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EXPERIMENTAL DETERMINATION OF THE HEAT EXCHANGE COEFFICIENT OF INDUSTRIAL STEAM PIPELINES

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Abstract

The article discusses and analyses the factors related to the use of a thermal imaging camera to determine heat loss in industrial steam pipelines at factories from chemical and metallurgical industry, by measuring their surface temperature. The generally accepted enthalpy method for determination of the loss has serious drawback it gives accurate results, but in averaged units in which it is impossible to take account of the contribution of the different parts and components of the pipeline in the total heat loss. The unavailability of information on where, how and in what way along the route this loss is formed does not allow prompt and specific measures to be taken for its reduction. An attempt has been made to structure empirically a reliable analytic dependence for determination of the heat exchange coefficient, bringing together the various factors influencing the heat exchange. By the method of the least squares the free coefficient and the exponent have been determined of criterion equation satisfying initial and boundary conditions of the experiment. Based on the obtained results for determining the heat losses by measuring the surface temperature of steam pipelines with a thermal imaging system, a reliable and acceptable method is proposed, which has a place in engineering practice. For this purpose, an industrial experiment has been carried out at three actually operating steam pipelines of different diameters and steam parameters. A criterion equation has been derived that can be used as a mathematical model for software products with a practical orientation for regular assessment of heat losses of steam pipelines. Values of heat losses determined through energy balance of heat carrier and heat flux from the outer surface of the steam pipelines have been compared. Results for the heat exchange coefficient, obtained through a balance have been compared with the analytically determined values based on current standards. A new method has been developed for express evaluations of the current heat losses of the steam pipeline in real time, as the sum of the losses through its individual components gives as average values 9÷12 % increased results for the losses compared to the enthalpy method. Its great advantage is that it can be used selectively to determine the losses through individual sections of the steam pipeline.

Keywords: heat losses from steam pipelines, thermal vision camera, heat exchange coefficient.

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1. Introduction

The economics and management of the chemical technologies and metallurgy, and in particular oil refineries, strive for sustainable development and environmental protection. Reducing the heat losses of facilities and heat transmission pipelines is a measure that increases the competitiveness of enterprises and reduces the cost of production. It is typical of the existing practice that heat loss during operation of heat transfer pipelines is determined by balance, through the change of enthalpy of the coolant between the beginning and end of the route. Such an approach combined with the existing level of measuring technique gives accurate results moreover the measurements is associated with relatively small loss of time. In many countries, it is legally approved as a metrology tool to detect heat loss of heat transfer trunk pipelines. The enthalpy method for determination of the loss has also a serious drawback – it gives accurate results, but in averaged units in which it is impossible to take account of the contribution of the different parts and components of the pipeline in the total heat loss. Since steam pipelines are of great length and different diameters and connect different productions, the unavailability of information on where, how and in what way along the route this loss is formed does not allow prompt and specific measures to be taken for its reduction. In the present study, a different approach related to the application of thermal imaging for determining local losses in steam pipelines is proposed. The conducted scientific research on the determination of linear and local losses in steam pipelines is important for practice, since this problem has not yet been solved. The proposed criterion equation and the obtained results for the heat loss values, by measuring the surface temperature of the steam pipes, knowing the value of the convective heat exchange coefficient under different climatic conditions, give adequate comparability of the results with the enthalpy method.

2. Materials and methods

The study of heat losses in steam pipes, as an integral part of the task of increasing the energy efficiency of industrial systems, is of a permanent nature and acquires extreme relevance in the modern world of highly developed technologies. A particularly important place in solving this task is the measurement of the temperature of pipelines. With the development of modern measuring devices, this task has been greatly simplified and the precision of its implementation has improved. Thermal imaging is a modern method with extreme precision, convenience and simplicity of use.

In connection with this, a methodology is presented in which, with the help of a thermal imaging camera, the total heat transfer losses in an industrial steam pipeline can be determined as a sum of the losses in the individual structural elements. The results are compared with analytical calculations by the enthalpy method.

The mathematical model on which the method is based was proposed in [1] and is based on the possibility to express the heat losses from the pipelines as the sum of the losses from the individual structural elements by using a thermal imaging camera. In essence, this is a new method for estimating heat losses that can be used in parallel with enthalpy:

$$q_{ou} = \gamma\pi D_{ou}\left(\alpha_k + \alpha_r\right)\left(T_{ou} - T_o\right), \tag{1}$$

where q_{ou}, W/m^2 is the heat flow from 1 m length of pipeline; γ is a dimensionless coefficient that takes into account the local heat losses in valves, fittings and supports of heat transfer pipelines; D_{ou}, m is insulation diameter; T_{ou}, K is temperatures of insulation surface; T_o, K is environment temperature; α_k, W/m^{2}K is the convective heat exchange coefficient; α_r, W/m^{2}K is the coefficient taking account of the radiation heat exchange.

