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TECHNICAL ASSESSMENT OF DISTRICT HEATING PIPELINES UNDER VARIABLE THERMAL LOADS WITH CONSIDERATION OF INSTALLATION DEFORMATIONS

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This study presents a methodology for assessing the technical condition of district heating pipelines under high wear, variable thermal loads, and limited modernization resources. Emphasis is placed on installation defects, cyclic temperature and pressure fluctuations, and corrosion-induced degradation. A case study of a return water pipeline in Kremenchuk, featuring a 3° installation misalignment and 10 cm flange displacement, demonstrated stresses of 220–250 MPa, exceeding the steel's yield strength in critical zones. Real operational conditions, including daily temperature fluctuations and load variations, were incorporated into the modeling to ensure accuracy. The approach enables prioritization of reconstruction zones, supports data-driven decision-making, and enhances the long-term operational efficiency of district heating networks under constrained budgets.

Keywords: district heating networks, service life, pipelines, mathematical modeling, temperature, stress-strain state.

Introduction

District heating networks in Ukraine are characterized by a significant level of physical deterioration during operation, which on average reaches 68 %. This leads to reduced reliability of heat supply systems, increased thermal losses, and higher expenditures on emergency and repair works. The problem is particularly acute in large cities such as Kyiv, Dnipro, and Kharkiv, where more than one-third of the networks have exceeded their standard service life and require urgent modernization.

The main factors contributing to the degradation of pipeline technical condition include corrosion, insufficient thermal insulation, the influence of groundwater, and unstable thermal and hydraulic operating modes. These factors result in emergency situations, substantial coolant losses, and a decrease in the energy efficiency of heat supply systems.

Under current conditions, it is essential to develop methodologies for assessing the residual service life of district heating networks, taking into account actual operational factors such as the stress-strain state of pipelines, thermal and pressure loads, and the impact of maintenance and repair activities. Reliable information on the technical condition and remaining service life of pipelines enables not only the prediction of their further operation but also the adoption of well-grounded decisions on reconstruction and thermal insulation optimization.

Solving these issues is highly relevant for enhancing the reliability of heat supply, reducing thermal losses, and decreasing the costs of repair and recovery efforts, which is of considerable socio-economic importance for regions with centralized heating systems.

Analysis of recent research

The assessment of the performance of district heating networks, along with methods for their improvement and modernization, has become the focus of intensive scientific research amid increasing demand for energy efficiency, reduction of heat losses, and digitalization of energy systems. Over the past 15 years, a significant body of theoretical and applied work has been developed in Ukraine and abroad, covering system analysis, thermo-hydraulic modeling, implementation of SCADA systems, and the integration of renewable energy sources into centralized heating networks.

For example, the study by Dirk Müller, Beatrice Nastasi, and colleagues presents a structural analysis of German district heating systems from the perspective of sustainable development (Müller et al., 2019). The authors consider centralized networks as components of a broader energy ecosystem, in which not only heat delivery but also integration with cooling, energy storage, and demand-side flexibility must be ensured. This systems-based approach accounts for complex interactions between heat sources, consumers, and auxiliary infrastructure, which is particularly relevant for urban networks in high-density areas.

In Swedish literature, particularly in the work of Sven Werner, system analysis is complemented by a historical approach: the evolution of heating networks from the second to the fourth generation is examined with a focus on energy efficiency, digital control, and minimization of losses (Werner, 2017). Werner emphasizes the importance of transitioning to low-temperature district heating based on flexible infrastructure capable of integrating renewables.

The issue of efficiency criteria is addressed by Petter Lauenburg and Fredrik Wernstedt, who propose the use of machine learning to forecast heat loads and enable adaptive control of heat supply (Lauenburg & Wernstedt, 2016). Their approach allows for the optimization of heat source operation, reduction of losses, and maintenance of stable parameters for the heat carrier. The authors highlight the importance of accurate consumption data, consumer segmentation, and implementation of intelligent control systems.

In the Ukrainian context, significant attention has been paid to analyzing the technical condition of domestic heating networks. In the study by H. H. Heletukha and co-authors, the current state of Ukraine's district heating (DH) system is examined, and its development prospects are evaluated (Heletukha et al., 2019). The authors analyze the factors contributing to the loss of competitiveness of DH and propose measures aimed at restoring the system.

In a study by Hongwei Fang and co-authors, thermal regime modeling in district heating systems is examined, accounting for losses, temperature variation of the heat carrier, and dynamic load conditions (Fang et al., 2015). The authors combine analytical and numerical methods, particularly the finite volume method, and emphasize the importance of using real consumption data for accurate network behavior forecasting.

