

AUTOMATED ANALYSIS OF ELECTRICITY CONSUMPTION DURING WATER TRANSPORTATION THROUGH A PIPELINE AFTER ITS RENOVATION BY ALTERNATIVE TECHNOLOGIES WITH CONSIDERATION OF TEMPERATURE FACTOR

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Abstract. The article considers the causes of energy consumption increase during operation of pressure pipeline networks of water supply systems and possibilities for their control. In an automated mode using mathematical modeling, an analysis was carried out of energy saving ways during water transportation in dilapidated pressure pipelines subjected to trenchless repair with alternative materials. The most effective repair options include applying a flexible polymer sleeve, multilayer hoses, polyethylene pipes and sprayed protective coatings to the inner wall of the pipeline, as well as pulling pipes made of unplasticized polyvinyl chloride into the pipeline. The role of information technologies is shown that allow us to solve problems of prompt planning of works on pipeline transport renovation with finding the optimal option by reducing energy consumption during water transportation taking into account the temperature factor when laying surface and underground pipelines.

Keywords: modeling, energy costs, temperature factor, pipelines, reconstruction technologies, protective materials, design assessment

АВТОМАТИЗИРОВАННЫЙ АНАЛИЗ ПОТРЕБЛЕНИЯ ЭЛЕКТРОЭНЕРГИИ С УЧЕТОМ ТЕМПЕРАТУРНОГО ФАКТОРА ПРИ ТРАНСПОРТИРОВКЕ ВОДЫ ПО ТРУБОПРОВОДУ ПОСЛЕ ЕГО РЕМОНТА АЛЬТЕРНАТИВНЫМИ ТЕХНОЛОГИЯМИ

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Аннотация. Рассмотрены причины увеличения энергетических затрат при эксплуатации напорных трубопроводных сетей систем водоснабжения и возможности управления ими. В автоматизированном режиме с использованием математического моделирования проведен анализ путей экономии электроэнергии при транспортировке воды в ветхих напорных трубопроводах, подвергнутых бестраншейному ремонту альтернативными материалами. В качестве вариантов ремонта рассматриваются наиболее эффективные технологии нанесения на внутреннюю стенку трубопровода гибкого полимерного рукава, многослойных рукавов-шлангов, полиэтиленовых труб и напыляемых (набрызгиваемых) защитных покрытий, а также протаскивания в трубопровод труб из непластифицированного поливинилхлорида. Показана роль информационных технологий, позволяющих решать задачи оперативного проектирования работ по реновации трубопроводного транспорта с отысканием оптимального варианта за счет снижения потребления электроэнергии при транспортировке воды с учетом температурного фактора при наземной и подземной прокладке трубопроводов

Ключевые слова: моделирование, энергозатраты, температурный фактор, трубопроводы, технологии реконструкции, защитные материалы, проектная оценка

INTRODUCTION

Effective management of energy consumption in various industries today is an important tool for achieving key goals in the field of energy efficiency and environmental protection [1-3].

For urban water utilities, the tasks of saving material and financial resources during the construction and repair of pressure pipelines made of alternative materials, as well as maintaining or reducing the cost of electricity during the transportation of liquids are a priority [4, 5]. These tasks become even more important if the temperature factor, which is typical for different regions with warm, moderate and cold climates, as well as the methods of laying the pipeline (underground, ground or above the ground), are taken into account [6, 7].

To successfully solve the problems of reducing energy costs in the case of pipeline repair, a significant role is given to the assessment of their technical condition and the selection of optimal materials for reconstruction or modernization. The required qualitative and quantitative indicators of water and maintaining energy costs during the operation of the engineering pipeline network should be ensured by the following requirements [8, 9]:

- an appropriate degree of reliability for uninterrupted water supply to consumers at any time of day or night in the required quantity;
- the ability to resist corrosion, as well as various other influences (stray currents, aggressive soils, etc.);
- using network elements made from modern building materials that have a long service life and lower hydraulic resistance coefficients;
- minimal amount of damage to ensure a high degree of tightness of the pipeline system.