Analyzing dependence 1 the main difficulties that must be overcome for the practical application of the proposed mathematical model is the correct determination of the three physical quantities included in the equation – the coefficient taking into account local heat loss, convective heat transfer coefficient and radiative heat transfer coefficient. As is known in engineering practice [2–4], the heat transfer coefficient is determined by criterion equations, which must include the Nusselt criterion (Nu) and includes the coefficients of convective and radiative heat transfer (α_k+α_r).

The coefficient taking into account the radiative heat exchange is determined unambiguously in accordance with the Stefan-Boltzmann law [5, 6] of dependence:

$$\alpha_r = \varepsilon_{ou}\sigma\frac{\left(\frac{T_{ou}}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4}{T_{ou} - T_o}, \tag{2}$$

where ε_{ou} is the degree of blackness of the insulated surface; σ, $W \cdot m^{-2}K^{-4}$ is the radiation coefficient of an absolute black body.

The difficulty stems from determining the degree of blackness of the steam line. The radiometric instruments for measuring temperature are affected by the so-called summary brightness [7, 8]. It is formed by the effective radiation (luminosity) of the object, radiation and throughput of the atmosphere as well as background created by the side emitters located close to the measurement. The device is graduated using an imitation of blackbody and it determines the effective (radiation) temperature as a function of the total brightness by linear scale. This temperature will be equal to the actual temperature only when a radiation coefficient close to that of a blackbody and the object is in conditions where the influence of the atmosphere and the accompanying background can be ignored. Such conditions are difficult to reach in industrial enterprises and in the measurements of industrial objects there are often prerequisites for admission of methodological error [9]. This error is significant when measuring objects with high reflection and temperatures close to the temperatures of the environment. The angle at which the lens is positioned relative to the normal to the axis of the pipeline has a considerable effect on the precision of the measurement.

The other component of the heat transfer coefficient is convective. In essence, this is the physical quantity with the highest degree of uncertainty, as it depends on climatic conditions and for the same object its value changes from free convection conditions to forced convection in the presence of wind [10, 11]. It is known from the theory of convective heat exchange that when air moves around a horizontal pipe, under the conditions of natural convection ($V = 0 \div 0.5$ m/s), the structure of the criterion equation of the form:

$$Nu = C_1 \cdot Gr^{0.25}, \tag{3}$$

where Gr is the Grasshof criterion; C_1 is a dimensionless coefficient determined experimentally.

It is also possible to use the dependence obtained from the Nusselt dependence:

$$\alpha_k = 1.16\left[\frac{(T_{ou} - T_o)}{D_{ou}}\right]^{0.25}. \tag{4}$$

Dependence (4) is essentially a modified version of criterion equation (3). Natural conditions of convection occur very rarely and for a short period of time, as the complete absence of wind is a climatic phenomenon. The wind rose for a certain geographical area is determined for air currents with speeds $V \geq 0.5$ m/s. This speed in pipelines with diameter $D_{ou} \geq 110$ mm determines the transient or turbulent mode of forced convection. Numerous studies of the envelope of a round tube located in free space with air at pronounced turbulence ($Re > 4 \cdot 10^4$) show that the Nusselt criterion can be determined by a criterion equation of the type:

$$Nu = C_2 Re^m \varepsilon_\psi, \tag{5}$$

where Re is the criterion of Reynolds.

The dimensionless multiplier C_2 and the exponent m are determined experimentally. The correction factor entered in the dependence, taking into account the deviation of the wind direction from the normal direction to the axis of the pipe, according to [12] is determined by the dependence:

$$\varepsilon_\psi = 1 - 0.54\cos^2\psi. \tag{6}$$

Equation (5) may be reduced to a form easier for practical use.

$$\alpha_k = C_2^* \frac{\upsilon^m}{D_{ou}^{1-m}} \varepsilon_\psi, \tag{7}$$

where $C_2^* = C_{2\lambda}/\upsilon^m$, J/m^3, K is a summarized coefficient; υ, m/s, is wind velocity.

