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МЕТОДИКА ОЦІНЮВАННЯ НАДІЙНОСТІ СТАЛЕВОЇ КОНСТРУКЦІЇ МАГІСТРАЛЬНОГО ТРУБОПРОВОДУ

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Анотація. У статті розглянуто чинники, що впливають на надійність сталевих магістральних трубопроводів під час стаціонарного режиму їх роботи. Наведено підбір імовірнісних моделей та визначення розподілу значень випадкових величин внутрішнього тиску продукту, що транспортується, та перепаду температур в підземному магістральному трубопроводі. Пропонується методика оцінювання надійності таких конструкцій (визначення ймовірності відмови та параметра надійності магістрального трубопроводу в експлуатаційному стані), наводиться порівняльний аналіз для трубопроводів різного зовнішнього діаметра та для різної величини внутрішнього тиску продукту, що транспортується. Розглядаються питання вибору оптимального рівня надійності магістральних трубопроводів. Сформульована і розроблена ймовірнісна методика відрізняється аналітичною простотою. Дана методика може застосовуватися як на стадії проектування, так і на стадії експлуатації магістрального трубопроводу: при прийнятті рішення про його капітальний ремонт, визначенні безпечного робочого тиску при фактичному технічному стані тощо.

Ключові слова: магістральний трубопровід, надійність конструкцій, випадкові величини навантажень та впливів, імовірнісний метод.

МЕТОДИКА ОЦЕНКИ НАДЕЖНОСТИ СТАЛЬНОЙ КОНСТРУКЦИИ МАГИСТРАЛЬНОГО ТРУБОПРОВОДА

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Аннотация. В статье рассмотрены факторы, влияющие на надежность стальных магистральных трубопроводов во время стационарного режима их работы. Приведен подбор вероятностных моделей и определение распределения значений случайных величин внутреннего давления транспортируемого продукта и перепада температур в подземном магистральном трубопроводе. Предлагается методика оценки надежности таких конструкций (определение вероятности отказа и параметра надежности магистрального трубопровода в эксплуатационном состоянии), приводится сравнительный анализ для трубопроводов разного наружного диаметра и для различной величины внутреннего давления транспортируемого. Рассматриваются вопросы выбора оптимального уровня надежности магистральных трубопроводов. Сформулированная и разработанная вероятностная методика отличается аналитической простотой. Данная методика может быть использована как на стадии проектирования, так и на стадии эксплуатации магистрального трубопровода: при принятии решения про его капитальный ремонт, определении безопасного рабочего давления при фактическом техническом состоянии и т. п.

Ключевые слова: магистральный трубопровод, надежность конструкции, случайные величины нагрузок и воздействий, вероятностный метод.

METHOD FOR RELIABILITY ESTIMATION OF THE MAIN PIPELINE STEELWORK STRUCTURE

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Abstract. Factors affecting the reliability of steel pipelines are under consideration in the paper. A selection of probability models is presented and the random variables magnitude distribution is determined for internal pressure of the product transported and for the thermal gradient in the buried pipeline. The method for estimating the reliability of such structures is suggested, the comparative analysis for pipelines having different external diameters and for different internal pressure values of the product transported is presented. The problem of choosing the best level of pipelines safety is considered. The formulated and developed probabilistic method is distinctive in its analytical simplicity. The given method can be used at the design stage as well as during operation of transit pipeline: in the process of decision making of its major repairs, determination of safety power pressure under the practical engineering state.

Keywords: main pipeline, reliability of structures, loads and impacts random variables, probabilistic method.

Introduction

In Ukraine, the length of the main oil and gas pipelines makes approximately 45 thousand km. Numerous pipelines have a great working lifespan. They operate quite often in extreme conditions, as they were laid in various topographic, geologic, hydrologic and climatic conditions. Damage and destruction of pipelines are most frequently caused by the pipe's wall weakening.