In order to reduce capital costs, the network is designed according to the principle of having minimal costs for construction and further efficient operation. The above requirement can be met provided that the diameter and material of pipelines with the appropriate hydraulic characteristics are correctly selected, ensuring the preservation or reduction of energy costs for

transporting water, as well as maintaining its organoleptic characteristics.

Numerous water losses in the system, as well as an increase in energy costs in water supply system pipelines, occur for the following reasons [10]:

- due to significant losses of liquid in the network caused by improper use of water in buildings and structures;
- impossibility of efficient operation of pumping equipment;
- unsatisfactory quality of urban water supply networks;
- low level of control over the operating parameters of pipeline system elements.

Foreign researchers note that the efficiency of hydrophore station control (i.e. pumping stations with several parallel pumps) plays a significant role in energy consumption in water distribution systems, when modeling is necessary by correlation between the amount of water supplied and electricity [11]. The proposed method has proven itself as a useful tool for assessing the daily consumption of electrical energy, taking into account the flow rate and growth of water pressure in the form of fuzzy numbers. The results obtained show that it is theoretically possible and reliable to use trapezoidal fuzzy numbers in the calculation to assess the daily consumption of electricity by hydrophore stations. The error in the assessment is less than 6%.

According to domestic experience, the maximum energy saving effect at pumping stations of water supply systems is achieved by implementing a set of measures, including equipment modernization, the use of energy-saving pumping equipment, monitoring the hydraulic mode of water supply in the pumping station area, the use of a set of tools to improve the hydraulic mode of the networks, as well as a system for optimal control of the water supply mode [12].

For the implementation of labor-intensive technical, economic and hydraulic calculations of construction projects and renovation of pipeline networks, domestic practice, for the purpose of optimizing hydraulic modes and thereby reducing energy consumption during

water transportation, widely uses automated software packages of the Samara State University of Architecture and Civil Engineering (SamGASU), Bentley WaterGEMS V8, VNII VODGEO, etc. The informational operation of the above programs is based on the principles of calculations (hydraulic, economic) of certain network elements taking into account the operation of pumping equipment and spare tanks [13-15].

The priority tasks of public utilities include correct and clear management of water supply systems in urban areas. The main goal of improving management systems is to develop cost-effective and efficient technologies that provide automatic control over the thermal state of pipelines and optimization of thermal conditions of water mains and distribution networks [16]. The scientific community has repeatedly emphasized the need to use low-roughness pipelines that operate within certain temperature ranges to minimize energy consumption during water transportation [17, 18]. Some researchers have come to the conclusion that the use of information technologies based on automated programs allows for the efficient operation of water supply networks under various influences that occur in real operating conditions of the facility during various repair and restoration work on the network [19, 20]. The information technologies listed above are capable of performing various tasks, which can be quite broad. For example, conducting analysis, as well as optimization of the parameters of elements of urban water supply systems, taking into account the issues in the field of energy conservation [21].

As an example, we can note the experience of laying pipelines in various areas of the northern territories of the country, where the soil contains ice (permafrost soils), and the average annual temperature is below zero. Ensuring the reliability of water supply and preventing freezing of pipes, which consists in preventing internal icing of the pipeline during operation and transportation of water for all types of pipeline laying, remains an important technological task [22].

At the same time, researchers note that internal icing of water pipelines that occurs during emergency shutdowns not only does not disrupt their operation, but also has in a number of cases the following advantages and economic benefits [23, 24]:

- a crust of ice that forms on the inner surface of the pipe acts as a protective film, preventing direct contact of water with steel; this potentially reduces the rate of corrosion of pipes, increases their service life and improves water quality;

- the formation of ice on the inner surface of the pipe smooths out its roughness, which leads to a significant reduction in pressure losses, which allows energy costs for liquid supply to be reduced by 18-20%.

