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Determination of annual heat losses from heat and steam pipeline networks and economic analysis of their thermomodernisation

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ABSTRACT

The paper presents a method of evaluation and selective thermomodernisation of overhead thermal pipeline networks. The expression "thermomodernisation" is used for determination of all those activities that deal with improvement of heat insulation features of the pipelines under consideration. The method is particularly useful for extensive and complex heat or steam pipelines. A novel method for the determination of annual heat losses from overhead pipelines into the environment has been developed in the work. The heat losses from the pipelines are generated during the whole year. The proposed method is based on the concept of one-off examination of the pipeline under consideration by means of a thermovision camera, performed in existing weather conditions. An example of an analysis has been carried out and results are presented for an existing industrial pipeline network. In this analysis the whole pipeline network was divided into segments characterised by identical technical features. To determine the annual heat loss, the operation of the considered pipeline during the whole year in different meteorological conditions was simulated numerically. Next, economic factors were calculated for each pipeline segment. Generally, the selection of line segments recommended for thermomodernisation was done on the basis of heat losses and *SPBT* (simple pay-back time) calculations.

1. Introduction

Steam and hot water pipeline networks are widely applied in industrial plants as well as in district heating systems. Chemical and petrochemical plants, factories producing fertilisers, cellulose and textile plants have the most extended and complex pipeline systems. Steam is also used as a basic energy carrier in sugar and generally in food industry as well in heavy industry like non-ferrous and iron metallurgy. These energy carriers are always sent to consumers by piping systems. For practical reasons, overhead pipeline networks are usually built in industrial plants. During the distribution of the aforementioned energy carriers by means of pipelines, there is always a problem of energy losses which result in increasing economic costs.

Diverse concepts, methods and algorithms are used for the determination of rational main technical parameters of heat pipeline network, e.g. diameter of the pipes, thermal insulation thicknesses and others. Objective functions used for the calculation of optimal values of technical parameters assumed to be decision variables [1–7] are formulated in various ways.

Work [1] presents the procedure for determination of optimal insulation thickness for multi-layer insulation of pipeline. The objective function and the restrictions are nonlinear in most of the insulation problems. A nonlinear optimisation method with constraints was applied for the minimum cost determination of insulated pipelines. The objective function consists of the heat loss and the material costs of the insulating layers and the tube as well. To solve this problem, an algorithm with a penalty function was applied. The sample thicknesses of insulating layers and the minimum costs depending on the temperature of the surrounding air and transported substance were determined and presented.

More general results of this topic analysis are included in work [2]. While the main objective of applying insulation in any plant is to achieve the minimum total cost during an assumed period (evaluation period), the appropriate insulation thickness is usually called the economic thickness. The general purpose was to find out for what insulation thickness further expenditure on insulation would not be justified by the additional financial savings on heat to be anticipated during the evaluation period. Although an increase in the amount of insulation applied will raise the initial installation cost, but it will reduce the rate of heat loss through the insulation. Therefore it is necessary to reduce the total cost during the evaluation period. In work [2], simple-to-use correlations, employing basic algebraic equations which are simpler than other available

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models involving a large number of parameters, requiring more complicated and longer computations, are formulated to arrive at the economic thickness of thermal insulation suitable for pipelines under consideration. The correlations are expressed as a function of steel pipe diameter and thermal conductivity of insulation for given surface temperatures.

In work [3] a more extended thermodynamic analysis of pipeline network operation was done because the principles of exergy analysis were employed for this purpose. In this paper, the energy and exergy losses occurring in the district heating network system have been investigated. The analysis indicates that exergy losses occurring during the transport of thermal energy to consumers are relatively large and primarily are dependent on the temperature of the hot water. Additionally, this analysis shows that these losses during transportation of energy carrier in the pipeline network can be reduced by decreasing heat losses in pipelines and by reducing the consumption of electrical energy used for the transport of hot water to the consumer. From the thermodynamic point of view, these heat losses should be kept at a minimum, which is possible by lowering the supply water temperature from the heat plant and by increasing thermal insulation thickness of the pipelines. Furthermore, if the supply temperature is reduced, the water flow rate in the district heating system must be increased, which results in higher pumping costs. To sum up, in the process of comprehensive design of the whole system, different aspects of future operation of the planned installation should be taken into account.

Paper [4] includes an example of thermo-economic optimisation. Four different thermo-economic techniques for optimum design of hot water piping systems were applied. The first one was a sequential optimisation of the pipe diameter based on minimisation of total cost without considering heat losses and then of insulation thickness based on minimisation of cost of insulation and heat losses. The second was simultaneous optimisation of pipe diameter and insulation thickness based on the first law of thermodynamics and cost whereas the third one was simultaneous determination of pipe diameter and insulation thickness based on maximisation of exergy efficiency without considering cost. Finally, the fourth was simultaneous determination of pipe diameter and insulation thickness based on maximisation of exergy efficiency and cost minimisation. The last method in which the exergy and cost parameters were used to determine the thermo-economic optimum is preferable because it provides an insight in terms of exergy as well as economics. Therefore, it was the recommended method to use in design studies. In this analysis it was found that exergy losses due to heat transfer were about 70% of the total exergy destruction. The final conclusion is that in hot water piping system design, not only the exergy destruction due to friction but also the exergy destruction due to heat transfer into the environment should be carefully analysed.

The exergy analysis was also employed for integrated evaluation of cooperation of low temperature district heating system with building heating installations [8]. In this analysis the overall system energy and exergy efficiencies were calculated and the exergy losses for the major district heating system components were evaluated. Based on these results, suggestions were given to further reduce the system energy and exergy losses as well increase the quality match between the consumer heating demand and the district heating supply. Similar studies on optimisation of integrated systems of district heating networks and building heating components are also presented in Refs. [6,7].

An extended multi-faceted analysis dedicated to determination of optimal pipelines parameters is included in Ref. [5]. The energy, economic and environmental evaluations of thermal insulation in district heating pipelines are discussed. The optimum insulation thickness, energy saving over a lifetime of 10 years, payback period, emissions of carbon dioxide, sulphur dioxide and carbon oxide by the heat producer were taken into consideration as well. In the process of determining optimal values of the considered pipeline parameters, a LCA (life cycle analysis) concept was applied. During the calculations of annual heating energy demands within the time assumed for this analysis, the changes of the meteorological parameters, especially atmospheric temperature, were taken into account. For this purpose, the well known degree-days method was applied. In this method the number of the so-called HDD (heating degree-days) is calculated within each considered year.

2. Purpose and content of the work

The analyses as presented above and other similar works are the source material for the development of different technical recommendations concerning the design of new pipelines. Moreover, they are useful during reconstruction and modernisation of the old ones. These recommendations are usually gathered in different official documents and standards, e.g. Refs. [9–12], which are a basic tool for engineers dealing with these problems in their work. Obviously, if such a need arises, these recommendations can be modified depending on the existing circumstances and requirements, but the general rules resulting from thermodynamic and economic principles must be complied with.

During the operation of water or steam pipelines, a continuous process of destruction of heat insulation occurs. This causes increased heat losses to the environment, which in turn causes increased operating costs for the network operator. The costs of heat losses can be reduced by improving the cover and thermal insulation of pipelines or total modification of the network including the replacement of pipelines, diameter adjustment to current flows and pipe route optimisation. However, such an undertaking requires specified above investment expenditures.

In further analysis only undertakings dealing with improvement of insulating power of pipeline thermal insulation were considered. The aforementioned undertakings have been named the “thermomodernisation” of the pipeline network.

After determination of the investment expenditure associated with thermomodernisation undertakings and financial savings resulting from reduction of heat losses, an economic analysis was carried out. Values of economic indicators were obtained as a result of the analysis. Hence, it was possible to compare the economic efficiency of thermomodernisation undertakings of the considered pipelines and to indicate the most interesting technical solutions from the economic point of view.

In practice, during the reconstruction of the pipeline, it is necessary to replace some faulty elements of pipeline fittings with new ones. The costs of all these undertakings (e.g. replacement of a valve for operational safety and others) which do not deal with the decrease in heat losses should not be added to the costs of heat insulation replacement. These costs ought to be calculated separately.