The relevance of mathematical modeling of pipelines is highlighted in the publication by I. S. Bernarska, which presents algorithms for calculating hydraulic regimes in systems with complex configurations (Bednarska & Rindyuk, 2021). It is demonstrated that the non-uniformity of gas-dynamic loads causes local stress concentration zones, which may lead to premature damage and loss of equipment tightness. The modeling results made it possible to identify critical sections of the structure where the allowable mechanical properties of the material are likely to be exceeded. The proposed approach can be applied to enhance the reliability and operational safety of pipeline fittings.

The monograph by Svend Frederiksen and Sven Werner describes the implementation of SCADA systems in centralized heating networks, emphasizing automated control capabilities, leak detection, loss reduction, and improved system response to load changes (Frederiksen & Werner, 2013). The importance of telemetry for real-time adaptive regulation is also stressed.

The use of geographic information systems (GIS) and energy management tools in modeling district heating networks is presented in the collective report by the Ukrainian Bioenergy Association. The study highlights that integrating GIS with analytical modules enables spatial visualization of network operations, assessment of potential damage risks to specific sections, and planning of reconstruction measures while considering the network's topology (UABIO, 2021).

The publication by Henrik Lund and colleagues substantiates the concept of fourth-generation district heating (4GDH), which is based on low-temperature heat carriers (40–60 °C), renewable energy sources, thermal storage, and digital control systems (Lund et al., 2014). The authors argue that such networks are essential for achieving climate goals and decarbonizing the heating sector.

Liu Xiaobin and co-authors explore the practical aspects of integrating renewable energy into heat networks, including solar collectors, biomass, and heat pumps (Liu et al., 2020). The study analyzes examples of hybrid systems combining centralized and decentralized heat generation, enabling load optimization and improved network flexibility.

Despite the considerable volume of scientific research devoted to improving the efficiency of heating networks, thermo-hydraulic modeling, and the adoption of digital technologies, the issue of assessing the

residual service life of pipelines remains insufficiently addressed. Most existing studies focus on optimizing thermal regimes or improving energy efficiency, while the accurate determination of technical condition, stress-strain behavior, and life cycle forecasting of network components require further in-depth investigation. Given the severe wear of pipelines and their critical role in ensuring reliable heat supply, studying their residual resource characteristics is an extremely relevant and necessary direction for further research.

The aim of this article is to analyze the technical condition of district heating pipelines under real operating conditions and to justify approaches for assessing their residual service life, taking into account thermo-hydraulic regimes, stress-strain states, thermal and technological loads, and the impact of maintenance interventions. The proposed approaches are intended to enhance the operational efficiency of district heating networks and to ensure their reliable and safe functioning under conditions of limited resources and a high level of infrastructure deterioration.

Materials and Methods

The state of centralized heat supply systems in most Ukrainian cities, particularly in Kyiv, is critical. More than one-third of the pipelines have exceeded their standard service life, and a significant portion of trunk and distribution networks is in an emergency or pre-emergency condition. According to open data sources, the total length of heating networks in the capital that have exhausted their operational resource exceeds 36 % of the overall system, as confirmed by the actual volume of emergency repairs and network reconstruction carried out in Kyiv (Kyiv City State Administration, 2019; Kyivteploenergo, 2021; Kyiv City State Administration, 2023).

This situation leads to significant heat losses during the transportation of the heat carrier, frequent accidents, unexpected consumer disconnections, and increased energy expenditures. These issues directly affect the reliability of heat supply and the economic performance of district heating companies.

In Kyiv, several specific conditions have been identified that further complicate the operation of heating networks. For instance, approximately 47 km of pipelines are laid in areas with high groundwater influence, leading to degradation of thermal insulation, corrosion of steel components, and loss of load-bearing capacity. An additional 20 km of pipelines are located beneath buildings, making access for repair or replacement extremely difficult. Under such conditions, it is advisable to conduct a preliminary and objective technical assessment of the pipeline condition before any intervention, enabling the identification of priority zones for repair and the rational allocation of reconstruction resources.

The relevance of this approach is also confirmed by the fact that heat losses in some sections of the networks can exceed 20 % of the total supplied heat. As a result, district heating companies are forced to constantly increase pressure and temperature of the heat carrier to compensate for losses, which in turn accelerates the wear of network components. This creates a vicious cycle: higher wear leads to greater losses, and greater losses lead to accelerated wear. Breaking this cycle is only possible through a systematic approach to pipeline condition monitoring and strategic planning of network reconstruction.

Moreover, in the current context, special attention is being paid to energy efficiency and the reduction of greenhouse gas emissions. Inefficient networks not only result in energy losses but also indirectly increase CO₂ emissions due to excess fuel consumption for additional heat production. Accordingly, the reconstruction of heating networks based on accurate technical condition data contributes to achieving both technical and environmental goals.

