.3t^{-0.03})-3.238}{-0.259}} \quad (11)$$

and for the bell:

$$\omega_{pb} = \int_0^t \frac{dt}{f_b(t)}, \text{ where } f_b(t) = 10^{\frac{\lg(95.5t^{-0.1})-3.238}{-0.259}} \quad (12)$$

The overall wear resulting from creep was determined in the calculations by assuming 1 year of operation of a power unit from the moment of a general overhaul. The limits of integration in connection with the assumed operation time are included in the interval: $0 \le t \le 8760\,h$. The dependence of the total wear degree on creep under stress relaxation conditions is presented for the bell by the formula:

$$\omega_{pb} = \int_0^{8760} \frac{dt}{f_b(t)} \quad (13)$$

For the curve, the degree of total creep wear will equal:

$$\omega_{pc} = \int_0^{100} \frac{dt}{f_c(t)} + \frac{8760-100}{T_{z/\sigma=54.5MPa}} \quad (14)$$

The above presented formula reflects the fact that the change of stress in the curve occurs until the 100th hour of operation of the object. After that time, the stress value stabilizes at 54.5 MPa.

By integrating the presented equations, the values of total creep wear for a 1-year operation of the power unit, having taken account of stress relaxation in the pipeline, will amount to, respectively:

for the bell: $\omega_{pb(relaxation)}$=0.005955 (15)

for the curve: $\omega_{pc(relaxation)}$=0.014023 (16)

7. Evaluation of the effect of stress relaxation on creep wear of the pipeline

In standardized procedures of evaluation of damage caused by creep, the constancy of stress induced by constant load is assumed. Calculations, as a principle, take account of the effect of pressure or temperature on the durability of an object.

Assuming that there is only a constant internal pressure throughout the assumed operational durability of the pipeline, the creep wear ratio is calculated from the formula:

$$\omega_p = \frac{T_i}{T_z} \quad (17)$$

where: T_i – operating time for which the creep wear is determined, T_z – theoretical operating time at a steady stress resulting from the effect of pressure

Assuming in the calculations the maximum stress in the curve induced by pressure of 66.2 MPa and the stress on the outer surface of the bell of 42.9 MPa [5], the theoretical operating durability determined on the basis of the characteristics of the pipeline material creep resistance will amount to, respectively:

for the curve: T_z=294.800 h (18)

for the bell: T_z=15.730.000 h (19)

In order to compare the durability determined by different methods, the calculations of the creep wear ratio with taking account of the internal pressure were made for one year of continuous operation of the pipeline, i.e. T_i=8.760 hours.

After taking into account the assumed operational durability and the theoretical operational durability at stress arising from the effect of pressure, creep wear of the bell will amount to:

$$\omega_{pb(steady)}=0.005569, \tag{20}$$

while the curve wear will reach:

$$\omega_{pc(steady)}=0.02916 \tag{21}$$

By referring the calculated ratios to the creep wear ratios calculated after taking into account the stress redistribution and relaxation, the following relative wear changes were obtained:

$$z_{bell}=\frac{\omega_{pb(relaxation)}}{\omega_{pb(steady)}}=1.07 \text{ for the bell} \tag{22}$$

$$z_{curve}=\frac{\omega_{pc(relaxation)}}{\omega_{pc(steady)}}=0.48 \text{ for the curve} \tag{23}$$

8. Summary of calculation results

In the case of pipelines operated for a long time, in order to ensure work safety during repairs, it is necessary to carry out inspections of welds and curves, which often involves the need to replace or repair these elements and this, in turn, necessitates the use of guy wires which change the operating conditions of the facility. The additional loads caused by the guy wire tension lead to a significant effect on the effort of the pipeline. The calculations of creep wear, ω_p, of intermediate pipelines, performed with taking into account the additional forces originating from dislocations of the pipeline connectors to turbine housing and valve chambers have shown that the omission of the effect of stress relaxation in power engineering facilities significantly overestimates the wear ratio, ω_p. The assumption made in the durability calculations that the stresses induced by the initial deformation of the pipeline are invariable leads to a conclusion that some parts of the pipeline after 100.000 hours of operation show total wear (ω_p >1) [5].

After taking into account the effect of creep in the characterization of the material as a result of the calculations made, the effect of redistribution and relaxation of stresses is observed, which effect leads to a rapid loss of stresses caused by the initial guy wire tension. In the pipeline area where the maximum stress (the outer surface of the bell) has been found as a result of initial displacement of pipeline connections, the durability reduction in relation to operation in steady conditions is approximately 7% and, in practice, it is included in the compute error. However, in the case of the curve, the effect of creep contributes significantly to increasing the durability of a component. The creep wear ratio ω_p on the inner surface has decreased by ca. 50% due to the redistribution of stress. The increase in the durability of components working in creep conditions is also confirmed in the works [14, 15] conducted by the Institute of Fluid-Flow Machinery, Polish Academy of Sciences.

Owing to the reliability of the data regarding the material, in particular in the case of objects operated for a long time, the calculations of durability made as part of this research project provide preliminary information on the expected further operating durability of a structural element. The comprehensive evaluation of the durability of an object should be supplemented with research on the material to enable determining the actual degree of material wear in the areas of the analysed element subject to the highest effort.

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