The aim of the paper is to present the economic efficiency analysis method of the thermomodernisation project involving the improvement of the outer shell of the pipe and thermal insulation of heat and steam pipelines. The final result is the determination of the implementation order of energy pipeline modernisation tasks justified from the economic point of view. The results of calculation of heat losses and quality assessment of the thermal insulation of the pipeline carried out on the basis of IR camera measurements of the existing heat pipelines have been applied in the economic analysis. A novel method based on a single thermovision measurement of temperature distribution on the outer pipeline shell and simulation of the considered pipeline operation during the whole annual period of its exploitation has been developed and applied for the determination of annual heat losses on the basis of infrared diagnostics.

The IR (infrared) measurements were realised in an existing industrial plant with the use of professional IR camera.

3. General description of the analysis

The developed and presented method is described using an example of an analysis for a real plant. In order to reasonably use the limited funds, the following sequence of operations during project implementation has been assumed:

- inventory of all pipelines in the area of the plant,
- selection of pipeline segments for further examination,
- thermovision measurements,
- calculation of heat losses for the pipeline segments,
- calculation of economic indicators of thermomodernisation projects for the selected segments.

The selection of pipeline segments for further examination has been done on the basis of an assumed coefficient proportional to the pipeline unit costs of heat losses. The following technical aspects were taken into consideration in the calculations:

- cost of lost heat unit,
- initially estimated pipeline unit heat losses,
- pipeline operation period per year.

As a result of pipeline network identification and the necessary preliminary calculations, the total pipeline length and location of pipeline segments specified for further examination were determined. The length of pipelines marked out for further testing was about 4 km. The tested pipeline network was divided into 36 segments. On the basis of IR camera measurement results, heat calculations and simulation of annual operation of the considered pipelines, the values of pipeline unit annual heat losses $Q_{A\ x}$ for the existing pipeline segments have been determined. Then, knowing the length of particular segments, total annual losses $Q_{L\ x}$ for the tested pipeline segments can be calculated and expressed in GJ/year. To this end, the following equation [13] can be applied:

$$Q_{L\ x} = \gamma Q_{A\ x} L \qquad (1)$$

While analysing the results, it should be mentioned that they represent the mean values for the segments of the whole pipeline system. In this analysis it has been assumed that the desirable technical state of the considered pipelines segments in terms of the acceptable level of heat losses is defined by the need for appropriate standards [9–12]. In the case of new circumstances or needs, other conditions than described in Refs. [1–8] or even requirements developed for any new circumstances may be implemented easily in the presented calculation method. The pipelines meeting the aforementioned criteria with reference to the technical state of their thermal protection are generally referred to in the paper as pipelines meeting standard requirements. For these pipelines, the annual individual heat loss $Q_{L\ st}$, which would be generated by each pipeline segment, was also calculated. The difference $Q_{L\ x} - Q_{L\ st}$ expresses the annual saving of energy obtained in the considered pipeline segment due to its thermomodernisation. The saving of energy is a source of economic profit which makes it possible to recover investment expenditure and to generate additional economic benefits.

4. Calculation of heat losses from the pipeline

Calculation of heat losses from the distinguished pipeline segments with the use of IR camera examination results for these pipelines, was the first step in the presented method of the considered networks evaluation. The requirements resulting from appropriate standards dealing with thermal protection of pipelines and heat equipment [9–12] have been assumed as a basis for these calculations. The calculated losses for existing pipeline segments and losses determined for the same pipeline segments but with insulation meeting appropriate standards, were compared in the next step. During the development of the calculation algorithm, the recommendations and methods included in the technical literature were also taken into consideration [13–19]. The applied calculation method can be presented in the following steps as described below. The presented calculation algorithm is developed only for overhead pipelines. Only the overhead pipeline segments were considered in further analysis.

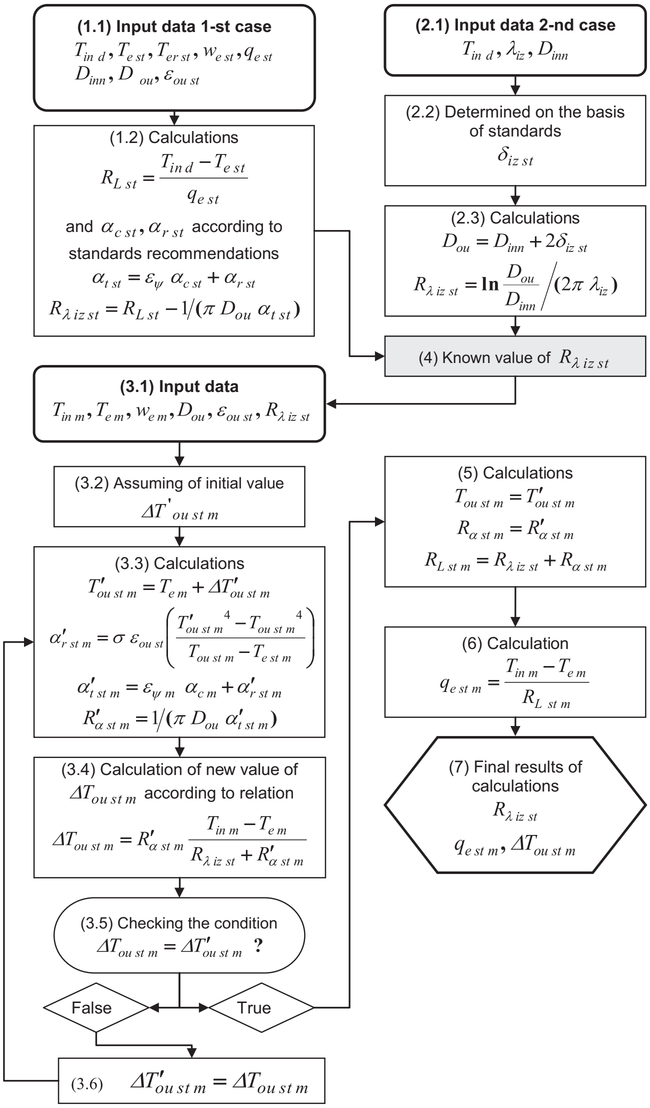

Fig. 1. Algorithm of unit heat loss calculations from the pipeline with insulation meeting standard requirements for meteorological conditions occurring during IR camera inspection of the considered pipeline.

4.1. Pipeline meeting standard requirements

In Fig. 1 a block scheme is shown which contains the main points of this analysis. In particular, Fig. 1 presents the ways of determining conductive resistance of insulation $R_{\lambda\ iz\ st}$, heat loss $q_{e\ st\ m}$ and temperature difference $\Delta T_{ou\ st\ m}$ between the outer pipeline shell and atmospheric air for pipeline with insulation meeting standard requirements. The aforementioned heat loss and temperature difference are determined for meteorological conditions occurring at the moment of pipeline inspection by IR camera. The calculated quantities constitute a reference level during the evaluation of existing pipeline.

For a given nominal diameter of pipeline D_{inn} and temperature of the fluid inside tube $T_{\mathrm{in\ d}}$, the permitted value of heat loss $q_{\mathrm{e\ st}}$ for unit length of pipeline [10,11] or recommended insulation layer thickness $\delta_{\mathrm{iz\ st}}$ [12] were determined on the basis of the aforementioned standards. Taking into consideration the thickness of thermal insulation and other parameters, insulation conduction resistance $R_{\lambda\ \mathrm{iz\ st}}$ was calculated for thermal insulation complying with standard requirements.

Input data for these calculations are presented in box (1.1)-case (1) or in box (2.1)-case (2), see Fig. 1. In case (1) the overall heat transfer resistance for the pipeline with insulation meeting standard requirements may be calculated from the relation, box (1.2), Fig. 1

$$R_{\mathrm{L\ st}} = (T_{\mathrm{in\ d}} - T_{\mathrm{e\ st}})/q_{\mathrm{e\ st}} \tag{2}$$

Next, the convective and radiative heat transfer coefficients for the other shell surface of the pipeline were calculated. For this purpose various known expressions taken from the technical literature can be used, e.g. in Ref. [9] convective heat transfer coefficient for horizontal pipeline in open air space is expressed as

$$\alpha_{\mathrm{c\ st}} = 8.9\frac{w_{\mathrm{e\ st}}^{0.9}}{D_{\mathrm{ou}}^{0.1}} \tag{3}$$

and radiative heat transfer coefficient – by the equation

$$\alpha_{\mathrm{r\ st}} = \sigma\left(\varepsilon_{\mathrm{ou\ st}}\frac{T_{\mathrm{ou\ st}}^4 - T_{\mathrm{er\ st}}^4}{T_{\mathrm{ou\ st}} - T_{\mathrm{e\ st}}}\right) \tag{4}$$

where temperature T is expressed in Kelvin scale.