In this form the equation is valid for a temperature interval, where thermal physical properties of air are not considerably changed. Equation (5) and its modified option (7) are universally recognized as a form, but the comparative analysis of the values of coefficients and exponents shows a certain difference. Probably this is due to the different conditions under which various researchers have conducted their experiments. For example, in [13] has offered the following values: $C_2 = 0.0239$ and $m = 0.805$ for Re in the interval $4\cdot10^4 \div 25\cdot10^4$ with multiplier $(T_o/T_{ou})^{0.25}$, considering the temperature difference between air temperature and insulation surface temperature. The same exponent but smaller multiplier $C_2 = 0.0266$ under compulsory participation of the criterion of Prandtl are offered by [14]. The American Society for Testing and Materials takes as a basis the equation of [15]. It easy for practical use and it is valid for conditions of moderate temperatures that are typical in insulated pipelines. In the formula (8) recommended by ASTM C 680-89, in the basic equation some additions and corrections have been introduced that account for the influence of the diameter of the pipeline and the thermophysical properties of the fluid at different temperatures [16].

$$\alpha_k = \left(\frac{1}{D_{ou}}\right)^2 \left(\frac{1}{T_{avg}}\right)^{0.181} (T_{ou} - T_o)^{0.266} \sqrt{1 + 1.277 \cdot v}, \tag{8}$$

where $T_{avg} = (T_{ou} - T_o)/2$, °C – average temperature of air film.

For express engineering estimates which do not require high precision, the modifications of equation (7) are used. For member states of the European Union the standard EN ISO 12241:1998 has been introduced, which has priority over national regulations [17]. According to this standard, the coefficient of convection for horizontally and vertically located pipes outside buildings is determined by the formula:

$$\alpha_k = 8.9 \frac{w_0^{0.9}}{D_{ou}^{0.1}} \varepsilon_\psi. \tag{9}$$

The equation (9) is valid provided that the product from the wind velocity and diameter $VD_{ou} > 8.55\cdot10^{-3}$, m^2/s. This dependence is used by [1] by setting a fixed value of $\varepsilon_\psi = 0.877$ at an angle $\psi = 45°$.

Regarding the definition of the coefficient, which takes into account the local heat losses of heat transfer pipelines, the configuration of the pipelines themselves is of great importance here. As a rule, the local losses are specific for the different heat transfer pipelines and they depend on their structural specifics. In his publication [1], the author proposes to uses the reference value $\gamma = 1.38$. Based on a dimensional analysis [18] for determining the losses through the supports and the other fittings, it is proposed a criterion equation of the following type to be used [19].

$$\frac{q_s}{C} = \left(\frac{\lambda}{\delta\alpha_s}\right)^b \left(\frac{F}{\delta^2}\right)^d \left(\frac{T_o}{\Delta T}\right)^e, \tag{10}$$

where q_s, W are the heat losses through the support; $C = \alpha_s\delta^2\Delta T$, W is a coefficient, making equation (10) dimensionless; α_s, W/m^{2}K is the coefficient of convective heat exchange from the non-insulated parts of the support; δ, m is the thickness of the structural components of the support; $\Delta T = T_P - T_0$, K is the temperature difference between the temperatures of the coolant and ambient air; F, m^2 is the area of the non-insulated part of the support; λ, W/(m·K) is the heat transfer coefficient of the material from which the supports are made; complex $\lambda/\delta\alpha_s = 1/Bi$ represents the reciprocal value of Biot criterion.

The values of the exponents depend on the structure of the support and for each case they should be determined experimentally. Calculated in this way losses of one support are multiplied by their number and added to the heat loss of the cylindrical portion. Experiments performed [19] show that depending on the parameters of the coolant and climatic factors, they are in the range of 180÷240 [W].

The studied object is the trunk steam pipelines at the territory of industrial enterprise. Three steam pipelines with different lengths, configurations and parameters of the steam were inspected, and the characteristics of each are:

– two parallel steam pipelines for low pressure superheated steam $P_{lp} = 1$ MPa and temperature $t_{lp} = 250$ °C, one of them is operating and the other one is standby. The operating steam pipeline has a length 3 317 m, out of which 2990 m with pipe diameter (with insulation) 800 mm, and remaining 327 m have a diameter 500 mm. The object of the study is the first section with 286 sliding and fixed supports;

– steam pipeline for medium pressure superheated steam $P_{mp} = 1.5$ MPa and temperature $t_{mp} = 315$ °C. The steam pipeline has total length 3355 m, and it consists of two sections. The studied object is 2867 m of the first section with pipe diameter 400 mm, where sliding and fixed supports are 298 counts;

– two parallel steam pipelines for high pressure superheated steam $P_{hp} = 2$ MPa and temperature $t_{hp} = 360$ °C, one of them is operating and it has a length of 3360 [m], as follows: 3163 m have a diameter 300 mm and 147 m have a diameter 200 mm. Both sections have been studied. Number of supports – 384.