It should be noted that icing is only possible when the water temperature is close to 0°C.

Certain patterns regarding the influence of the temperature parameters of the environment and the supplied liquid on the hydraulic characteristics of pipelines were noted by researchers in the middle of the last century [25]. The main tasks were to determine the friction pressure losses along the length of the flow during hydraulic and aerodynamic calculations of pipelines of all types, especially for the supply of water, oil and gas over long distances.

In recent years, in foreign practice, one of the types of forecasting the electrical load of a water supply pipeline system for the purpose of its effective management also uses the principle of combining weather (temperature) conditions as input variables. Foreign researchers propose calculating a complex parameter - a thermal index, where two types of weather parameters are incorporated (temperature and relative humidity) [17].

The issues of saving and maintaining energy costs are on the agenda in regions with cold and hot climates. For example, the northern part of our country, called the Far North, has the peculiarity of having permafrost soils on almost the entire territory. They can be found in the Arctic, part of the Arkhangelsk Region, the Komi Republic and a large area of the Siberian

region. The average annual temperature in this area is below zero. Thus, this will obviously affect the efficiency of the pipeline [26].

In the southern regions where liquids such as oil are pumped, increasing the energy efficiency of the pipeline-pumping station system requires a comprehensive approach based on mathematical modeling that incorporates the influence of both the temperature factor and changes in the characteristics of centrifugal pumps [27].

METHODS

The research consists of assessing the energy costs for transporting water when restoring the transport capacity of an old steel pipeline with a diameter of 325 mm and a length of 1,45 km for underground and above-ground installation options and for the corresponding temperature conditions.

The research method consists in the analysis of design solutions for selecting an optimal method of trenchless repair of an underground pipeline in an automated mode, in which, taking into account the temperature factor, the possibility of reducing energy costs for transporting water is assessed. Several automated complexes were subject to operation [28].

The following trenchless technologies were considered as methods for restoring the capacity of an old steel pipeline:

- pulling pipes made of unplasticized polyvinyl chloride UPVC SDR 41 (with an outer diameter of 225 mm, an inner diameter of 214 mm and a socket diameter of 265 mm) into a steel pipeline, followed by filling the intertube space with mortar; SDR is the ratio of the pipe diameter to its wall thickness;
- pulling and securing in an old steel pipeline a multilayer polymer sleeve-hose Primus Line, pre-deformed in the factory and fastened with tape, followed by its straightening within the old pipeline after inflation with steam under pressure;
- pulling deformed polyethylene pipes into an old pipeline using Swagelining technology without forming an intertube space;

- applying a sprayed Scotchkote coating with an appropriate wall thickness that ensures the load-bearing capacity of the pipeline system after repair;

- application of a sprayed Subcote coating with an appropriate layer thickness, which guarantees an increase in the load-bearing capacity of the repaired section of the pipeline after restoration work;

- use of a thin polymer sleeve as an internal lining that ensures the load-bearing capacity of the pipeline being restored.

Figure 1 shows in general terms fragments of the implementation of some of the listed trenchless technologies that are adopted to solve the problems of renovation of steel pipelines. Primus Line (top left), Swagelining (top right), Subcote and Scotchkote spraying (bottom left), and polymer sleeve pulling by method of air blowing and UV polymerization (bottom right).

Figure 2 shows the internal surfaces of an old pipeline after treatment with protective coatings Subcote (left) and Scotchkote (right).

Scotchkote protective coating is a non-soluble aliphatic isocyanate polyurethane that cures after application to the internal surface of the pipeline within 8-10 minutes.

The Subcote material is based on a polyurethane resin that quickly polymerizes on the inner wall of the pipeline being restored. This coating has a wide range of applications, allowing for effective spraying on the inner surface of pipes made of steel, cast iron, concrete, chrysotile cement and even old polymer pipes.