Finally, the heat conduction resistance of pipeline standard insulation can be calculated (see also Fig. 1 box (1.3)) by the relation

$$R_{\lambda\ \mathrm{iz\ st}} = R_{\mathrm{L\ st}} - 1/(\pi\, D_{\mathrm{ou}}\, \alpha_{\mathrm{t\ st}}) \tag{5}$$

where $\alpha_{\mathrm{t\ st}}$ is the total heat transfer coefficient on the outer pipeline shell and is expressed by the sum

$$\alpha_{\mathrm{t\ st}} = \varepsilon_{\psi}\,\alpha_{\mathrm{c\ st}} + \alpha_{\mathrm{r\ st}} \tag{6}$$

Another way of calculation should be applied for case (2) of input data. In this case for the known temperature inside the pipeline and pipe diameter, the thickness of heat insulation layer $\delta_{\mathrm{iz\ st}}$ is determined on the basis of standard recommendations [12], boxes (2.1) and (2.2) in Fig. 1. In the successive step the heat conductive resistance of pipeline insulation meeting standard requirements is calculated (box (2.3), Fig. 1) by means of relation

$$R_{\lambda\ \mathrm{iz\ st}} = (\mathbf{ln}(D_{\mathrm{ou}}/D_{\mathrm{inn}}))/2\pi\,\lambda_{\mathrm{iz}} \tag{7}$$

where

$$D_{\mathrm{ou}} = D_{\mathrm{inn}} + 2\delta_{\mathrm{iz\ st}} \tag{8}$$

Finally, in this manner the value of thermal resistance of pipeline insulation $R_{\lambda\ \mathrm{iz\ st}}$ meeting standard requirements has been calculated, see also box (4) in Fig. 1.

In the algorithm presented above, some simplifying assumptions have been made. At the beginning the thermal resistance of steel pipe wall and resistance of internal convective heat transfer between fluid and pipe wall were omitted due to their negligible small values in comparison with other components of thermal resistance. In consequence, the temperature of insulation of the inner surface was assumed to be the same as the temperature of fluid flowing inside the pipeline. Additionally, in the presented calculation scheme it has been assumed that the coefficient of thermal conductivity of insulation does not depend on temperature. In fact, because of multi-way heat transfer inside fibrous or porous insulation materials [14,18], there is a dependence between effective heat conductivity coefficient and temperature. This relationship may be described with satisfactory accuracy usually by means of polynomial relation [20,21]

$$\lambda_{\mathrm{iz}}(T) = a_0 + a_1\,T + a_2\,T^2 \tag{9}$$

where a_0, a_1, a_2 are constants.

Generally, in this case the unit heat flux transferred through the pipeline insulation into the environment is described by means of relation (10), [21]

$$q_{\mathrm{e\ st}} = \frac{a_0(T_{\mathrm{in}} - T_{\mathrm{ou}}) + a_1\left(T_{\mathrm{in}}^2 - T_{\mathrm{ou}}^2\right)\Big/2 + a_2\left(T_{\mathrm{in}}^3 - T_{\mathrm{ou}}^3\right)\Big/3}{(\mathbf{ln}(D_{\mathrm{ou}}/D_{\mathrm{inn}}))/2\pi} \tag{10}$$

Generally, on the basis of Eqs. 9 and 10 two simplified solutions can be obtained. In the case $(a_0 \neq 0)\wedge(a_1 \neq 0)$ and $a_2 = 0$ we obtain the solution for linear dependence of λ_{iz} on temperature. In cases $a_0 \neq 0$ and $(a_1 = 0)\wedge(a_2 = 0)$ we obtain the solution with fixed value of thermal conductivity $\lambda_{\mathrm{iz}}(T) = \lambda_{\mathrm{iz}}$. This solution can be used in the case with small differences between temperatures T_{in} and T_{ou}. Temperature scales used in Eqs 9 and 10 must be the same type (°C or K).

In order to simplify the calculations, an average value of heat conductivity coefficient $\overline{\lambda}_{\mathrm{iz}}$ determined for estimated temperature range $(T_{\mathrm{in}} \div T_{\mathrm{ou}})$ can be implemented. This value can be calculated as follows

$$\overline{\lambda}_{\mathrm{iz}} = a_0 + a_1(T_{\mathrm{in}} + T_{\mathrm{ou}})/2 + a_2\left(T_{\mathrm{in}}^2 + T_{\mathrm{in}}\,T_{\mathrm{ou}} + T_{\mathrm{ou}}^2\right)\Big/3 \tag{11}$$

In the next stage, we will analyse the behaviour of the standard pipeline under consideration in meteorological conditions occurring during thermovision examination of the existing pipeline. Exactly the unit heat loss $q_{\mathrm{e\ st\ m}}$ and temperature difference $\Delta T_{\mathrm{ou\ st\ m}}$ between the outer pipeline shell and the environment were calculated. Input data for these calculations are specified in box (3.1), Fig. 1.

Further calculations require applying an iteration procedure [17]. After assuming an estimated initial value of temperature difference $\Delta T'_{\mathrm{ou\ st\ m}}$ between outer pipeline shell and the environment for standard pipeline in weather conditions occurring during thermovision measurements, the total heat transfer coefficient $\alpha'_{\mathrm{t\ st\ m}}$ for these conditions was calculated using Eqs (3), (4) and (6), see boxes (3.2) and (3.3) in Fig. 1. Now, thermal resistance $R'_{\alpha\ \mathrm{st\ m}}$ of the heat transfer between the outer pipeline shell and the environment can be determined, box (3.3) in Fig. 1. In the subsequent step the first approximate temperature difference $\Delta T_{\mathrm{ou\ st\ m}}$ between pipeline shell and atmospheric air is calculated. This temperature difference is calculated based on the assumption that the steady state in the heat transfer process is attained, which can be expressed as

$$q_{\mathrm{e\ st\ m}} = \frac{\Delta T_{\mathrm{ou\ st\ m}}}{R'_{\alpha\ \mathrm{st\ m}}} = \frac{T_{\mathrm{in\ m}} - T_{\mathrm{e\ m}}}{R_{\lambda\ \mathrm{iz\ st}} + R'_{\alpha\ \mathrm{st\ m}}} \tag{12}$$

After some transformations from Eq. (12) an expression can be obtained that is useful for calculating the desirable quantity $\Delta T_{\mathrm{ou\ st\ m}}$, box (3.4) in Fig. 1. Next, the assumed value of this temperature difference should be compared with the calculated value, see box

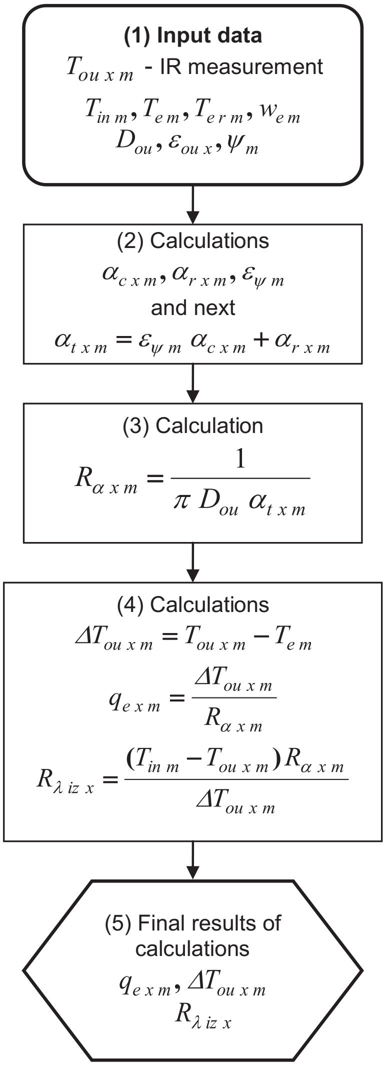

Fig. 2. Algorithm of unit heat loss calculations from the pipeline with existing pipeline thermal insulation for meteorological conditions occurring during IR camera inspection of the considered pipeline.