According to design documentation the main characteristics of installed insulation of the three steam pipelines are the same and it consists of glass wool rolled with Rabitz wire netting, three layers of 50 mm each layer and conductivity coefficient $\lambda = 0.47$ W/m·K and another cover of galvanized sheet with thickness 0.8 mm. At the time of measurement ambient temperature T_0 in the range – 8 to 26 °C and wind with variable velocity (V) and direction with gusts of 0.7 to 7.4 m/s are recorded in north – northeast direction, which is a deviation to the axis of the pipe rack in the range 45° to 70°. This is the prevailing direction of the wind rose during most of the year in the area where the object of study is located. Measurements with thermal imaging equipment were made during the night to avoid as far as possible uneven heating by sunshine and the influence of the reflected heat radiation from the buildings and industrial facilities adjacent to the pipe rack.

The determination of the spectral emissivity $\varepsilon(\lambda, T)$ and the objective positioning factor $\varepsilon(\beta)$ have a direct bearing on the reliability of the measurements of the surface temperature of a steam pipe by radiometric way through thermal imaging equipment. In this case, it concerns the determination of the spectral emissivity of galvanized sheet metal from which the outer coating of the insulation of industrial steam pipes is made.

The essence of the experiment consists in determining the temperature in the studied areas of the surface of specially developed laboratory samples in a radiometric way by means of standard thermal imaging equipment operating in the long-wave range and comparing the results with reference measurements. At a fixed wavelength at which the thermal imaging camera operates, the operator sets the device different values of the degree of blackness of the object, while the degree of blackness of solid bodies coincides with their spectral emissivity. Thus, when the measured temperature matches the reference temperature, the value of $\varepsilon(\lambda, T)$ is uniquely determined. Analogous measurements at different temperatures of the object allow to determine graphically a functional dependence $\varepsilon(\lambda, T) = f(T)$. Once the degree of blackness and the spectral emissivity have been determined unambiguously, the relative error obtained during the measurement with the thermal imaging equipment can be calculated if the lens is positioned at an angle β to the normal. This error must be compensated by the operator, by correcting the result with the lens positioning coefficient $\varepsilon(\beta)$, but for this purpose the function $\varepsilon(\beta) = f(\beta)$ must be known. This function is individual and characteristic of each object because it depends on its geometric shape and its degree of blackness.

Of interest is the possibility to define a conditionally called «confidence zone», where the deviations of the lens from the normal lead to insignificant errors from an engineering point of view, and it is not necessary to make a correction of the result.

When conducting the experiments in real conditions, a based method was used of on the plan of the experiment, which is carried out in four stages.

First stage. Based on the readings of permanent instrumentation during the night on the date of the experiment a heat balance is carried out and heat losses of the sections of the three operating pipelines, designated as object of study, are determined. Losses are determined separately for each of the three steam pipelines:

$$\Delta Q_{los} = (Q_0 + Q_{bu}) - \sum_1^n D_i h_i, \tag{11}$$

where (Q_0+Q_{bu}), W is the thermal capacity, determined as a sum of the heat of the steam from the Thermal Power Station and the waste heat boilers, adjoined to the relevant steam pipeline, and $\sum_1^n D_i h_i$ is the heat consumed by the production structures.

Apart from the indicated way (11), the losses can be represented in the following way:

$$\Delta Q_{los} = Q_b + Q_{rad} + Q_{konv}, \tag{12}$$

where Q_{konv} is convective component of heat losses; Q_b are the heat losses through the supports and fittings, determined according to the proposed equation (10); Q_{rad} is the radiation component of the losses, which, as known, may be determined through the equation:

$$Q_{rad} = \varepsilon_{ou}\sigma\left[\left(\frac{T_{ou}}{100}\right)^4 - \left(\frac{T_o}{100}\right)^4\right]\pi D_{ou} L, \tag{13}$$

where T_{ou}, D_{ou} and L are respectively the average value of the surface temperature, the outer diameter and the length of the studied section.

Second stage. Parallel to this the measurements of the surface temperature of the steam pipelines and visible part of supports, speed and wind direction and outdoor temperature of atmosphere are carried out. At a certain ambient temperature (T_0) and surface temperature (T_{ou}), determined by thermal vision measurements based on the convective losses Q_{konv}, determined by balance at the first stage in complaince with the law of Newton- Richman, the specific value of the heat transfer α_k may be determined for each different experiment:

$$\alpha_k = \frac{Q_{konv}}{(T_{ou} - T_0)\pi d_{ou} L}. \tag{14}$$

Third stage. The results of experiments are processed and summarized in order to obtain a reliable mathematical model to be used for the structuring of the appropriate software product allowing determination of heat losses in real time. There are several scientifically sound methods for processing data from the experiment [20–22]. The most popular and most often used method is the method of least squares. This method, as known [23], is based on the equation:

$$SUM = \sum_1^n (\bar{y}_i - y_i) = \min, \tag{15}$$

where $\bar{y}_i$ is the average experimental value of the magnitude sought; y_i is its value according to the mathematic model.