Due to lack of information on the actual loads and quite a rough idea of the mechanical characteristics values of the structure's material [4, 5], which determines its resistance to the actual load, determining the pipe's strength state is the main prerequisite for assessing the reliability of pipeline systems. The strength state values are determined depending on the loading stability conditions, reference data on the mechanical characteristics, technology level and other factors. The admissible strength state values are determined with account of the engineering experience in creating the analogous structures. At present, there are no theoretical and experimental grounds to determine the strength state components; the stochastic nature of operating loads, impacts and structural characteristics of the used materials are not taken into consideration [13]. This causes the increased specific amount of metal per a pipeline and using unreasonably high strength state values. For example, according to Construction Norms and Regulations, SNiP 2.05.06-85 [7], the total factor of strength redundancy, including the pipeline's operating conditions, safety as to the material, as to the load, etc. can make 3.0. The existing standards and design rules in this field of construction, based on a normative method for designing a structure according to its edge states, do not permit a comprehensive assessment of the pipeline's reliability according to the today's requirements, because they do not explicitly consider the factors of time and the probabilistic nature of the bearing capacity and loads characteristics.

Analysis of the factors affecting the reliability of main pipelines

In the construction of main pipelines, significant internal efforts, strain and deformations occur [11, 12]. This is due to the action of heavy random workloads and structure impacts. For probability calculation of the pipeline, under the impact of many random factors, it is necessary to develop models of these random factors [9, 10], in order to pass on to the distribution of the structure's determining parameter (strain, forces, etc.), using these models, and by its extreme value for a certain time period to forecast the probability of failure-free operation for the entire running period.

As noted in [4, 5], the reliability and safety of main pipelines operation depend on many different factors that affect their strength and durability. Most of them are random in the practice of main pipelines running. The main factors that affect the stress-strained state of a main pipeline, are the internal pressure of the product p transported through the pipe; thermal gradient Δt; the axial curvature of the pipeline κ. Internal pressure and thermal gradient in pipelines undergo changes, both lengthwise and temporal.

According to the experimental data, collected in the process of studying an operating main pipeline, pressure values variations were observed in the pipe during the observation period. It can only be possible to determine the pressure variation rule, if a sufficient number of statistical studies is conducted. Therefore, the task is to make a reasonable approximate choice of a pressure distribution model both along the length of the pipeline and a temporal one. Thus, validation of the parameters for probabilistic methods of the studied structures calculation becomes a prerequisite when performing calculations.

Probabilistic models selection and determining distribution of random pressure values magnitude in the main pipeline

In the operating main pipeline, while studying the statistical parameters, collected for a long period of its operation, it was found that magnitudes of the pressure value $p_1, p_2, \ldots, p_n$ tend to temporal changes τ. In practical calculations of main pipelines the operating pressure change is taken into account, based on the rates and regulations, by the coefficient (factor) of the operating pressure overload in the pipeline – n, given depending on the way the pipeline structure is laid. The operating pressure overload factor is given in the regulations within wide limits, namely $n = 0{,}8 \ldots 1{,}2$. The internal pressure and the operating pressure overload factor are included into the basic formula for determining the pipe's wall thickness. Considerable attention should be paid to the closer estimation of the operating pressure in the pipeline and to specifying the overload factor for each particular condition of the main pipeline running mode.

It is important to choose a probabilistic model and to determine the laws of pressure and its distribution. Analysis of the experimental data obtained on the basis of pressure observations in the main pipeline «Lysychansk – Kremenchuk» is given below. The general data sample makes 3436 values, obtained within three months. The general nature of the pressure fluctuations for the entire period of observation depended mainly on changes in the pipeline's workload and the system's power control. The pressure changes diagram for 3 months period is shown in Figure 1.

Fluctuations of the pressure values in this mode of the pipeline operation are obviously caused by the technological factors connected with the operation peculiarities of the compressor equipment and hydraulic features of the system itself. Such factors are of random nature and cause accidental overloads of the pipeline structure that should be considered when calculating the reliability and designing main pipelines.

Values $p_1, p_2, \ldots, p_n$ – the pressure magnitudes in the stationary operation mode – will be considered, as a preliminary hypothesis, independent and identically distributed random variables falling under the distribution law $F(p)$. Let us perform processing of the statistic data collected for quite a long period of the pipeline's running, T = 3 months. In the pipeline operation, for the mentioned time period, 11 intervals have been found in its stationary mode of operation. Therefore, in order to improve the reliability of the results obtained, one interval was exposed to at least 20 measurements of pressure and duration of the period was not less than 12 hours.