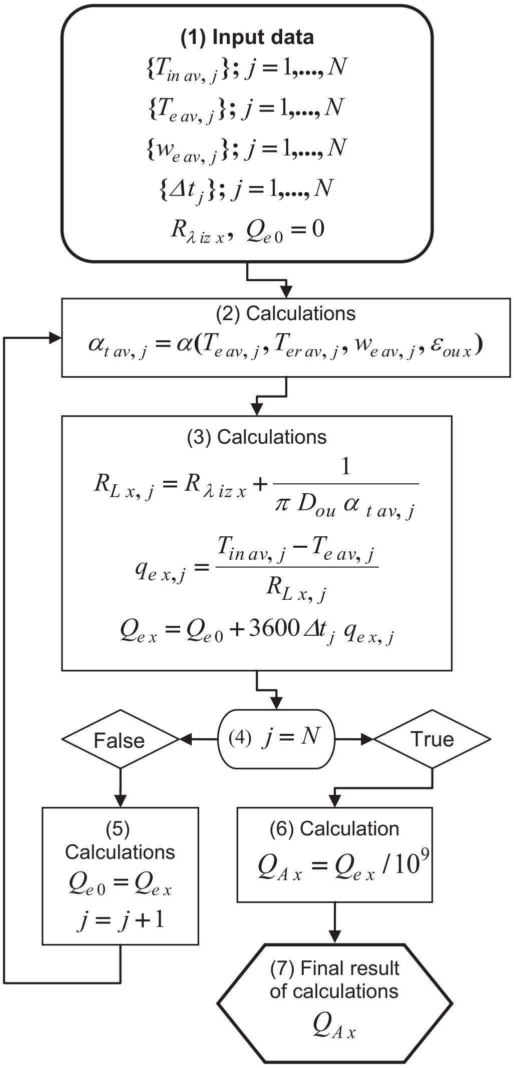

Fig. 3. Algorithm of unit annual heat loss calculation for the considered pipeline with existing pipeline thermal insulation for the whole annual period of pipeline operation.

(3.5). If the result of this comparison is false, the obtained value of $\Delta T_{\mathrm{ou\ st\ m}}$ should be taken as the initial value and calculation procedure should be repeated starting from box (3.3), Fig. 1. If the result of the aforementioned comparison achieves the desirable accuracy, the current value of $R'_{\alpha\ \mathrm{st\ m}}$ is assumed for further calculations, see box (5). Now, the overall heat transfer resistance is calculated as follows

$$R_{\mathrm{L\ st\ m}} = R_{\lambda\ \mathrm{iz\ st}} + R_{\alpha\ \mathrm{st\ m}} \tag{13}$$

whereas the unit heat losses into the environment from the pipeline with thermal insulation meeting standard requirements in weather conditions during measurements can be calculated by means of relation, see box (6) in Fig. 1

$$q_{\mathrm{e\ st\ m}} = (T_{\mathrm{in\ m}} - T_{\mathrm{e\ m}})/R_{\mathrm{L\ st\ m}} \tag{14}$$

4.2. The tested pipeline

Fig. 2 demonstrates a way of calculating heat losses for the tested pipeline and meteorological conditions occurring during its inspection by means of an IR camera. Input data for these calculations are presented in box (1), Fig. 2. The main parameter is average temperature $T_{\mathrm{ou\ x\ m}}$ of the outer shell of the tested pipeline. This temperature is determined on the basis of IR camera measurement results. The convection and radiation heat transfer coefficients, $\alpha_{\mathrm{c\ x\ m}}$ and $\alpha_{\mathrm{r\ x\ m}}$ respectively, for the outer shell are calculated in the next step. The aforementioned coefficients are determined with the use of Eqs (3) and (4) formulated for the tested pipeline and weather conditions existing during IR camera inspection. Next, by means of Eq. (6) the total heat transfer coefficient $\alpha_{\mathrm{t\ x\ m}}$ is calculated, see box (2) in Fig. 2. In a subsequent step (box (3), Fig. 2) the thermal resistance of heat transfer between the shell and the environment is determined from the relation

$$R_{\alpha\ \mathrm{x\ m}} = 1/(\pi\,D_{\mathrm{ou}}\,\alpha_{\mathrm{t\ x\ m}}) \tag{15}$$

Afterwards, the set of final quantities useful for the testing of the considered pipeline can be worked out (see also box (4) in Fig. 2). This set contains the real temperature difference between the shell of the tested pipeline and the temperature of the environment at the moment of IR inspection

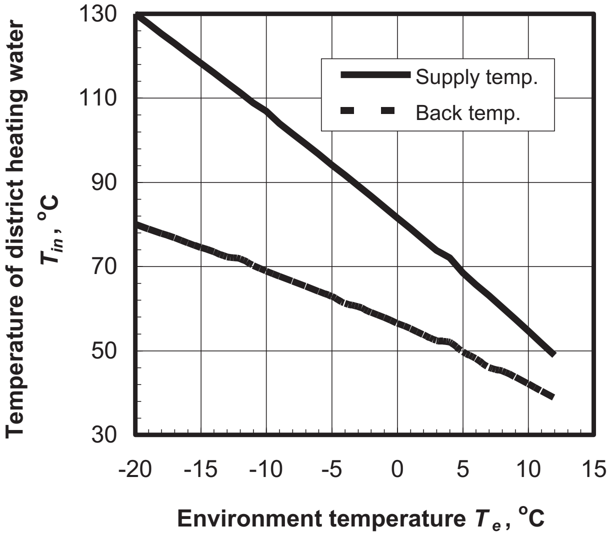

Fig. 4. Relationship between the temperature of the environment and the desirable temperature of district heating water.

$$\Delta T_{\mathrm{ou\ x\ m}} = T_{\mathrm{ou\ x\ m}} - T_{\mathrm{e\ m}} \tag{16}$$

and unit heat loss

$$q_{\mathrm{e\ x\ m}} = \Delta T_{\mathrm{ou\ x\ m}}/R_{\alpha\ \mathrm{x\ m}} \tag{17}$$

as well as heat conduction resistance of tested pipeline insulation $R_{\lambda\ \mathrm{iz\ x}}$. This resistance results from the assumption that heat flux conducted through the insulation is equal to heat flux emitted from the shell into the atmosphere, which can be expressed by formula

$$R_{\lambda\ \mathrm{iz\ x}} = (T_{\mathrm{in\ m}} - T_{\mathrm{ou\ x\ m}})/q_{\mathrm{e\ x\ m}} \tag{18}$$

The specified thermal resistance of pipeline insulation for its existing state can be also treated as a measure of its technical quality in terms of thermal protection of the considered pipeline.

4.3. Determination of annual heat losses

Knowing the thermal features of the existing insulation, especially its thermal resistance, the pipeline operation was simulated at different values of atmospheric temperature occurring in the considered period of the year. Fig. 3 shows a scheme of heat loss $Q_{\mathrm{A\ x}}$ forecasts for the tested pipeline with existing thermal insulation during the whole annual potential period of its exploitation. The same algorithm can be applied to calculate the annual heat loss $Q_{\mathrm{A\ st}}$ from the pipeline with satisfactory thermal insulation, i.e. with insulation meeting the required standards. For industrial pipelines the considered period amounts to 8760 h/year (whole year) and for district heating pipelines in Poland it amounts to about 5400 h/year. Duration of the designed heating period depends mainly on the so-called climate zone. Five climate zones have been created in Poland with special design recommendations dealing with heating systems capacity and thermal protection of these systems and heated objects [16].

During a simulation of district heating pipelines operation, the necessary changes of heating water temperature [16] required during the heating season were taken into account. The aforementioned relationship for the considered pipeline network may be found in Fig. 4. However, for industrial process pipelines the parameters of steam and hot water have usually fixed values regardless of the time of the year [17].