In the specific experiments conducted and the data processing and given the set goals, it seems acceptable to present the results as a generalized dependence in accordance with the theory of similarity. The generally recognized equation (5) is used as a physical model. Strictly speaking the function of the type $Nu = f(Re, \varepsilon_\psi)$ implies performance of two-factor experiments, but the use of formula (6) simplifies the task and it reduces it to a simple power function, which in logarithmic coordinates is an equation of straight line of the type:

$$LnNu = Ln(C_2\varepsilon_\psi) + mLn\mathrm{Re}. \tag{16}$$

It is convenient to apply the substitution $x = LnRe$, $y = LnNu$ and $b = Ln(C_2\varepsilon_\psi)$ which converts equation (16) in the type $y = b+mx$, where y is the experimentally determined magnitude, based on the specific values of the coefficient of convective heat exchange, determined as per equation (16) and b and m are the unknown constants. After determination of constants m, b and correction coefficient for the wind direction to the axis of the pipe ε_ψ, the equation of the mathematical model is obtained through anti-logarithm.

Fourth stage. The reproducibility of results and adequacy of the mathematical model is verified by statistical test known as regression analysis. The models where uniformity of dispersion of reproducibility and dispersion of adequacy are observed shall be considered appropriate.

3. Results and discussion

The results are based on the systematic measurements of the steam network at an oil refinery. Multiple measurements were performed over ten months in the climatic seasons typical for the region and it is not possible all of them to be summarized and presented in the scope of a single article. That's why in **Table 1** shows a representative sample of data from five calendar days with different combination of weather conditions.

Table 1

Representative abstract of measurements reports

Parameters Data	Velocity	Direction	Temperature	Kinematic viscosity	Thermal conductivity coefficient	LP (1 MPa)		MP (1.5 MPa)		HP (2 MPa)	
	w	ψ	T_o	v	λ_{air}	T_{ou}	T_b	T_{ou}	T_b	T_{ou}	T_b
Dimension	m/s	arc. deg	°C	m^2/s	W/m K	°C	°C	°C	°C	°C	°C
15.06.2021	0.85	70	22	15.11	0.0257	42	58	41	69	48	75
07.10.2021	3.2	50	13	14.66	0.025	37	53	39	64	42	70
18.01.2022	7.4	60	–8	12.9	0.023	25	49	25	57	31	66
06.03.2022	4	45	2	13.8	0.0243	30	55	31	62	38	69
10.05.2022	2.1	50	26	15.2	0.026	45	59	46	71	35	76

The table shows the average surface temperatures of the three steam pipelines. The measurements were made with a thermal imaging system FLIR, Therma CAM P 60 at equal distances; the beginning is the point from which the steam pipeline is coming out from the Thermal Power Station and the end – the ending point of the object of the study. **Fig. 1** show the change in surface temperature along the three steam pipelines, recorded as of 18/01/2022.

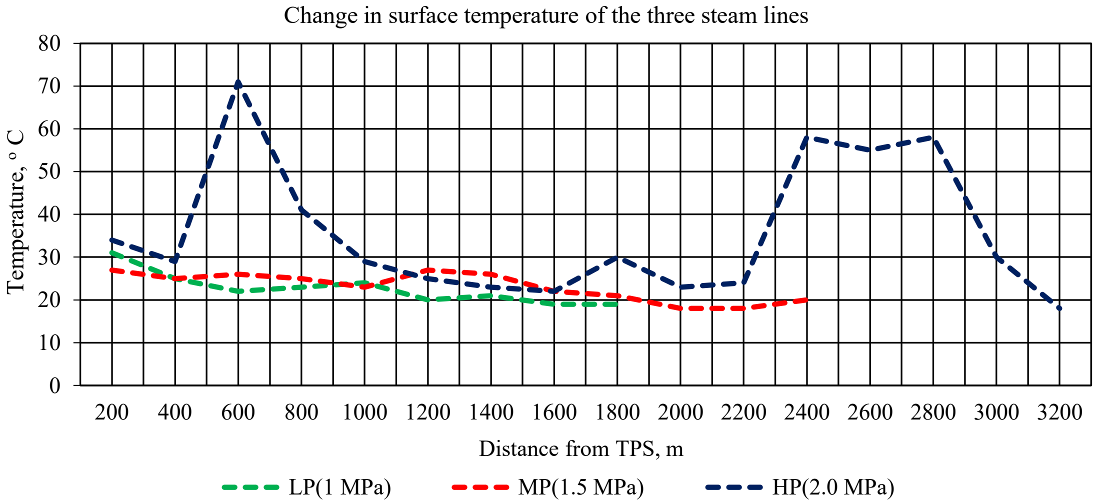

Fig. 1. Modification of the surface temperature of steam pipelines

From the data in the graphs, it can be seen that along the length of the steam pipes, the surface temperature follows a downward trend from the beginning to the end points. It is especially characteristic in the end sections with a smaller diameter.