For the technology of inserting a flexible polymer sleeve into a pipeline and fixing it, in relation to its wall thickness, as well as strength characteristics, materials were used indicated in [29].

The costs of electrical energy for transporting water to the point of consumption are determined by automated programs, where 9 parameters characterizing the operation of the pipeline system are highlighted in the dialog box [30].

The type of dialog box is presented in Table 1.

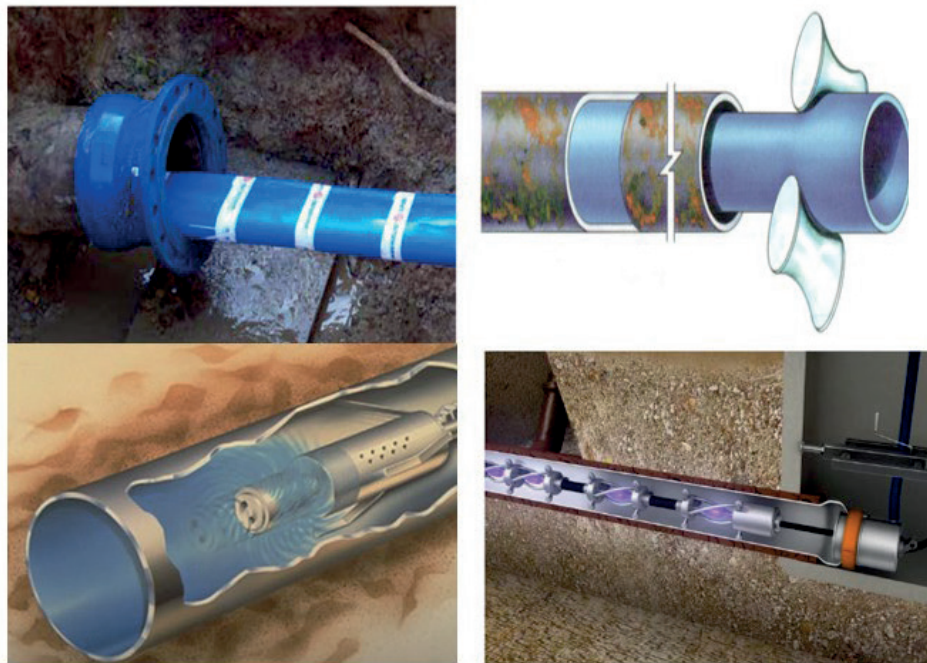


Figure 1. Selective methods of pipeline renovation using technologies

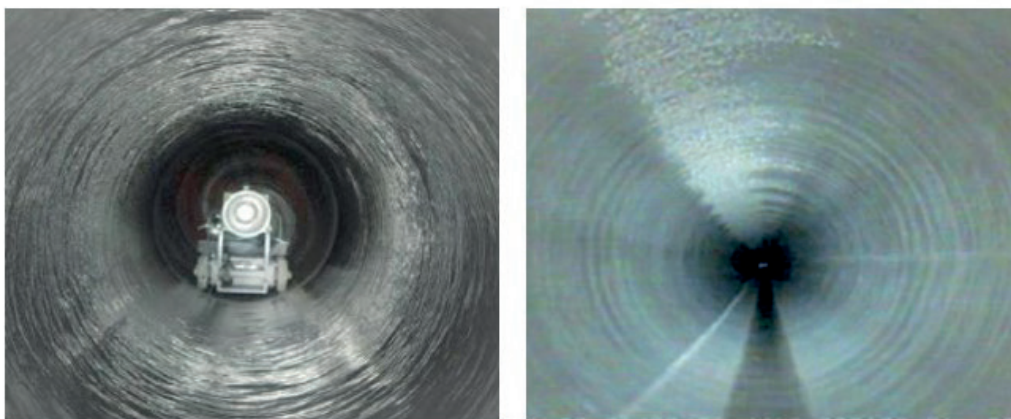


Figure 2. Illustration of the internal surfaces of a restored steel pipeline with spray coatings applied