In this manner, the annual heat losses were forecasted for the considered pipelines. Values of the temperature inside the pipeline $T_{\mathrm{in\ av},\,j}$, the environmental temperature $T_{\mathrm{e\ av},\,j}$ and wind speed $w_{\mathrm{e\ a\ v},\,j}$ gathered during the whole year and averaged for successive time sub-periods Δt_j (time steps) constitute the files of input data for these calculations, box (1) in Fig. 3. A crucial parameter for these calculations is determined from Eq. (18) heat conductivity resistance of insulation of the tested pipeline. Next, step by step, for the successive j-th time sub-periods we calculate the total heat transfer coefficients $\alpha_{\mathrm{t\ av},\,j}$ (on the basis of Eqs (3), (4) and (6)), the heat transfer resistances $R_{\mathrm{L\ x},j}$ and the fluxes of heat losses $q_{\mathrm{e\ x},j}$ for the unit length of the considered pipeline, boxes (2,3) in Fig. 3. The obtained values of heat fluxes after multiplication by time of their occurrence, are summed in an iteration loop, boxes (3, 4, 5) in Fig. 3. In this way, the annual heat loss of the tested pipeline $Q_{\mathrm{A\ x}}$ for unit length is calculated, boxes (6, 7) in Fig. 3. After applying the aforementioned procedure for the pipeline meeting standard requirements, the annual heat loss $Q_{\mathrm{A\ st}}$ for a standard pipeline is obtained and constitutes a reference level. The presented algorithms can be mathematically expressed by means of Eqs. 19 and 20

$$Q_{\mathrm{A\ x}} = 10^{-9}\sum_{j=1}^{N} 3600\Delta t_j\, q_{e\ \mathrm{x},\ j} \tag{19}$$

$$Q_{\mathrm{A\ st}} = 10^{-9}\sum_{j=1}^{N} 3600\Delta t_j\, q_{\mathrm{e\ st},\ j} \tag{20}$$

Thus, after application of Eq. (1), the forecasted annual saving of heat due to implementation of the thermomodernisation project for the considered pipeline segment may be expressed as follows

$$\Delta Q_{\mathrm{L}} = Q_{\mathrm{L\ x}} - Q_{\mathrm{L\ st}} = \gamma\, L\,(Q_{\mathrm{A\ x}} - Q_{\mathrm{A\ st}}) \tag{21}$$

The saved energy ΔQ_{L} is a source of profit which is generated by the implemented project. This is a crucial parameter beside the investment expenditure on the considered pipeline reconstruction and it is applied in further economic analysis.

4.4. Example calculations

On the basis of the algorithms presented in previous subsections, the following parameters which characterise the distinguished segment, were determined for each considered pipeline segment:

$q_{\mathrm{e\ st\ m}}$ – linear pipeline unit flux of heat loss for the pipeline complying with standard requirements, W/m,

$q_{\mathrm{e\ x\ m}}$ – linear pipeline unit flux of heat loss for the pipeline with higher temperature of the external shell than that resulting from standard requirements, W/m,

ξ – relative heat loss defined as proportion of heat loss for existing pipeline and heat loss for pipeline meeting standard requirements.

The relative heat loss as specified above, is defined by means of relation

$$\xi = q_{\mathrm{e\ x\ m}}/q_{\mathrm{e\ st\ m}} \tag{22}$$

In Figs. 5–7 results of example calculations of the aforementioned parameters for pipeline diameters amounting to 150 mm, 200 mm and 250 mm have been presented. In this case temperature and pressure of the steam amounted to 0.5 MPa and 500 K. The parameters $q_{\mathrm{e\ x\ m}}$, ξ, $Q_{\mathrm{A\ x}}$ have been shown in the shape of curves as functions of temperature difference between the environment and potentially different values of shell temperature. However, parameters $q_{\mathrm{e\ x\ m}}$ and $Q_{\mathrm{A\ x}}$ are represented only by single points belonging to the aforementioned appropriate lines. In point $\xi = 1.0$ the temperature difference between pipeline shell and the environment is characteristic for the pipeline with thermal insulation meeting standard requirements.

The diagrams allow to determine heat loss and other parameters for a given pipeline segment with various temperature values of the external pipeline shell. The specified quantities are useful in the process of evaluating the potential for the reduction of pipeline heat losses. Moreover, these quantities are necessary to make an economic evaluation of pipeline thermomodernisation projects.

5. Description of measurements and uncertainty analysis of the obtained results

In order to verify the developed calculation method, the results obtained with the use of the aforementioned procedure have been compared with the annual pipeline heat losses determined on the basis of heat balance of production and consumption of energy carrier [22]. The IR measurements of all pipeline segments marked out for the testing were an important part of this analysis. On the basis of these measurement results the temperature differences $\Delta T_{\mathrm{ou\ x\ m}}$ were determined between shell and air at the moment of IR pipeline testing for the examined pipeline segments. The temperature differences are of crucial importance for the determination of heat losses for existing pipelines, Eqs. 16 and 17. Fig. 8 presents a sample of IR camera measurement results for the selected pipeline segment.

In general, the calculation results correspond relatively well to the annual measured heat losses determined by means of the balance method. However, the observed heat losses for the considered pipeline network pieces were higher by 30÷40% than the calculated losses. Based on the analysis of the obtained results and other circumstances the following reasons for the discrepancy between the calculated and observed results have been identified:

- penetration of thermal insulation by snow- or rain-water in the case of a leaky outer pipeline shell,
- intensive cooling of pipelines during rain periods and the inability to quantify the effects,
- standard annual meteorological conditions were assumed in the calculation algorithm of annual heat losses, therefore the presented calculation results express only average prognostic heat losses.

The phenomena mentioned in two first points were not taken into account in the calculation procedure as described above. To sum up, although the observed heat losses were higher than the losses calculated on the basis of IR measurements, the obtained results were considered satisfactory. A similar tendency was observed also for other pipeline networks. It means that the real payout time is shorter than the calculated value of SPBT, thus the real economic efficiency of the considered thermomodernisation project will be always better than expected. To sum up, this is a better situation in the economic evaluation of the project than the opposite one.

In order to recognise better the influence of measurement errors on heat loss calculation results, an analysis of measurement uncertainties has been carried out. This analysis was carried out for three pipeline segments which are presented in Figs. 5–7.

A mathematical model for the measurement was the relation describing the unit heat loss flux of the real pipeline. This formula results from relation (17) and relations (3,4,6,15,16).

$$\begin{aligned} q''_{\mathrm{e\ x\ m}} &= \gamma\, q_{\mathrm{e\ x\ m}} \\ &= \gamma\, \pi\, D_{\mathrm{ou}} \left(8.9 \frac{w_{\mathrm{e\ m}}^{0.9}}{D_{\mathrm{ou}}^{0.1}}\, \varepsilon_{\psi\ \mathrm{m}} + \sigma\, \varepsilon_{\mathrm{ou\ x}} \frac{T_{\mathrm{ou\ x\ m}}^4 - T_{\mathrm{er\ m}}^4}{T_{\mathrm{ou\ x\ m}} - T_{\mathrm{e\ m}}} \right) \\ &\quad \times \left(T_{\mathrm{ou\ x\ m}} - T_{\mathrm{e\ m}} \right) \end{aligned} \tag{23}$$

The following parameters were assumed as measurement quantities: γ, D_{ou}, $w_{\mathrm{e\ m}}$, $\varepsilon_{\mathrm{ou\ x}}$, $T_{\mathrm{ou\ x\ m}}$, $T_{\mathrm{er\ m}}$, $T_{\mathrm{e\ m}}$. For all considered pipeline segments, the correction factor ε_{ψ} was equal to 0.807 (angle $\psi = 45°$).

Next, the combined standard uncertainties [23] of the total heat losses including linear and local heat losses were calculated. For this purpose it was necessary to determine individual standard uncertainties for all measurement quantities.

Values of multiplier γ and its standard uncertainty were assumed on the basis of literature recommendations after taking into account the number of fittings and fixing elements [12–15]. The assumed values are given in Table 1.

The value of wind speed and its measurement standard uncertainty were determined on the basis of the accuracy data for the measuring device and additionally taking into consideration the observed fluctuations of the measured parameter during the IR pipeline inspection period.