The lowering of the surface temperature is explained by the lowering of the temperature of the steam flowing in the steam pipe, which is due to both heat losses and throttling and as a result of hydraulic resistances. The measured surface temperatures of the steam pipe with a pressure of 1.5 MPa are closer to the temperatures of the steam pipe with a steam pressure of 1 MPa than to the temperatures of the steam pipe with a steam pressure of 2 MPa, which is explained by the different wind speed in the measurements of the three steam lines: the wind speed is the highest in the measurements of the steam line with a steam pressure of 2 MPa (5 m/s), and the wind speed is the smallest wind (3 m/s) during the measurements of the steam pipeline with a steam pressure of 1.5 MPa. From the analysis of the performed thermal imaging measurements and the graphs built based on the measured temperature of the surface of the insulation, it is clearly seen that the insulation of a high-pressure steam pipeline is in the worst condition. Variation of the surface temperature of a high-pressure steam pipeline (2 MPa) in the end sections, which is a prerequisite for large heat losses in this area. The insulation of the steam pipeline with a steam pressure of 1.5 MPa is in the best condition.

For the determination of total heat loss as part of the heat balance three parallel measurements have been performed within the duration of the night work shift on the date of the experiment. The readings of permanent instrumentation have been used and the same methodology used in the preparation of monthly production reports (8). The heat loss through the supports and fittings (10) and the radiation component of heat loss (11) have been additionally determined. The convective part of the heat loss as set out in the methodology in item 5. The results obtained are presented in **Table 2** and **Fig. 4** below.

Table 2

Results of the heat balance as per enthalpy method

Heat streams Data	Qo MW			∑Qbu MW			∑Di*hi MW			∑Qlos MW		
	LP	MP	HP	LP	MP	HP	LP	MP	HP	LP	MP	HP
15.06.2021	7.8	4.9	6.5	8.6	3.0	0.0	15.3	7.1	5.8	1.1	0.7	0.7
07.10.2021	10.8	9.6	11.0	9.4	3.2	0.0	18.4	11.0	9.4	1.8	1.8	1.6
18.01.2022	23.2	14.5	17.2	3.0	3.1	0.0	28.0	13.5	13.0	4.3	4.1	4.1
06.03.2022	17.9	15.8	13.0	8.8	0.0	0.0	23.2	12.9	10.1	3.4	2.9	2.9
10.05.2022	12.6	5.2	10.7	8.9	2.9	0.0	20.2	7.2	9.8	1.4	0.9	0.8
Average	14.5	10.0	11.7	8.9	2.5	0.0	21.0	10.4	9.6	2.4	2.0	2.0

Fig. 2 shows the losses of the three studied steam pipelines. For all three convective losses have the largest share.

The link between Nu criterion and *Re* criterion in logarithmic coordinates is shown in **Fig. 3**.

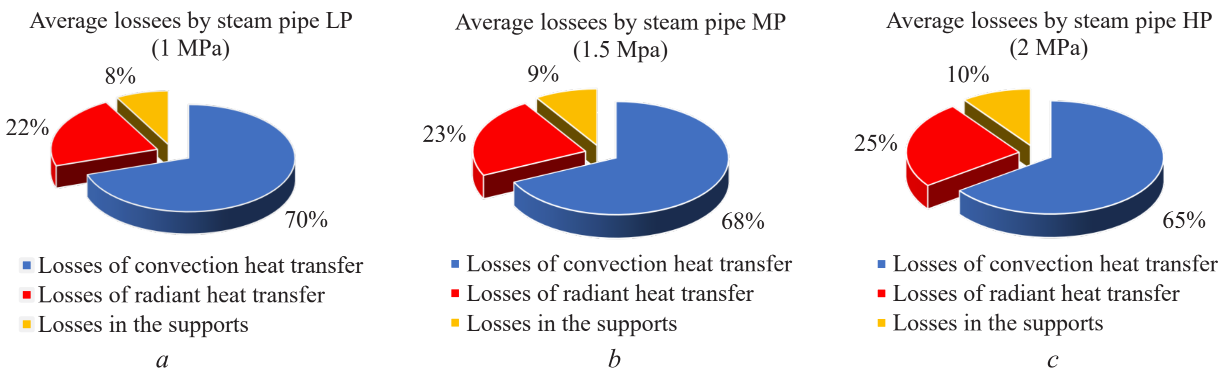

Fig. 2. Structure of the heat losses: *a* – average losses steam pipe – 1 MPa; *b* – average losses steam pipe – 1.5 MPa; *c* – average losses steam pipe – 2 MPa