Table 1. Input information of the dialog box of the program for calculating energy costs for underground steel pipeline conditions

1. Pipeline material	steel
2. Inner diameter of the pipeline, m	0,315
3. Length of the pipeline, m	1450
4. Water flow rate, m ³ /s	0,072
5. Efficiency of the pumping unit	0,95
6. Temperature of the liquid flow	10
7. Temperature of the pipe wall	10
8. Coefficient in the formula for specific resistance of the pipe material K	0,0017
9. Power n for diameter in the formula for specific resistance	5,1359

The temperature of water transported from an underground water source, as well as the temperature of the steel pipeline wall for two installation options are taken as follows:

-10 oC, and the pipe temperature is 30 oC (for ground installation in a hot climate);

-10 oC, and the pipe temperature is 10 oC (for underground installation, i.e., when the pipe temperature is identical to the temperature of water from an underground water supply source).

The base water flow rate for all cases is taken to be 0,072 m³/s (or 72 l/s), and the specific hydraulic resistance for a steel pipe is calculated using the formula

$$A = 0,0017 \cdot d^{-5},1359.$$

A preliminary analysis of the printouts for two installation options for a steel pipeline at a flow rate of 0,072 m³/s showed that the power consumption is, respectively,:

$E_u = 31,397$ thousand kWh/year (underground installation)

$E_o = 29,191$ thousand kWh/year (ground installation)

Thus, owing to the change (decrease) in the viscosity of the transported liquid during ground

laying, due to the increase in the temperature of the pipeline wall and the change in the coefficient of hydraulic friction λ from 0,015247 to 0,013867, the values of electricity consumption differ by 1,0701 times (or 7,01%). With regard to the use of the technology of pulling a PVC-U pipe into the steel pipeline for its repair, a preliminary strength calculation of a two-layer pipe structure was performed using an automated program with a dialog box presented in Table 2 [31].

The resulting two-layer structure after repair and construction work meets the strength conditions. In particular, it ensures:

- compliance with the conditions of maximum permissible deformation in the pipe cross-section;

- resistance to floating, i.e. overcoming the Archimedes force of the round shape of the polymer pipe pulled into the restored pipeline.

The calculated data for the "steel + PVC-U" structure showed that the resulting two-layer pipe structure meets the listed strength requirements.

Table 2. Input information of the dialog box of the program for strength calculation of a two-layer structure "steel + PVC-U"

1. Diameter of the pipeline to be renovated, m	0,315
2. Diameters of the new pipeline pulled into the old one: outer, m inner, m	0,225 0,214
3. Volumetric weights, N/m ³ : cement mortar pulled pipe transported water	25000,0 9500,0 9800,0
4. Internal pressure of the transported medium corresponding to the reduced design stress	0,00
5. Value of possible vacuum in the inter-pipe space, MPa	0,00
6. Standard service life of the pulled pipeline, years	50,0
7. Maximum operating temperature of the pulled pipeline, degrees Celsius	30,00
8. Maximum permissible value of ovalization of the cross-section, %	5,0

As far as the renovation using Primus Line technology is concerned, two versions of the pulled-through sleeve-hose were subject to analysis:

- two-layer aramid fabric with a thickness of 9,0 mm with an outer diameter of 315 mm and an inner diameter of 297 mm;
- similar single-layer fabric with a layer thickness of 6,5 mm; while the outer and inner diameters are 315 and 302 mm, respectively.

According to the calculated data obtained as a result of using the software package [32],

when using the Swagelining technology with a polymer pipe SDR 50 with a diameter of 355 mm, subjected to preliminary thermomechanical compression and subsequent expansion after pulling into the old steel pipeline, the internal diameter of the two-layer pipe structure will be 300,73 mm (Table 3). Table 3, as an example, also provides data on pipes with a wide range of SDR values, which can be considered as an alternative to the selected option.