Since for many particular distributions the formula to determine centering and normalizing constants a_n and b_n are known, and can be expressed in the considered time interval τ, and the distribution parameters are known as well, the model selection problem can be reduced to the selection of the distribution $F(p)$, so that its parameters for the studied time interval τ would give the equation $a_n = a,\ b_n = b$.

Let us perform further estimation of the probability that the obtained sample does not contradict to, or, conversely, sustains the assumption about the types of laws regulating random values distribution. Let us take the criterion of Pearson – χ_q^2 value. It should be noted that to solve the equations $a_n = a,\ b_n = b$ in most cases the two-parameter or three-parameter distributions are necessary, as they can more accurately provide the possibility of the

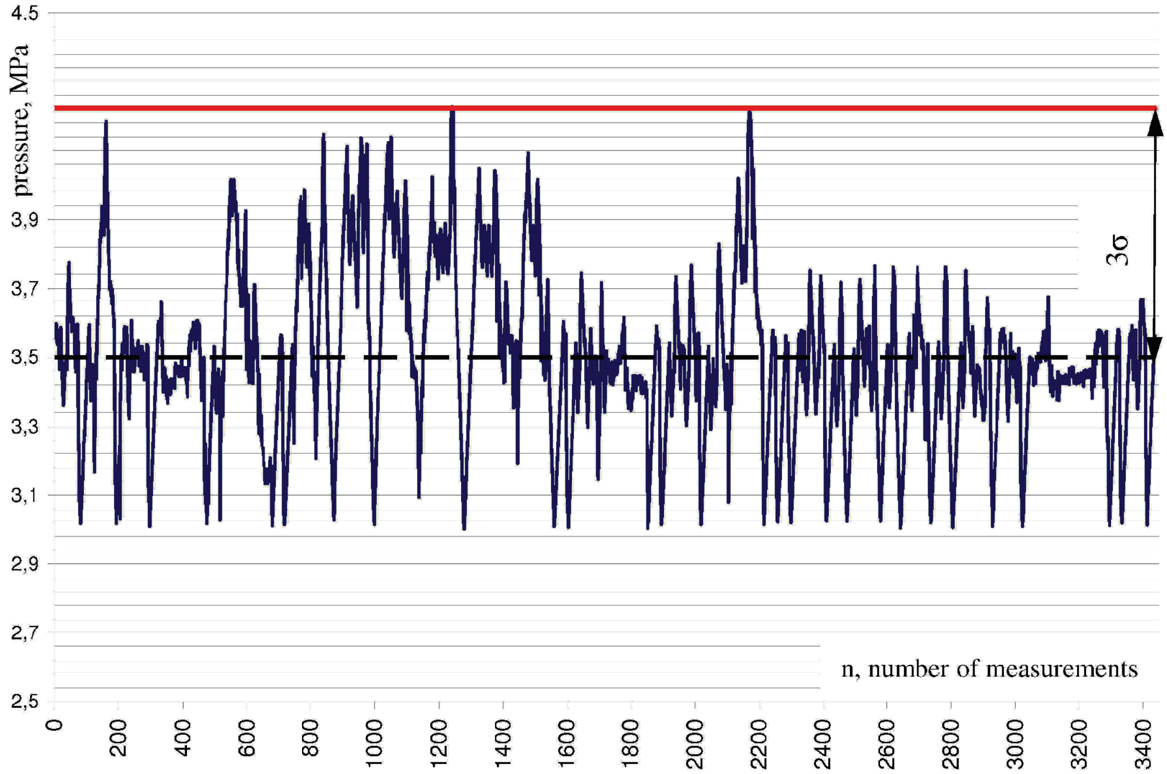

Figure 1. Pressure changes in the main pipeline for 3 months period.

model description. Further, to describe the spread in pressure values at the stationary operating mode of main pipelines, we are going to apply the normal distribution law, as the most particular according to the considered samples.

Analyzing Table 1, one can also see the correlation between the mean value of the internal pressure random variable and its standard deviation. The calculations demonstrated that the correlation factor of these parameters is 0.931. This indicates a nearly linear correlation between the parameters, i.e., the constant value of the pressure variations factor of pipelines.

Mean variation coefficient makes 6.9 %, which is taken as a design factor for further research.