Emissivity coefficient $\varepsilon_{\mathrm{ou\ x}}$ of the outer pipeline shell is a very important parameter during the thermovision measurements of the shell temperature as well as for heat loss calculations. This parameter was tested in the laboratory using special samples of pipeline outer shell taken from the existing pipelines and “in situ” method during the testing of the existing pipelines. Various techniques were applied during these measurements. The general principle is to measure the

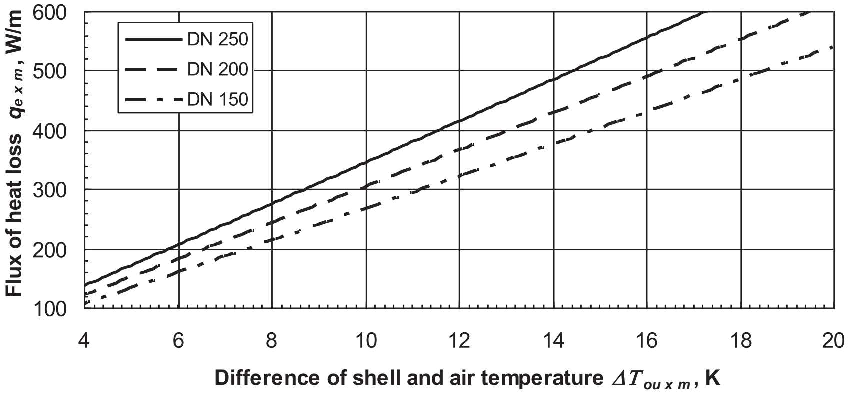

Fig. 5. Unit heat losses from steam pipeline.

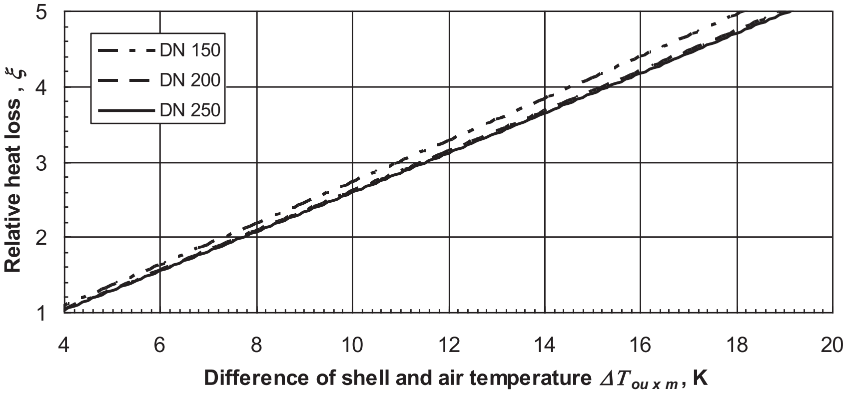

Fig. 6. Relative heat losses from steam pipeline.

temperature by means of an additional device (e.g. thermocouple) and simultaneously with the use of the IR camera. Next, emissivity must be adjusted to obtain from the camera the same temperature value as indicated by the thermocouple. Different techniques of temperature measurement of the tested surface by means of the thermocouples were applied. In the laboratory the thermocouple wires were directly welded close one to another to the tested metallic element [24,25]. This metal constitutes the so-called "third metal" in the construction of the thermocouple; it participates in the measurement process but does not have an effect on the temperature measurement result. Moreover, during emissivity testing, temperature measurements by means of touch type thermocouple or by thermocouple fixed to the tested surface were applied as well and the method in which the tested surface is covered with paint of known emissivity was also applied [26].

The measurements of the pipeline shell temperature were carried out with the use of IR camera of ThermaCAM SC2000 type, manufactured by FLIR company. During the pipeline thermovision inspection, the whole length of each considered pipeline segment was tested. The considered pipeline segments were divided into small pieces and for each such piece an infrared thermogram was made. Next, on the basis of these thermograms, for each distinguished pipeline piece, an average temperature representative for the whole piece was determined. The final temperature $T_{\mathrm{ou\ x\ m}}$, representative for the whole considered pipeline segment was calculated as an arithmetic mean of piece temperatures. The experimental standard deviation of the mean [23] of the measured temperature was assumed as standard uncertainty of this parameter. The obtained results for segment No 21 are presented in Table 1.

Values of atmospheric air temperature $T_{\mathrm{e\ m}}$ and its standard uncertainty were determined in a similar way as the parameters for wind speed, Table 1.

The radiative temperature of the environment T_{er} results from the thermal radiation of the ground surface and sky radiation. It is recommended to carry out the measurement when the apparent temperature of the sky measured by the IR camera is almost level and its value is similar to air temperature. In the case of differences between these temperatures, an arithmetic mean of these values can be applied as a representative temperature, especially while testing vertical surfaces [27]. For other positions of the tested surface, the calculation of the equivalent radiative temperature is more sophisticated. A proposal of a calculation method for these cases is presented in Ref. [27]. Generally, in the situation of non-uniform cloudy sky it is possible to create the mathematical models of clouds and sky for the description of sky radiation [28]. Unfortunately, this method is more complex and time consuming. In the case of low temperature of the sky, which occurs on cloudless sky nights (most of the stars can be seen), the temperature of top parts of old and rusty shells of overhead pipelines usually drops below the temperature of atmospheric air [29]. This phenomenon is caused by very intensive radiation of the top part of the pipeline into relatively cold atmospheric space. Generally, it is not recommended to carry out the IR camera inspections in such conditions because in this situation more advanced methods of measurements and calculations are necessary.

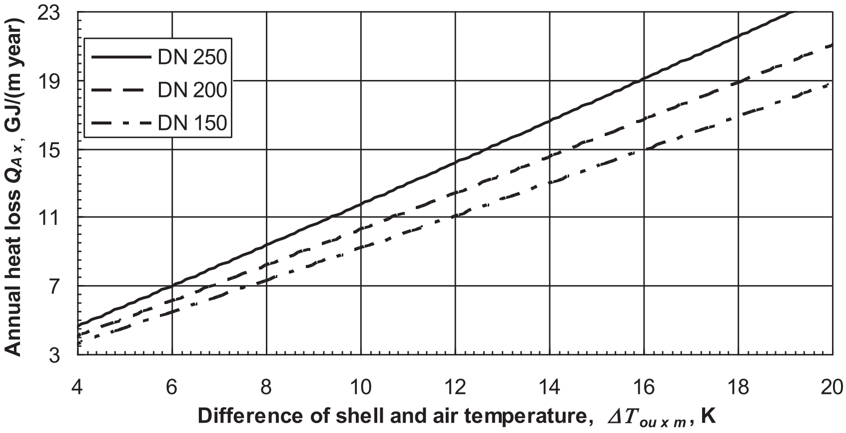

Fig. 7. Annual heat losses from steam pipeline.

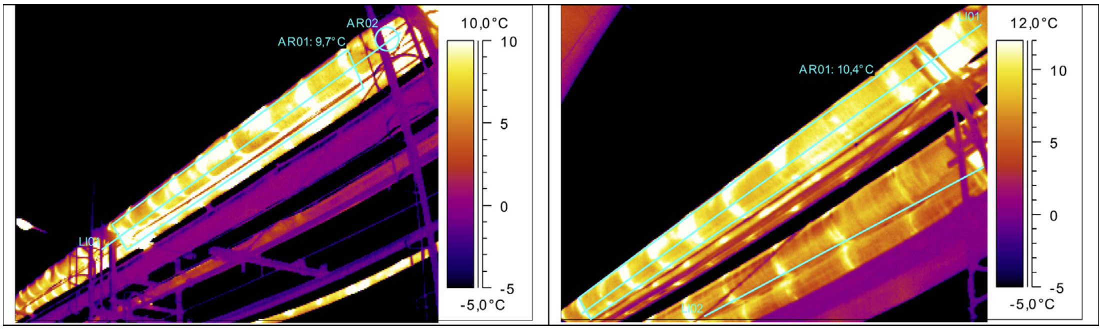

Fig. 8. Examples of IR camera measurement results for pipeline segment No 21 (DN 250).

The measurement results of the radiative temperature of the environment and its standard uncertainty are presented in Table 1.