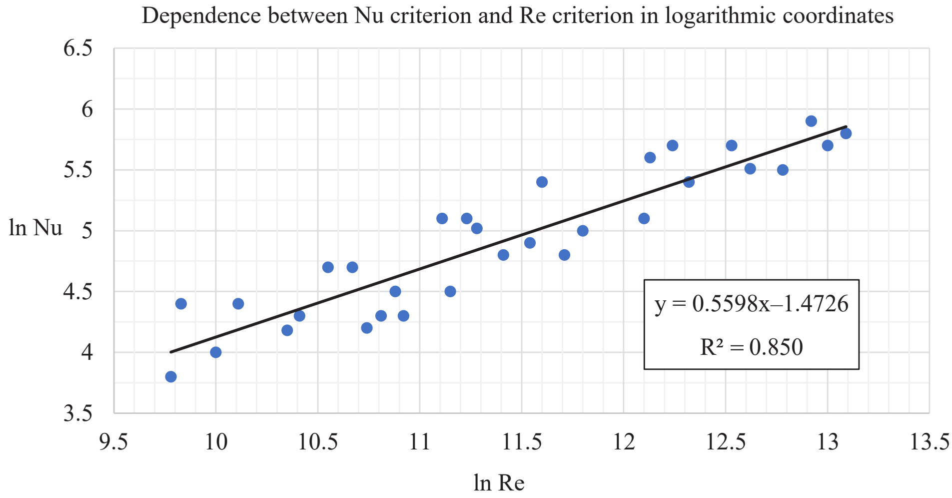

Fig. 3. Experiment results

As seen of the conditions of the experiments performed within the specified initial and boundary conditions, related to the characteristics of the studied object and the obtained value for the correlation coefficient, equation (5) will be the following:

$$Nu = 0.23\,\mathrm{Re}^{0.56}\,\varepsilon_{\psi}. \tag{17}$$

The equation (17) is valid for Re values of $1.7 \cdot 10^4$ to $46 \cdot 10^4$ and in the temperature range of experiments conducted from –8 to +26 [°C] it does not claim for comprehensiveness and only applies to the objects studied and the specific conditions.

Equation (17) can also be represented as follows:

$$\alpha_k = 0.23 \frac{\lambda}{d}\left(\frac{\upsilon \cdot d}{\nu}\right)^{0.56}. \tag{18}$$

After mathematical transformations let's obtain:

$$\alpha_k = 0.23 \cdot \lambda \cdot \upsilon^{0.56} \cdot d^{-0.44} \cdot v^{-0.56}. \tag{19}$$

Assuming 0 °C as the reference temperature, the criterion equation can be presented, as a practical application:

$$\alpha_k = 4.43 \cdot \upsilon^{0.56} \varepsilon_{\psi}. \tag{20}$$

The obtained values for the coefficient of convective heat transfer are compared with the values obtained according to the current standards and are presented graphically in **Fig. 4**.

Analyzing the data, it can be seen that at wind speeds above 4 m/s the differences are already significant. At a speed of 7.4 m/s, the lowest results for α_k were obtained according to the American standard ASTM C 680-89 and the highest according to EN ISO 12241. The reason for the increased dispersion at higher speeds probably lies in different conditions, in which the experiments were performed. When determining the heat loss and insulation thickness of the steam line, the exact value of αk is not known before, but the assumption even at 100 % error leads to an increase in the calculated heat loss of no more than 3–5 %, as the thermal resistance through the surface the insulation is several times less than the resistance determined by its thickness. In order to create a methodology with reliable results for the values of heat losses by measuring the surface temperature of steam pipelines, it is necessary to know the exact value of the convective heat transfer coefficient in different climatic conditions, as steam pipelines are long and even small inaccuracy to large errors in the results. For the specific purposes of the present study, the obtained results give adequate comparability of the results with the enthalpy method. Undoubtedly, the algorithm proposed by [1], supplemented with the module for determining ε_ψ and losses through supports, is logical, reasonable and efficient. This makes the method suitable for rapid estimates of current heat losses and modeling of heat flow from the surface of steam pipelines in the event of climate change, but cannot replace the enthalpy method, which is based on production and accounting of industrial enterprises.