Selection of probabilistic models and determining distribution of the thermal gradient random values magnitude in the main pipeline

Another important factor affecting the stress-strain state of the structure, and thus, its reliability, are seasonal temperature changes t_1, t_2, t_3... in the pipeline caused by the outside environment. In the process of main pipelines running, the magnitude of this change is not constant and varies temporally both within a year and in the context of many years variability. The calculation formulas take into account the value of thermal gradient Δt between the pipeline operation temperature and the temperature at which it was built. The thermal gradient also determines the buckling stability of the pipeline, provided by the respected pipeline curvature, pipeline laying depth, balancing.

Experimental studies of pipelines showed that changes in the thermal gradient occur cyclically throughout the year. Meanwhile, the greatest temperature changes are typical for the summer period and are short if compared to the total running period. Therefore, the reduced probability of the thermal gradient estimated value emergence should be taken into consideration when designing pipelines.

In this research, the choice of the random value distribution law has been made according to the experimental temperature observations in the main pipeline «Kelif – Shabarhan» in the section of 100 km long. The general sample makes 366 daily temperature values yearly. The general nature of the temperature change oscillation during the whole period is shown in Figure 2.

Table 1. Estimation of the distribution law consistency with the observation data of the pipeline's pressure changes when operating in the stationary mode

Number	Period duration, hours	Number of measurements per a period	Mean value, MPa	Standard deviation, MPa	Consistent distribution
1	17,5	35	3,410	0,0271	Normal
2	14,6	22	3,500	0,0259	Normal
3	23,0	46	3,827	0,0421	Normal
4	36,1	23	3,810	0,0448	Gamma-distribution
5	26,8	30	3,779	0,0360	Normal
6	20,2	71	3,447	0,0295	Normal
7	35,3	127	3,437	0,0220	Gamma-distribution
8	28,9	99	3,337	0,019	Normal
9	15,8	55	3,439	0,0274	Normal
10	14,8	46	3,397	0,0239	Normal
11	19,0	57	3,504	0,0322	Normal

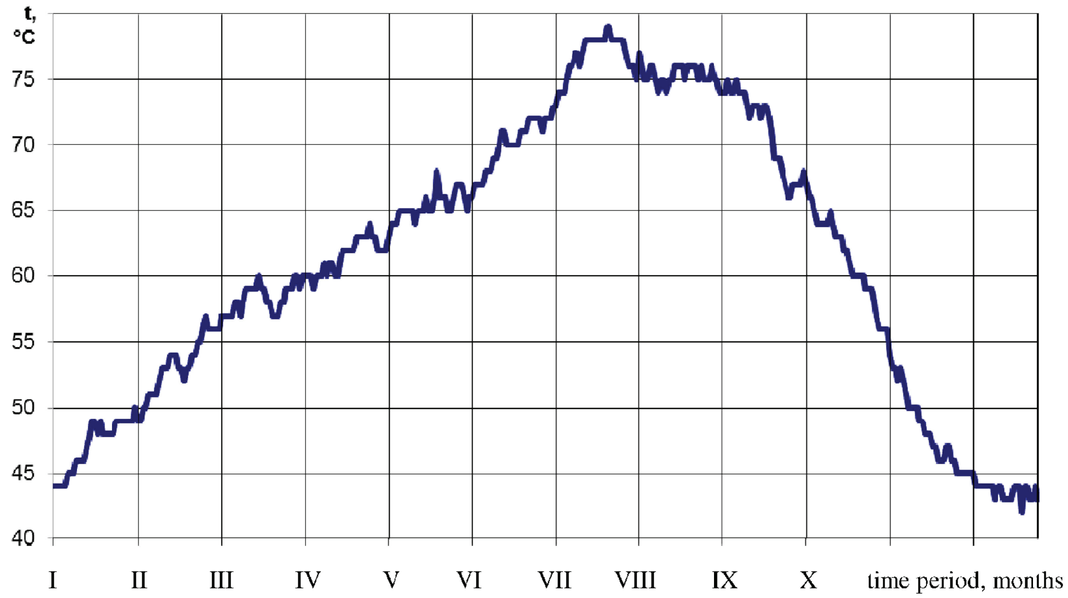

Figure 2. Diagram of the temperature t changes on the main pipeline surface per year.