Table 3. Output summary information with data on pipeline diameters and pressure losses at different SDR values

Calculated values	Values of SDR						
	11	17	21	26	33	41	50
Internal diameter after renovation, mm	248,77	272,16	280,76	287,45	292,96	297,54	300,73
Head loss after renovation, m	2,995	1,791	1,498	1,309	1,174	1,074	1,011

As follows from the calculated data in Table 3, when using Swagelining technology with SDR 50 pipeline, pressure losses are minimal, which will allow achieving the greatest energy saving effect during water transportation.

RESULTS AND DISCUSSION

Below is a comparative analysis of alternative methods for renovating an old steel pipeline.

A. Calculation of energy savings for transporting water in a two-layer pipe structure "steel + PVC-U" for underground installation and an efficiency of 0,95.

Value of the coefficient of specific resistance of a PVC-U pipe: $APVC-U = 0,0008 \cdot d - 5,1977$ [4].

Energy savings for a two-layer ground pipeline are negative equal to -16.965 thousands kWh per year.

Thus, it should be noted that this reconstruction option using a PVC-U pipe is unacceptable due to the increase in energy costs due to a significant narrowing of the flow cross-section of the pipeline after repair.

B. Calculation of energy savings for transporting water in a two-layer pipe structure "steel + Primus Line sleeve-hose" for underground installation and an efficiency of 0,95.

Option 1. Using a two-layer aramid fabric 9.0 mm thick (outer diameter is 315 mm, inner diameter is 297 mm) as a protective coating, the specific resistance coefficient is $A = 0.0004 \cdot d - 5.7276$.

The energy savings for a two-layer ground pipeline are 10.899 thousands kWh per year.

Thus, it should be noted that, despite the slight narrowing of the flow cross-section of the pipeline after repair, this reconstruction option using the coating is acceptable because of the reduction in energy costs due to the reduction in hydraulic resistance of the pipeline wall.

Option 2. Using a single-layer aramid fabric 6,5 mm thick (outer diameter is 315 mm, inner diameter is 302 mm), the specific resistance coefficient is $A = 0,0004 \cdot d - 5,7276$.

The energy savings for a two-layer ground pipeline are 12.768 thousands kWh per year.

Thus, we note that this renovation option is not expensive in terms of energy savings.

C. Calculation of energy savings for water transportation in a two-layer pipe structure "steel + pre-compressed polyethylene" (Swagelining) for underground installation and an efficiency of 0,95.

The possibility of using SDR 50 polymer pipes (outer diameter is 355 mm, inner one is 300,73 mm) as a protective coating is considered, the coefficient of specific resistance is $A = 0.0009 \cdot d^{-5} \cdot 2146$.

The energy savings for a two-layer ground pipeline are 7.919 thousands kWh per year.

Therefore, it can be concluded that this reconstruction option is somewhat inferior to the above-mentioned renovation options in terms of energy savings.

D. Calculation of energy savings for water transportation in a two-layer pipe structure "steel + spray coating" (Scotchkote) for underground installation.

When applying the coating, the internal diameter of the steel two-pipe pipeline will be $315 - 2 \cdot 5 = 305$ mm, and the specific resistance coefficient is $A = 0,0008d^{-5},1883$.

Energy savings on a two-layer ground pipeline amount to 12.84 thousands kWh per year.

This reconstruction option is not expensive in terms of energy savings.

E. Calculation of energy savings for water transportation in a two-layer pipe structure "steel + spray coating (Subcote)" for underground installation and efficiency of 0,95.

After carrying out repair and restoration work, the internal diameter of the steel two-pipe pipeline will change and become $315 - 2 \cdot 4 = 307$ mm, and the specific resistance coefficient is $A = 0,0008d^{-5},19$.

Energy savings on a two-layer ground pipeline amount to 13.423 thousands kWh per year.