Ukrainian regulatory documents, such as DBN V.2.5-39:2008 and the “Rules for Technical Operation of Thermal Installations and Networks”, stipulate the need for regular technical inspections of pipelines. However, in practice, these requirements are often ignored or fulfilled in a formal manner, without the application of modern diagnostic techniques. The availability of objective diagnostic data and engineering models makes it possible to forecast pipeline behavior over time, which forms the basis for well-informed decisions on repair, partial or complete pipe replacement, or changes in network operation modes.

Another factor that highlights the relevance of comprehensive technical assessments is the limited funding allocated for reconstruction. Often, local budgets can only afford partial network renewal, making it essential to have tools that can identify priority sections with the highest risk of failure or loss. This approach ensures rational use of resources and maximizes the effectiveness of infrastructure modernization investments.

In this context, engineering diagnostics and mathematical modeling methods gain particular importance. These methods account for thermo-hydraulic conditions, stress-strain states of pipelines, load histories, thermal influences, and corrosive environments. The combination of field inspections and numerical calculations enables quantitative assessment of the residual service life of pipelines, identification of severely degraded sections, and the development of a technical and economic justification for reconstruction.

This study employs an integrated approach to analyzing the performance of district heating networks, combining stress-strain analysis of pipelines, thermo-hydraulic modeling, and residual life forecasting under real-world operating conditions (Bednarska & Rindyuk, 2025; Chernousenko et al., 2022).

To assess the strength of district heating pipeline components, an approach based on the theory of elasticity and the equations of continuum mechanics was employed. The primary equation describing the stress-strain state (SSS) under conditions of plane axisymmetric loading is the equilibrium equation:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + f_r = 0, \quad (1)$$

where σ_r is the radial stress, σ_θ is the tangential (hoop) stress, and f_r is the body force in the radial direction.

The strain state is described using the compatibility equations and Hooke's law, taking into account the thermal component:

$$\varepsilon = \frac{1}{E}(\sigma - \nu(\sigma_r + \sigma_\theta)) + \alpha \Delta T, \quad (2)$$

where E is the Young's modulus, ν is the Poisson's ratio, α is the coefficient of thermal expansion, and ΔT is the temperature change.

To model the distribution of temperatures and pressures in district heating pipelines, a system of energy and hydrodynamic balance equations was employed (continuity, Navier – Stokes for steady flow, and energy equation accounting for heat losses, respectively):

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0, \\ \rho(\vec{v} \cdot \nabla) \vec{v} &= -\nabla p + \mu \nabla^2 \vec{v} + \rho \vec{g}, \\ \rho c_p \left(\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T \right) &= \nabla \cdot (\lambda \nabla T) + q, \end{aligned} \quad (3)$$

where ρ is the density; $\vec{v}$ is the flow velocity vector; p is the pressure; μ is the dynamic viscosity; c is the specific heat capacity; λ is the thermal conductivity; and q is the volumetric heat source.

Heat losses from the pipelines are estimated using a simplified heat transfer equation through a cylindrical wall, taking into account the thermal insulation:

$$Q = \frac{2\pi L(T_{in} - T_{out})}{\frac{\delta}{\lambda_{ins}} + \frac{1}{\alpha_{out}}}, \quad (4)$$

where Q is the heat loss; L – the pipeline length; T_{in} and T_{out} are the internal and external temperatures of the pipe, respectively; δ is the insulation thickness; λ_{ins} is the thermal conductivity of the insulation material; and α_{out} is the heat transfer coefficient to the environment.

Particular attention is given to the consideration of operational factors that significantly affect the residual life of the pipes and the overall reliability of the system. These factors include residual stresses, corrosion-induced wall thinning, non-uniform temperature fields, and cyclic pressure fluctuations. All these factors are integrated into the computational model as additional input parameters.

Residual stresses that arise in pipelines after welding or thermal operations are incorporated into the total stress field as initial loading. In numerical modeling, this is implemented by superimposing the pre-load stress-strain state onto the primary loading caused by pressure and temperature. Accordingly, the total stress in the pipe element is expressed as:

$$\sigma_{tot} = \sigma_{oper} + \sigma_{res}. \quad (5)$$

Corrosion-induced wall thinning of the pipeline is accounted for by modifying the geometric parameters in the model. The actual wall thickness is defined as the difference between the initial value and the losses due to corrosion:

$$t = t_0 - \Delta t_{cor}. \quad (6)$$

This directly affects the magnitude of the calculated stresses, which typically increase inversely with wall thickness.

The non-uniform temperature distribution across the pipe wall and along the length of the pipeline causes local deformations, leading to the development of thermal stresses. In the model, this is taken into account by superimposing the temperature field $T(r, z)$, obtained either from thermal analysis or operational measurements.