The temperature variation, shown in Figure 2, is generally typical of main pipelines, which was confirmed by the 10 years long observations of the same pipeline and by the data, obtained from other pipelines. So, it can be taken as the estimated one to determine reliability. Let us verify the initial hypothesis that the thermal gradient values Δt_1, Δt_2, Δt_3, ..., Δt_n, on the surface of the main pipeline are independent and their distribution corresponds to the standard normal. For this purpose, we will apply the Pearson's criterion, as we did before. The calculation performed is presented for ten intervals in the tabular form (Table 2). In our case, the estimated level of significance is 5 %.

The criterion's limit value for the given significance level and the selected number of intervals makes $\chi^2_{0,05} = 14{,}1$. Thus, since $\chi^2_q < \chi^2_{0,05}$, the original hypothesis is confirmed, and the law of thermal gradient's random value distribution is consistent with the normal distribution. The diagram comparing these distributions is shown in Figure 3.

Determining the probability of failure and the reliability parameter of the main pipeline in the operating condition

Since all the random values affecting the general safety margin of the studied pipeline come within the normal distribution law, we can assume that the reliability function $\widetilde{Y}$ is of normal nature [4], too.

Under the normal distribution law, it is enough to calculate the safety characteristic to determine the structure failure probability:

$$\beta = \frac{\overline{Y}}{\hat{Y}}, \quad (1)$$

where $\overline{Y}$ – the mathematical expectation of the structure's safety margin;

$\hat{Y}$ – the safety margin standard.

The performed studies have shown that the safety margin function of the pipeline (4) may be, with sufficient accuracy and the obtained results security, linearized (replaced by a straight line) along the entire range of the random arguments possible values. For linear dependence of the reliability

Table 2. Verification of the hypothesis about the temperature distribution normality

Number	Interval limits Δt, °C		Number of observations within one interval	Laplace function's values for the interval limits		Probability of falling into the interval	χ_i^2
1	8	12	9	0,0000	0,0446	0,0446	2,277
2	12	16	27	0,0446	0,0968	0,0522	2,250
3	16	20	39	0,0968	0,1841	0,0873	1,562
4	20	24	38	0,1841	0,3085	0,1245	1,254
5	24	28	56	0,3085	0,4602	0,1516	0,005
6	28	32	53	0,4602	0,6179	0,1577	0,388
7	32	36	48	0,6179	0,7580	0,1401	0,211
8	36	40	39	0,7580	0,8643	0,1063	0,000
9	40	44	38	0,8643	0,9332	0,0689	4,499
10	44	48	10	0,9332	1,0000	0,0668	1,215
						$\chi_q^2 =$	12,661

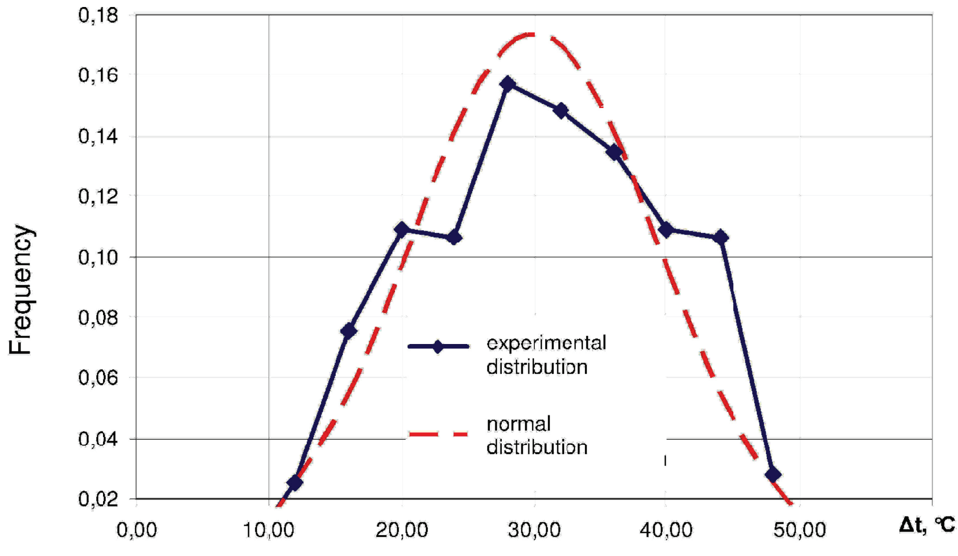

Figure 3. Comparison of the temperature change Δ*t* experimental and normal distributions.