This reconstruction option is also not expensive in terms of energy savings.

F. Calculation of energy savings for water transportation in a two-layer pipe structure "steel + polymer sleeve" for underground installation and efficiency of 0,95.

When inserting and fixing a thin polymer sleeve into a pipeline, the internal diameter of the steel pipeline will become $315 - 2 \cdot 3 = 309$ mm, and the specific resistance coefficient is $A = 0,0007d^{-5},2791$.

The wall thickness of the thin-wall polymer pipeline equal to 3 mm was selected based on the results of the automated calculation [33].

The energy savings for the two-layer ground pipeline is 14.513 thousands kWh per year.

Thus, it should be noted that this reconstruction option is the most acceptable in comparison with the others in terms of energy savings.

Table 4 presents the summary calculation results for underground installation, which allow the designer to assess the degree of potential reduction in energy costs for water transportation after renovation work on the steel pipeline (base option) with alternative trenchless methods has been executed.

Table 4. Summary data on reduction in electricity costs for underground installation after execution of renovation work (without the unacceptable option of renovation with PVC-U pipe)

Name of the double-layer pipeline	Reduction in electricity consumption compared to the base case, %
Steel + sleeve-hose (Primus Line)	
Option 1	34,0
Option 2	40,7
Steel + pre-compressed polyethylene (Swagelining)	25,2
Steel + spray coating (Scotchkote)	40,9
Steel + spray coating (Subcote)	42,7
Steel + polymer sleeve	46,2

Taking into account the data in Table 4, the method of pulling a polymer sleeve into a steel pipeline and fixing it inside the pipeline can be adopted as the most acceptable trenchless renovation technology in terms of the energy costs, among other methods under consideration, for which the energy consumption can be reduced by 46,2%.

According to calculations, given the cost of 1 kWh equal to 5,25 rubles for industry, the monetary costs for renovation options for the case of underground pipeline laying with a pump efficiency of 0,95 and a flow rate of 0,072 m³/s will amount to the values presented in Table 5.

Table 5. Comparative data on the values of energy costs and savings in money when transporting water through a renovated pipeline depending on the repair method

Name of the double-layer pipeline	Energy savings on water transportation per year in thousands of kWh	Reduction of water transportation costs per year in thousands of rubles.
Steel + sleeve-hose (Primus Line) Option 1	10,899	57,22
Option 2	12,768	67,03
Steel + pre-compressed polyethylene (Swagelining)	7,919	41,57
Steel + spray coating (Scotchkote)	12,84	67,41
Steel + spray coating (Subcote)	13,423	70,47
Steel + polymer sleeve	14,513	76,19

Thus, the cheapest option for savings on electricity when transporting water can be considered as the "steel + polymer sleeve" method. This trenchless technology is considered the least expensive in terms of money savings. Other technologies can also be used, but they provide a slightly smaller effect on energy savings. It should be noted that the use of any other methods of pipeline renovation among the trenchless technologies used in practice is not excluded after assessing the values of possible energy savings when using them.

CONCLUSIONS

1. Based on the results of modeling using automated programs, a project assessment of the possible reduction in electricity costs (taking into account the temperature factor) during the transportation of water through an old pressure

pipeline, after repair and restoration work has been executed, was obtained using a specific example.

2. Based on the analysis of calculated data, the dynamics of the reduction in energy costs for transporting water through a restored pipeline, as well as savings in funds for several alternative methods for pipeline repair, are presented.

3. The technology of applying a protective coating in the form of a polymer sleeve has been identified as the most effective method of trenchless pipeline renovation in terms of the possibility of achieving energy saving effects.

4. It has been proposed that the management of the operating parameters of the pipeline system should be carried out at the design stage by selecting the most cost-effective option for its construction and repair, taking into account cost estimates, temperature conditions of the ambient environment and the transported water, as well as the minimum cost of electricity consumption.

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