Now, the combined standard uncertainty [23] of the heat loss from the pipeline can be calculated on the basis of the relation

$$u_{\mathrm{c}}\left(q''_{\mathrm{e\ x\ m}}\right) = \left|\left\{\sum_{i=1}^{7}\left[\frac{\partial(q_{\mathrm{e\ x\ m}})}{\partial(y_i)}\ u(y_i)\right]^2\right\}^{0.5}\right| \tag{24}$$

Values of the expression given in the 5th column of Table 1 indicate which parameters have the major influence on the uncertainty of heat loss determination. The most important is the measurement accuracy of the outer shell temperature, wind speed and multiplier γ.

In the next step, the expanded uncertainty [23] of the heat loss determination is calculated on the basis of the relation

$$U = k\, u_{\mathrm{c}}\left(q''_{\mathrm{e\ x\ m}}\right) \tag{25}$$

where k – coverage factor [23].

In further analysis it has been assumed that $k = 2$. Thus, the confidence interval for the measured quantity is defined as $\langle q''_{\mathrm{e\ x\ m}} - U,\quad q''_{\mathrm{e\ x\ m}} + U\rangle$.

The final calculation results for the considered pipeline segments are gathered in Table 2. These results indicate that relative expanded uncertainties for the considered pipeline segments belong to the range $20 \div 25\%$.

The obtained values are lower than the differences given at the beginning of this chapter and amounting to $30 \div 40\%$. The initial part of this chapter also provides potential reasons for the divergences of calculation results for heat losses and the amounts of losses which actually occurred in the year under consideration.

Table 1
Input data and results of uncertainty calculation of heat loss flux for pipeline segment No 21 (DN 250) at the moment of thermovision inspection.

Subscript of parameter y	Denotation	Dimension	Value	Value of expression $(\partial q_{\mathrm{e\ x\ m}}/\partial y_i)\ u(y_i)$, W/m
$i = 1$	γ	–	1.38	19.2
	$u(\gamma)$	–	0.05	
$i = 2$	D_{ou}	m	0.49	9.9
	$u(D_{\mathrm{ou}})$	m	0.01	
$i = 3$	$\varepsilon_{\mathrm{ou\ x}}$	–	0.95	2.3
	$u(\varepsilon_{\mathrm{ou\ x}})$	–	0.02	
$i = 4$	$w_{\mathrm{e\ m}}$	m/s	2.5	30.1
	$u(w_{\mathrm{e\ m}})$	m/s	0.2	
$i = 5$	$T_{\mathrm{ou\ x\ m}}$	°C	11.2	47.9
	$u(T_{\mathrm{ou\ x\ m}})$	K	1	
$i = 6$	$T_{\mathrm{e\ m}}$	°C	0.0	–7.5
	$u(T_{\mathrm{e\ m}})$	K	0.2	
$i = 7$	$T_{\mathrm{er\ m}}$	°C	0	–9.3
	$u(T_{\mathrm{er\ m}})$	K	1	

Table 2
List of final results for the considered pipeline segments.

Specification	Denotation	Dimension	Segment 21 (DN250)	Segment 12 (DN200)	Segment 25 (DN150)
Heat loss flux	$q''_{\mathrm{e\ x\ m}}$	W/m	529	424	324
Combined standard uncertainty	$u(q''_{\mathrm{e\ x\ m}})$	W/m	59	44	39
Expanded uncertainty	U	W/m	118	88	78
Expanded uncertainty	–	%	22.3	20.8	24.1

Another reason for the identified divergences may be the fact that in uncertain situations during the analysis the procedure was to underestimate the losses and the expected economic benefits rather than to overestimate them.

6. Analysis of economic efficiency of a thermomodernisation project

In order to analyse the economic effectiveness of modernisation to be undertaken, the expected results and costs must be calculated. This analysis included the costs of thermal insulation and

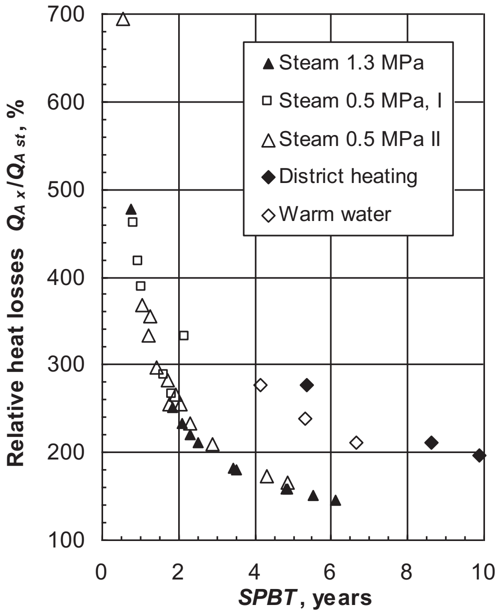

Fig. 9. Dependence of SPBT and the technical state of thermal insulation of the pipelines for the considered pipeline networks.

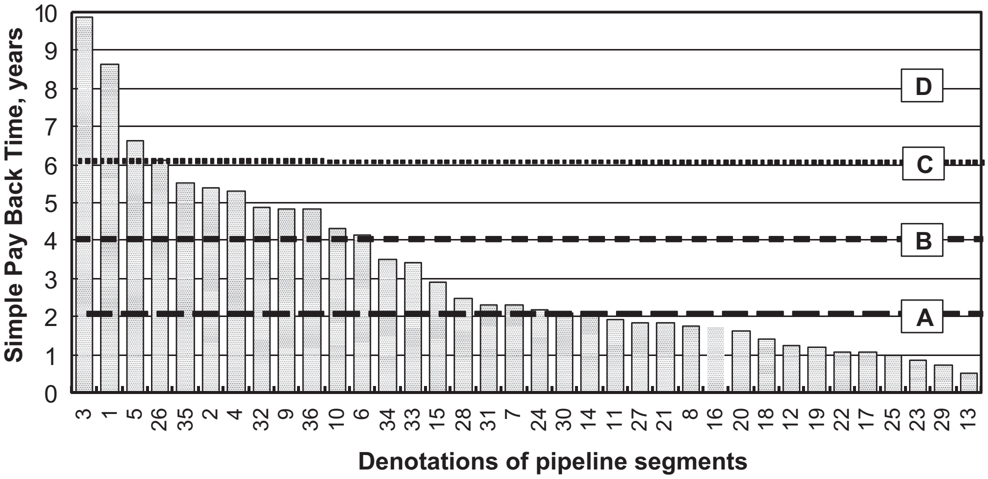

Fig. 10. Arrangement of pipeline network segments according to SPBT.

pipeline covering removal, costs of insulation installation, thermal insulation costs and sheet metal covering [30]. The gathered data show that the mean cost of replacement of 1 m of pipeline insulation ranges from PLN 240 to PLN 630 depending on the pipeline diameter, temperature and type of flowing medium.

Despite significantly oversized pipelines, the concept of complex replacement of pipelines including pipes and fittings has been rejected. Comparing the costs of insulation replacement with data concerning the replacement of whole pipelines it has been proved that the insulation replacement cost, in spite of high unit costs, accounts for about 25% of the cost of whole pipeline replacement. Hence, it leads to low economic efficiency of the investment project in this case of pipeline diameter reduction.

The analysis has shown that not all the analysed segments needed thermomodernisation. In the said case it was advisable to rebuild them selectively. Based on calculation results, *SPBT* was calculated for all examined segments of the network in the industrial plant. The results of the analysis have shown that *SPBT* of thermomodernisation of the said pipeline segments ranges from 0.5 to 10 years. The values of SPBT were calculated with the use of the following formula

$$SPBT = I_0/(c_q \ \Delta Q_L) \qquad (26)$$

Fig. 9 presents the dependence of SPBT upon the state of pipeline insulation of district heating water, warm water and steam networks. $Q_{A\ x}$ and $Q_{A\ st}$ values correspond to heat losses respectively, in real pipeline and pipeline meeting standard requirements. Fig. 9 shows that $Q_{A\ x}/Q_{A\ st}$ ratio may reach even 700%.

If necessary, additional economic factors like NPV (net present value), DPB (discounted pay-back), IRR (internal rate of return) or others [31], can be easily implemented in the presented method.

Fig. 10 presents an arrangement of pipeline network segments according to the value of SPBT. In the figure, the characteristic areas dealing with the economic efficiency of the thermomodernisation project have been shown:

- A-range of very high economic efficiency, $SPBT < 2$ years,
- B-range of high economic efficiency, $2 < SPBT < 4$ years,
- C-range of medium economic efficiency, $4 < SPBT < 6$ years,
- D-range of low economic efficiency, $SPBT > 6$ years.