function, its statistic parameters can be calculated for the relevant statistical parameters of the arguments according to the following formulas:

– mathematical expectation

$$\overline{Y} = Y\left(\overline{R}_y, \overline{p}, \overline{\Delta t}, \overline{\kappa}\right); \quad (2)$$

– standard

$$\hat{Y} = \sqrt{A_1^2 \hat{R}^2 + A_2^2 \hat{p}^2 + A_3^2 (\Delta \hat{t})^2 + A_4^2 (\hat{k})^2}\,, \quad (3)$$

where $A_1 = \left.\frac{\partial Y}{\partial R}\right|_{R=\overline{R}}$, $A_2 = \left.\frac{\partial Y}{\partial p}\right|_{p=\overline{p}}$, $A_3 = \left.\frac{\partial Y}{\partial (\Delta t)}\right|_{\Delta t=\overline{\Delta t}}$, $A_4 = \left.\frac{\partial Y}{\partial \kappa}\right|_{\kappa=\overline{\kappa}}$.

Expectation of the bearing capacity reserve of the pipeline structure is determined as (4)

$$\overline{Y} = \overline{R} - \sqrt{\left(\frac{\overline{p}D_{in}}{2\delta}\right)^2 + \left(\mu\frac{n\overline{p}D_{in}}{2\delta} - \alpha E\Delta\overline{t} + \frac{D_{out}}{2}\overline{\kappa}EK_s\right)^2 - \frac{\overline{p}D_{in}}{2\delta}\left(\mu\frac{n\overline{p}D_{in}}{2\delta} - \alpha E\Delta\overline{t} + \frac{D_{out}}{2}\overline{\kappa}EK_s\right)}\,. \quad (4)$$

To determine the standard $\hat{Y}$, let us first compute the required design factors:

$$A_1 = \frac{\partial Y}{\partial R} = 1; \quad (5)$$

$$A_2 = \left.\frac{\partial Y}{\partial p}\right|_{p=\overline{p}} = \frac{\frac{\delta\overline{\sigma}_{hs}^2}{\overline{p}}(2-\mu) - 2\mu D_{in}\left(\overline{\sigma}_{long} + \overline{\sigma}_{bend}\right) - D_{in}\left(\mu\overline{\sigma}_{long} + \overline{\sigma}_{bend}\right)}{2\delta\sqrt{\overline{\sigma}_{hs}^2 + \left(\overline{\sigma}_{long} + \overline{\sigma}_{bend}\right)^2 - \overline{\sigma}_{hs}(\overline{\sigma}_{long} + \overline{\sigma}_{bend})}}; \quad (6)$$

$$A_3 = \left.\frac{\partial Y}{\partial \Delta t}\right|_{\Delta t=\overline{\Delta t}} = \frac{\alpha E(\overline{\sigma}_{hs} - 2(\overline{\sigma}_{long} + \overline{\sigma}_{bend}))}{2\sqrt{\overline{\sigma}_{hs}^2 + \left(\overline{\sigma}_{long} + \overline{\sigma}_{bend}\right)^2 - \overline{\sigma}_{hs}(\overline{\sigma}_{long} + \overline{\sigma}_{bend})}}; \quad (7)$$

$$A_4 = \left.\frac{\partial Y}{\partial \kappa}\right|_{\kappa=\overline{\kappa}} = -\frac{\left(D_{in}p(1-2\mu) + 2\delta E\left(2\alpha\Delta t + \overline{\kappa}D_{out}K_s\right)\right)\cdot D_{out}EK_s}{2\sqrt{p^2D_{in}^2\left(1-\mu+\mu^2\right) + D_{in}p\delta E(1-2\mu)\left(2\alpha\Delta t + \overline{\kappa}D_{out}K_s\right) + \delta^2E^2\left(2\alpha\Delta t + \overline{\kappa}D_{out}K_s\right)^2}}\,. \quad (8)$$

The following values are indicated in the above formulas: D_{in} – internal diameter of the pipeline; D_{out} – outer diameter of the pipeline; δ – wall thickness of the pipeline; μ – Poisson's ratio; E – module of steel elasticity; α – coefficient of linear thermal expansion; κ – curvature of the pipeline; K_s – coefficient taking into account the influence of foundation soil reaction on the longitudinal stress values in main pipelines; σ_{hs} – hoop stress in the pipeline; σ_{long} – longitudinal stress in the pipeline; σ_{bend} – stress arising from the axis bend of the pipeline.