The corresponding thermal strain is calculated using the following equation:

$$\varepsilon_T = \alpha \cdot (T - T_0), \quad (7)$$

where α is the coefficient of thermal expansion of the pipe material.

Cyclic pressure fluctuations in the system lead to the development of fatigue damage in the pipe metal.

To quantitatively describe fatigue degradation, the Palmgren – Miner damage accumulation hypothesis is used:

$$D = \sum_{i=1}^n \frac{n_i}{N_i}, \quad (8)$$

where n_i is the number of cycles at a given pressure amplitude, and N_i is the fatigue life (limit number of cycles to failure) at this amplitude. When $D \geq 1$, the service life is considered exhausted. The values of N_i are determined from S – N curves (Coffin – Manson curves) for the pipe steel, taking into account the operating temperature.

Results and discussion

For the practical implementation of the proposed approach to assessing the technical condition of district heating pipelines, a representative section of the return water heating main in the Rakivka microdistrict of the city of Kremenchuk was selected (Fig. 1).

The operating organization identified defects in the newly installed section of the district heating network. During operation, a pipe leak occurred. Measurements showed that parts of pipeline (Inlet No. 1, Fig. 1, *b*) were laid with a misalignment of 3 degrees, resulting in a 10 cm displacement between the pipe flanges. However, using jacks, the pipes were lifted and reconnected.

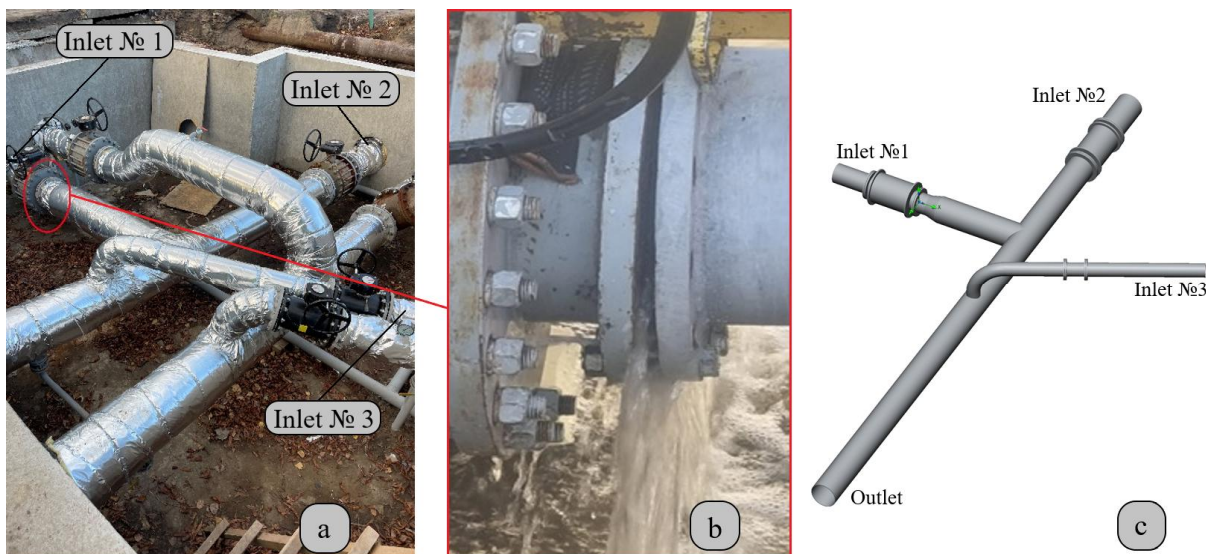


Fig. 1. Research object: *a* – section of return water pipeline; *b* – flange leakage location; *c* – 3D model of pipeline section

It is evident that such displacement caused significant deformations in the pipeline metal, which was taken into account in the presented study.

The process of assessing the damage accumulation of the object was of particular interest. As shown in Fig. 1, the studied pipeline section has a rather complex configuration – heat carrier flows through three valves, with the flow rate through each valve varying throughout the day (Fig. 2).

Consequently, distributions of velocity, dynamic pressure components, and pipe metal temperature also change. At the same time, the coolant temperature in the investigated section of the return water pipeline also changes. It fluctuates within the range of 40–68 °C, depending on the ambient temperature (Fig. 3). The above-mentioned data were obtained from the operating organization.