In the analysed example, the values of payout time for particular pipeline segments show great differentiation. Therefore, it is not recommended to modernise the whole pipeline network but only those pieces that satisfy the value of economic factors. On the basis of analysis results, the 24 of 36 considered pipeline segments have been recommended for modernisation. For these pieces the payout time was shorter than 4 years. Modernisation of the pipeline network should be started from the pipeline segments with the smallest value of payout time.

7. Concluding remarks

The technical condition of steam and water pipelines usually varies despite of their similar technical features, construction year and operation period. As a result, heat losses from pipelines into the environment are different, too. Thus, it is reasonable to divide the pipeline network into segments in order to reconstruct only those pipelines for which the economic factors are satisfied. These pieces can be selected taking into account the results of thermovision inspection of the pipelines and economic calculations.

The thermomodernisation projects should be performed selectively for the respective segments of pipelines in conformity with the increasing value of payout time. In this way, investment expenditures are spent in the most effective way from the economic point of view. The analysis and calculations confirmed the effectiveness of the described method to achieve the high economic efficiency during thermomodernisation of heat pipelines.

An evaluation methodology based on an one-off IR camera examination of the pipeline under consideration has been developed, applied in the project and presented in the paper. In this method the thermal resistance of insulation of the existing pipeline is compared with pipeline insulation meeting the requirements of appropriate standards. Next, the annual heat losses from the aforementioned pipelines are forecast taking into account standard natural fluctuations of meteorological parameters during the entire year. For district heating pipelines the changes of water temperature resulting from the need to adjust it according to the temperature of the environment should be also taken into consideration. For industrial pipelines, the temperature of the energy carrier (steam or hot water) has usually a fixed value.

Abbreviations

DN	nominal diameter
DPB	discounted pay-back
NPV	net present value
SPBT	simple pay-back time
IRR	internal rate of return

IR	infrared
LCA	life cycle analysis
PLN	domestic currency

Nomenclature

c_q	unit cost of heat (PLN/GJ)
D	diameter (m)
I_0	pipeline segment investment cost (PLN)
L	length of the pipeline segment (m)
N	number of time sub-periods distinguished in the annual period of pipeline operation
$q_{\mathrm{e\ st}}$	linear permitted pipeline heat loss determined for standard environment conditions and recommended in the standards for the needs of the pipeline design process (W/m)
$q_{\mathrm{e\ st\ m}}$	linear heat loss which would be generated by pipeline meeting standard requirements for environment conditions occurring during IR camera testing of the considered pipeline (W/m)
$q_{\mathrm{e\ x\ m}}$	linear heat loss which is generated by the existing considered pipeline for environment conditions occurring during its IR camera testing (W/m)
$q''_{\mathrm{e\ x\ m}}$	sum of linear and local heat losses which is generated by the existing considered pipeline for environment conditions occurring during its IR camera testing (W/m)
$Q_{\mathrm{A\ st}}$	annual heat loss from a unit linear piece of pipeline meeting standard requirements (GJ/(year·m))
$Q_{\mathrm{A\ x}}$	annual heat loss from a unit linear piece of existing pipeline (GJ/(year·m))
$Q_{\mathrm{L\ st}}$	annual heat loss from a pipeline segment meeting standard requirements (GJ/year)
$Q_{\mathrm{L\ x}}$	annual heat loss from the existing pipeline segment (GJ/year)
$R_{\lambda\ \mathrm{iz\ st}}$	thermal resistance of pipeline insulation meeting standard requirements ((m·K)/W)
$R_{\lambda\ iz\ x}$	thermal resistance of insulation of the existing considered pipeline ((m·K)/W)
$R_{\mathrm{L\ st}}$	overall heat transfer resistance of thermal protection components of the pipeline meeting standard requirements for standard environment conditions ((m·K)/W)
$R_{\mathrm{L\ st\ m}}$	overall heat transfer resistance of pipeline thermal protection components meeting standard requirements for environment conditions occurring during IR camera testing of the pipeline ((m·K)/W)
$R_{\alpha\ \mathrm{st\ m}}$	resistance of heat transfer between pipeline shell and the environment for the pipeline meeting standard requirements and environment conditions occurring during its IR camera testing ((m·K)/W)
$R_{\alpha\ \mathrm{x\ m}}$	resistance of heat transfer between pipeline shell and the environment for the existing pipeline and environment conditions occurring during its IR camera testing ((m·K)/W)

SPBT

SPBT	value of SPBT (years)
$T_{\mathrm{e\ st}}$	air temperature for standard environment conditions (°C)
$T_{\mathrm{e\ m}}$	air temperature for environment conditions occurring during IR camera testing of the pipeline (°C)
$T_{\mathrm{er\ st}}$	environment radiative temperature for standard environment conditions (K)
$T_{\mathrm{er\ m}}$	environment radiative temperature for environment conditions occurring during IR camera testing of the pipeline (K)
$T_{\mathrm{ou\ st}}$	outer shell temperature of pipeline meeting standard requirements for standard environment conditions (°C)
$T_{\mathrm{ou\ st\ m}}$	outer shell temperature of pipeline meeting standard requirements for environment conditions occurring during IR camera testing of the pipeline (°C)
$T_{\mathrm{ou\ x\ m}}$	outer shell temperature of the existing pipeline for environment conditions occurring during IR camera testing of the pipeline (°C)
$u(y)$	standard uncertainty of parameter y ([y])
$u_{\mathrm{c}}(q''_{\mathrm{e\ x\ m}})$	combined standard uncertainty of the considered heat loss (W/m)
ψ	extended uncertainty (W/m)
$w_{\mathrm{e\ st}}$	wind speed for standard environment conditions (m/s)
$w_{\mathrm{e\ m}}$	wind speed occurring during IR camera testing of the pipeline (m/s)

Greek letters

$\alpha_{\mathrm{c\ st}}$	convective heat transfer coefficient for standard environment conditions (W/(m^2 K))
$\alpha_{\mathrm{r\ st}}$	radiative heat transfer coefficient for standard environment conditions (W/(m^2 K))
$\alpha_{\mathrm{c\ x\ m}}$	convective heat transfer coefficient for existing pipeline and environment conditions occurring during IR camera pipeline testing (W/(m^2 K))
$\alpha_{\mathrm{r\ x\ m}}$	radiative heat transfer coefficient for existing pipeline and environment conditions occurring during IR camera pipeline testing (W/m^2 K))
α_{t}	total (convective and radiative) heat transfer coefficient, meaning of other subscripts as above (W/(m^2 K))
γ	multiplier considering additional local heat losses in pipe fittings and fixing elements, etc. in relation to linear heat losses, usually $\gamma = 1.2 \div 1.38$
$\delta_{\mathrm{iz\ st}}$	thickness of thermal insulation recommended by standards (m)
Δt	time step in simulation of pipeline operation during the year (h)
ΔQ_{L}	saving of heat in a pipeline segment due to its thermomodernisation (GJ/year)
$\Delta T_{\mathrm{ou\ st\ m}}$	temperature difference between shell of pipeline meeting standard requirements and air at the moment of IR camera pipeline testing (K)
$\Delta T_{\mathrm{ou\ x\ m}}$	temperature difference between the shell of the existing pipeline and air at the moment of IR camera pipeline testing (K)
$\varepsilon_{\mathrm{ou}}$	emissivity coefficient of outer pipeline shell
ε_{ψ}	correction factor of convective coefficient depending on ψ angle
λ_{iz}	heat conductivity coefficient of insulation (W/(m·K))
π	constant $\pi = 3.14$
σ	Stefan–Boltzmann constant equal to $5.67 \cdot 10^{-8}$ (W/(m^2·K^{-4}))
ξ	relative heat loss
ψ	angle between pipeline axis and wind direction (°)

Subscripts

av	average value
d	pipeline design requirements
i n	fluid inside the pipeline
i n n	inner diameter of insulation
j	successive number of time step
m	environment conditions during IR camera measurements
ou	outer pipeline shell
st	conditions meeting standard requirements
x	existing state of pipeline insulation/shell

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