According to the above algorithm, one may perform the reliability calculation for any main pipeline, taking into account variability of its parameters: the strength of steel, operating pressure, thermal gradient, depth of laying.

This method can be used both at the design stage and at the pipeline operation stage: when deciding on its repairs, identifying safe operation pressure at the actual technical condition, etc.

For example, at the design stage, having compared the obtained failure probability value for the main pipeline's area with the normative values [2] for structures of this type (consequences class SS3, liability category A) – $1 \cdot 10^{-6}$ ($\beta = 5{,}05$) it is possible to estimate the reliability level of the structure. In addition, having adopted the normative value of failure probability as the original one, by means of the developed method, it is possible to solve the inverse problem: to design the pipeline structure with a given reliability level.

To determine the impact of the operating pressure change on the reliability of the main pipeline, the calculations of the «Lysychansk – Kremenchug» main pipeline's area have been made with changes in its operating pressure and its diameter (which determines the bandwidth).

The results of the safety characteristic calculations with changes of the mentioned parameters are presented in Table 3 and graphically shown in Figures 4 and 5.

Analysis of the diagrams in Figures 4 and 5 shows that with increase in the diameter of the pipeline, its reliability reduces. Moreover, variations in the values of safety characteristic for small diameter pipelines can be explained by the structural constraints of the pipeline's minimum wall thickness, which naturally increases the margin of safety and, therefore, reliability.

For large diameter pipelines, such spread of values is not observed, and the safety characteristic value approaches to 5.45.

As the analysis shows [3], significant impact on the stress-strain state and on the estimated value of

Table 3. Values of the main pipeline's safety characteristic β depending on the mean pressure and the diameter of the pipe

Operating pressure p, MPa	Reliability parameter β depending on the outer diameter D_{out}, mm			
	720	820	1020	1220
3,5	6,20	5,85	5,49	5,45
4,0	6,04	5,67	5,46	5,45
4,5	5,87	5,69	5,53	5,43
5,0	5,70	5,72	5,45	5,44
5,5	5,76	5,57	5,49	5,43
6,0	5,61	5,60	5,48	5,43