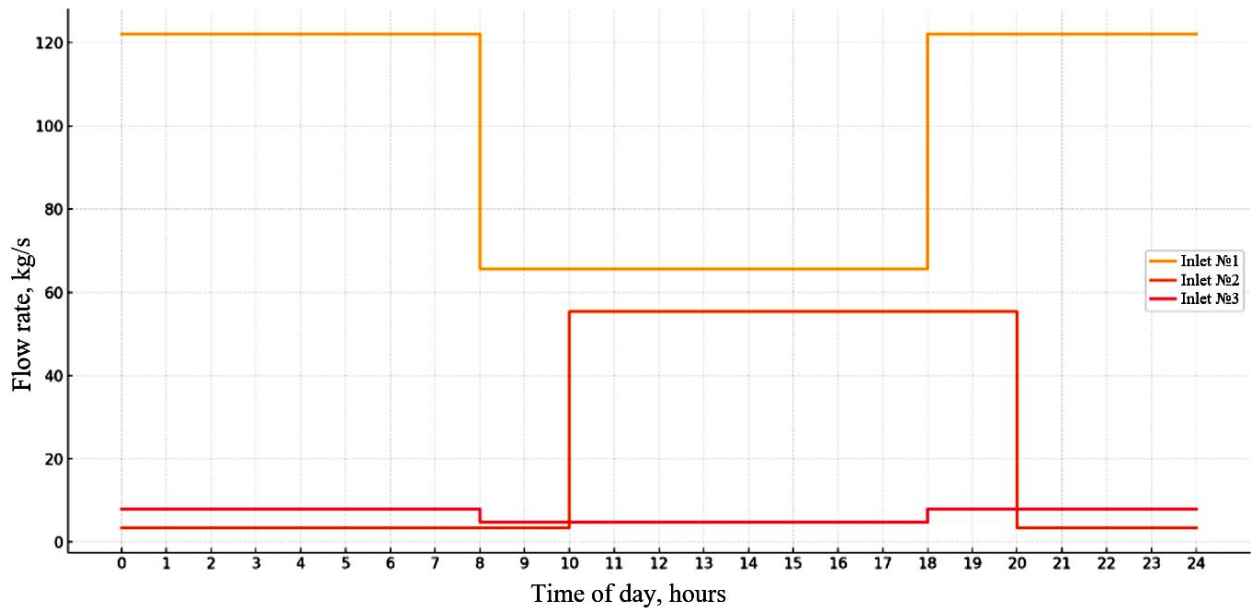


Fig. 2. Daily variation of the heat carrier flow rate through the pipeline system

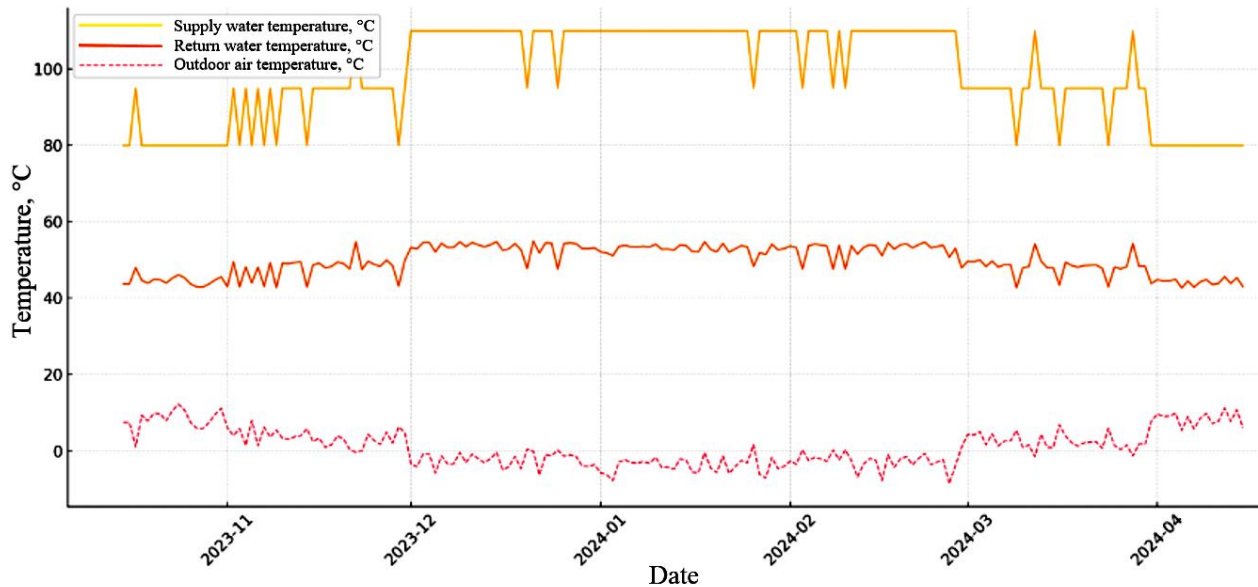


Fig. 3. Approximate graph of heat carrier temperature variation in Kremenchuk (heating season 2023–2024)

The work determined the distributions of velocities, pressures (Fig. 4), heat carrier temperatures, and pipe metal temperatures, and based on these, calculated the dynamics of the stress-strain state changes in the pipe metal (Fig. 5).

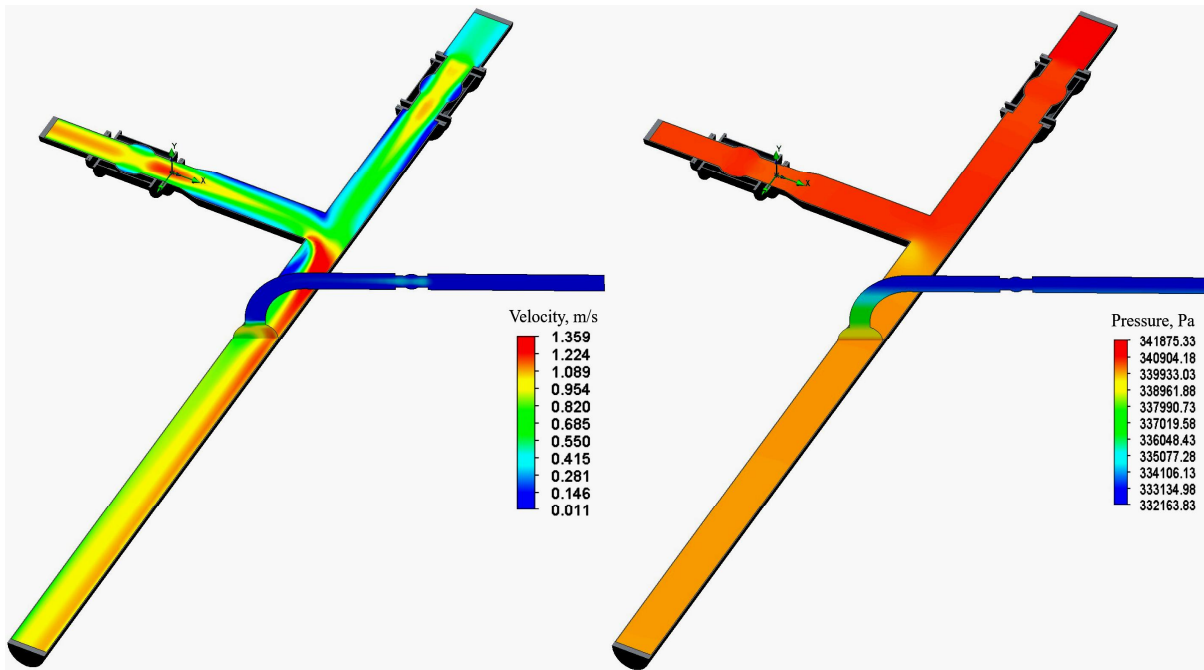


Fig. 4. Distribution of heat carrier velocities and pressures along the pipeline section