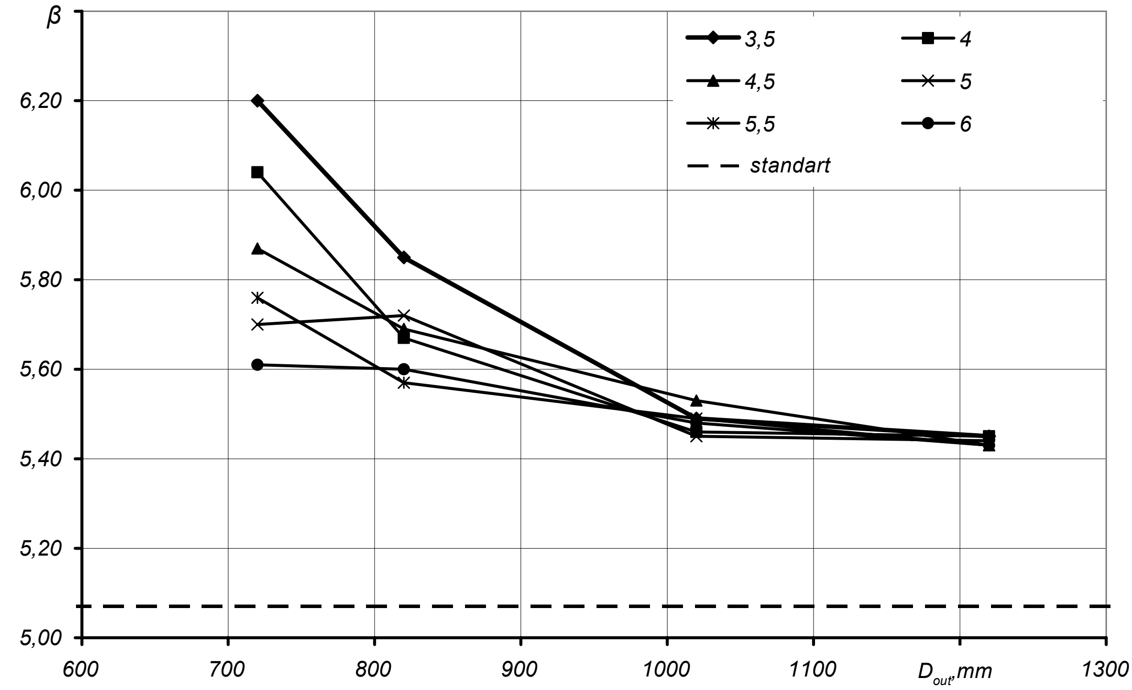

Figure 4. Correlation of the safety characteristic β for main oil pipelines of different diameters at different operating pressures: ▬ ▬ – standard value of safety characteristic.

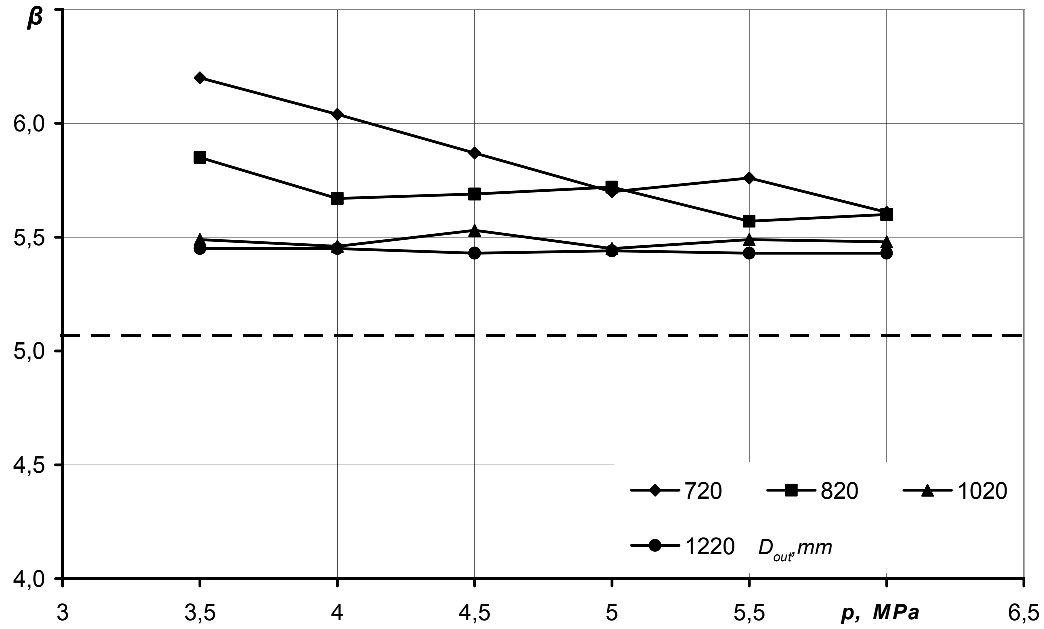

Figure 5. Diagrams of the $\beta - p$ correlations at different diameters (external) of the pipeline with the minimum design wall thickness δ.

the pipeline's wall thickness is made by its inaccurate laying. It is taken into account in the described method of calculating the reliability level using the parameter of deviations from the project curvature $\tilde{\kappa}$.

Conclusions

1. The reliability theory can be adapted to calculate the main pipeline's steelwork structure, taking into account the internal pressure load, temperature impacts, the impact of stress caused by the elastic bending and the reaction of the foundation soil on the pipeline.
2. Parameters of the internal pressure p of the transported product, thermal gradien Δt, curvature of the pipeline κ and steel tensile strength R_y, measured at different time are independent random variables. The frequency of these parameters values in calculations of the of pipeline steel structure reliability is described by the normal distribution law with sufficient accuracy.
3. With increase of the main pipeline's diameter, its reliability reduces, despite the respective increase of the wall thickness.
4. With increase of the operating pressure, structure reliability of main pipelines, designed to answer the current standards [7], does not practically change.
5. Steel structure reliability of the main pipeline designed on the basis of deterministic calculation according to the existing standards [7] is sufficient, which is illustrated by the values of failure probability: $Q(\beta) = 2{,}82 \cdot 10^{-10} \ldots 5{,}45 \cdot 10^{-6}$ (at the rate of $1 \cdot 10^{-6}$).

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