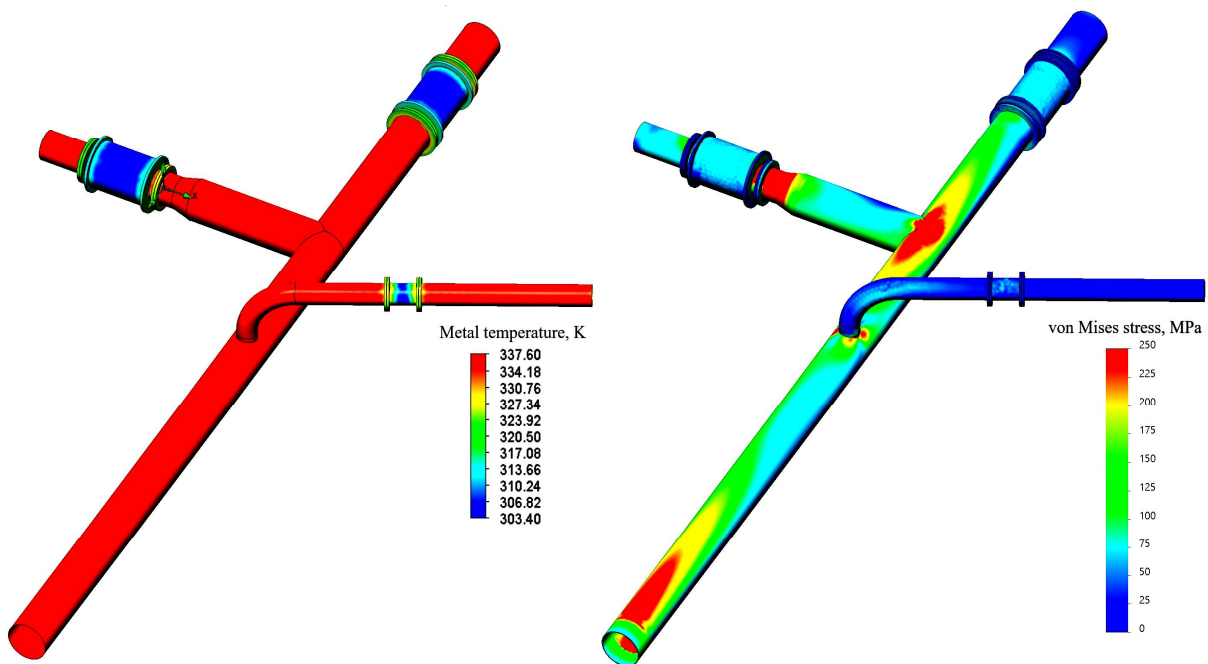


Fig. 5. Distribution of metal temperature and stresses along the pipeline section

The analysis of the obtained results confirmed the decisive influence of pipeline installation defects on the stress-strain state of the metal. A separate numerical experiment simulating the installation process (pipe displacement using jacks) of section No. 1 of the pipeline revealed the occurrence of stresses in the range of 220 to 250 MPa, which is close to the yield strength of the pipe material (steel 20).

Against the background of installation stresses, the stresses arising due to heat carrier pressure and temperature gradients are relatively small, ranging from 20 to 30 MPa. However, in the flange area of inlet No. 1, the tee zone, and the support location (outlet), these stresses combine with the installation stresses, which at certain hours during the day leads to exceeding the yield strength of the pipeline material. The stress variation graph at the control point (tee zone), obtained using dynamic simulation of pipeline operation over 24 hours, is shown in Fig. 6. At 4 a. m., the stress exceeds 250 MPa.

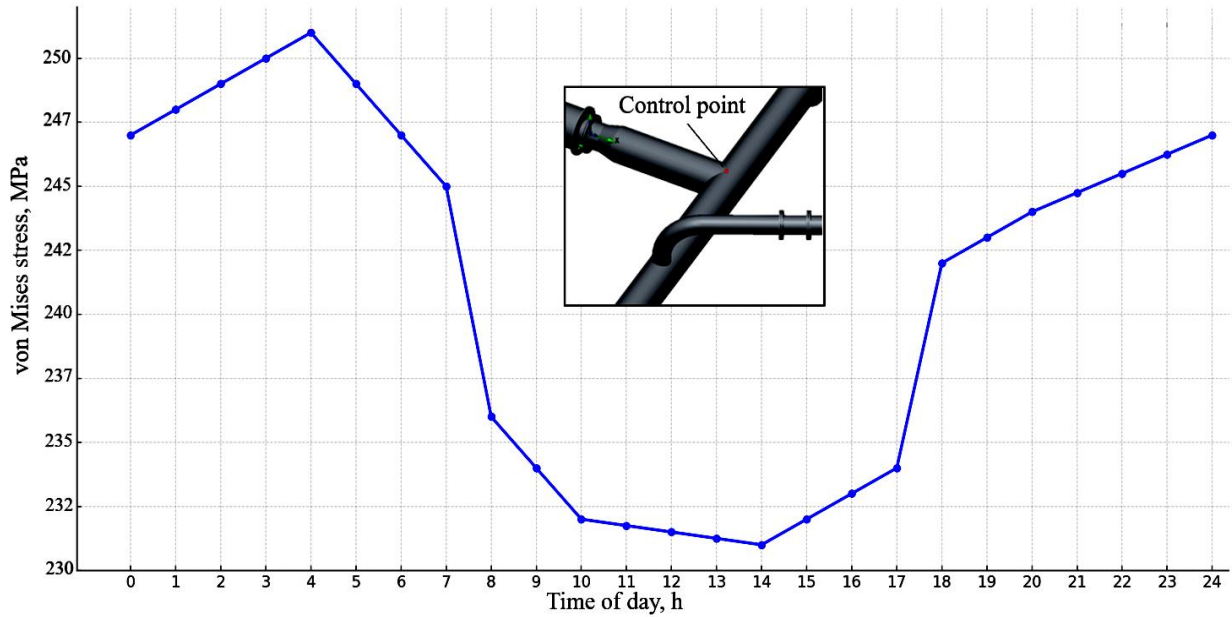


Fig. 6. Daily variation of stresses at the control point of the pipeline

Determining the static component of damage in this case is not a complex task, since both the current operating time and temperatures are known, and the literature provides all necessary information on the properties of the pipeline material. For example, see the standard COY-H EE 40.1-21677681-57:2011 “Methodology for Determining the Residual Life of District Heating Pipelines with a Standard Service Life”.

The cyclic component of damage can be determined based on Neuber’s method and Wöhler curves, which describe the dependence of allowable cycle counts on strain amplitude.

However, from a time-consumption perspective, accounting for cycles of heat carrier temperature changes depending on the ambient temperature during the heating season presents a challenge.

If it is impossible or difficult to establish the types of individual cycle impacts, and only the total number of cycles, n , up to the evaluation moment of accumulated damage is known, the accumulated cyclic damage can be conservatively estimated using the simplified formula:

$$D = \frac{n_{\max}}{N}, \quad (9)$$

where $n_{\max}$ is the number of cycles to crack initiation corresponding to the most severe loading condition (the regime with the maximum strain amplitude in the studied zone).

If necessary, a more detailed analysis of cyclic damage can be performed.

Based on the methodology described above, which accounts for the allowable number of cycles to crack initiation and the cumulative damage level during pipeline operation, the residual life assessment was carried out. The calculation covered thermal and mechanical loads characteristic of real operating conditions of district heating systems during the heating season. The summarized data are presented in Table.

Resource Indicators of the District Heating Pipeline Section

S/N	Resource indicator	Control point
1	Current operating time, hours	8000
2	Number of cycles	180
3	Cyclic damage, %	3.1
4	Static damage, %	3.4
5	Total damage, %	6.5
6	Residual life, hours	124800

Thus, the simulation results made it possible to determine the degree of metal damage in characteristic zones of the pipeline and to estimate the individual residual life for the section operating under the most severe conditions. The calculated residual life of the metal of the control section of the pipeline exceeds 14 years under unchanged operating conditions.

Conclusions

The study proposes a methodology for assessing the technical condition of district heating pipelines, taking into account installation deformations, variable thermal loads, and actual operating conditions. The methodology was tested on a specific section in Kremenchuk. The proposed methodology combines mathematical modeling of the stress-strain state, thermo-hydraulic analysis, and engineering evaluation of fatigue and static wear of the pipeline material.

The numerical simulation results demonstrated a significant impact of installation defects on the mechanical stress levels in the pipes, particularly at control points where stresses exceeded the material's yield strength. Distributions of temperature, pressure, stress, and strain were determined, enabling a quantitative assessment of material damage and calculation of the residual life for the investigated section.

The analysis confirms the feasibility of applying a combined approach that integrates measurement data, engineering analytics, and numerical modeling to improve the accuracy of pipeline condition forecasting. The obtained results can be used to prioritize district heating network rehabilitation programs, optimize operating modes, and ensure the reliability of heat supply under limited financial resources.

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ОЦІНКА ТЕХНІЧНОГО СТАНУ ТРУБОПРОВОДІВ ТЕПЛОВОЇ МЕРЕЖІ ЗА ЗМІННОГО ТЕПЛОВОГО НАВАНТАЖЕННЯ З УРАХУВАННЯМ ДЕФОРМАЦІЙ МОНТАЖУ

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У статті розглянуто актуальну проблему оцінювання технічного стану трубопроводів теплових мереж в умовах високої зношеності, змінного теплового навантаження та обмежених ресурсів для модернізації. Акцент зроблено на впливі монтажних дефектів, циклічних змін температури і тиску, а також корозійного зношення на залишковий ресурс труб. Мета статті – аналіз технічного стану трубопроводів теплових мереж на прикладі реальних експлуатаційних умов, а також обґрунтування підходів до оцінювання їхнього залишкового ресурсу з урахуванням теплогідрравлічних режимів, напружено-деформованого стану, температурно-технологічних навантажень і впливу ремонтних втручань.

Для практичної реалізації запропонованої методики досліджено ділянку теплотраси зворотної води в місті Кременчук, де зафіксовано монтажне відхилення труб на 3°, що спричинило осьове зміщення фланців на 10 см. Числове моделювання підтвердило виникнення монтажних напружень у металі трубопроводу в межах 220–250 МПа, які, у поєднанні з експлуатаційними навантаженнями (20–30 МПа), призводять до перевищення межі текучості сталі 20 у низці критичних зон. Враховано реальні температурні графіки, за яких температура теплоносія коливалась у межах 40–68 °С. Показано вплив добової зміни температури теплоносія на напружено-деформований стан контрольної ділянки трубопроводу тепломережі.

Виконано розрахунок пошкоджуваності з урахуванням статичних і циклічних навантажень. У контрольній точці виявлено сумарне пошкодження 6,5 % за поточного напрацювання 8000 год, що відповідає залишковому ресурсу 124800 год.

Запропонована методика дає змогу обґрунтовано визначати пріоритетні зони для реконструкції, підвищувати ефективність експлуатації тепломереж та сприяє ухваленню раціональних управлінських рішень на основі об’єктивних даних в умовах обмежених фінансових ресурсів.

Ключові слова: теплові мережі, ресурс, трубопроводи, математичне моделювання, температура, напружено-деформований стан.