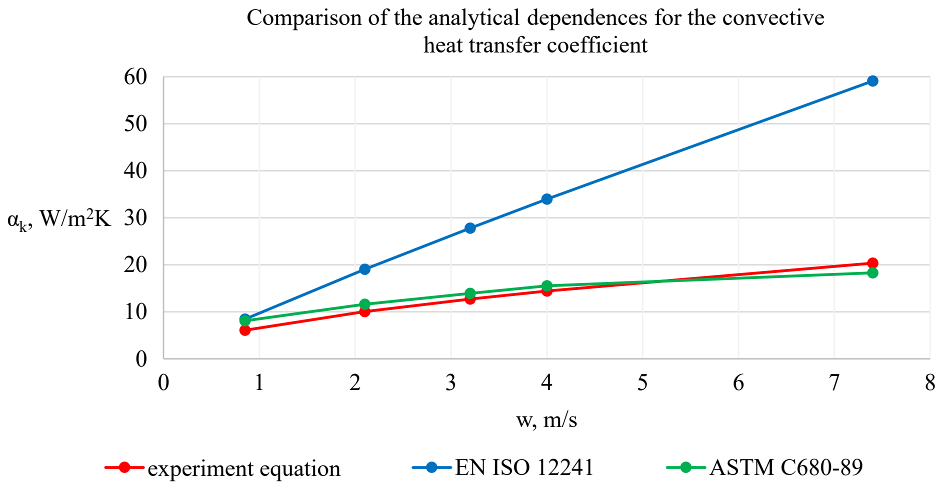

Fig. 4. Comparison of experimental results with standards

Based on the results obtained from the conducted experiments, it can be argued that the proposed methodology avoids the biggest drawbacks of the enthalpy method. The determination of the enthalpy of individual steam flows is carried out on the basis of the results of the material balance, which means that all systematic errors in the measurements directly reflect in the accuracy of the method. The impossibility of accurately measuring the flow rate of two-phase fluids and determining the specific value of the moisture content of the steam in order to determine the enthalpy and. Another fundamental disadvantage of the method is that it does not allow to determine the share in the total heat losses of the different sections and structural elements of the heat pipe. The lack of information where, how and by how along the route they are formed does not allow for their quantitative assessment in order to take timely and adequate measures to reduce them.

The proposed mathematical model is a very important stage in the development of a comprehensive new approach for determining the heat losses of steam pipelines with a complex configuration. The work on the problem will continue in the direction of writing engineering-applicable software for determining the total heat losses of steam pipelines located on overpasses by measuring their surface temperature using thermal imaging equipment.

4. Conclusions

The proposed new method and its application, when analyzing the operation of three real working steam pipelines with different diameters and steam parameters, is extremely useful for determining the heat losses of individual sections from heat networks of industrial enterprises. It can also be used to assess one or another management impact, specific repair or replacement of compromised insulation. The conducted experiment shows that with a standard multi-pixel thermal imaging system, it is possible to capture and visualize frames, through which to make a qualitative analysis of the state of the insulation and to visualize the local heat losses of industrial networks. Based on the data obtained from the experiment, the proposed new criterion equation was also derived. The obtained results are compared with the current standards (developed on the basis of the enthalpy method) and show a good convergence of the results. For the linear sections of the steam pipelines, the obtained values for the heat losses have a difference of no more than 3÷5 %.

The developed method for expert evaluations of the current heat losses of the steam pipeline in real time, as a sum of the losses through its individual components, gives (local and linear) as average values 9÷12 % increased results for the losses compared to the enthalpy method. Its great advantage is that it can be used selectively to determine the losses through individual sections of the steam pipeline.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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References

[1] Kruczek, T. (2013). Determination of annual heat losses from heat and steam pipeline networks and economic analysis of their thermomodernisation. Energy, 62, 120–131. doi: http://doi.org/10.1016/j.energy.2013.08.019

[2] Pavlenko, A., Cheilytko, A., Ilin, S., Belokon, Y. (2022). Determination of porous constructions heat transfer coefficient. Procedia Structural Integrity, 36, 3–9. doi: http://doi.org/10.1016/j.prostr.2021.12.075

[3] Acikgoz, O., Batur Çolak, A., Camci, M., Karakoyun, Y., Dalkilic, S. A. (2022). Machine learning approach to predict the heat transfer coefficients pertaining to a radiant cooling system coupled with mixed and forced convection, International Journal of Thermal Sciences, 178, 107624. doi: http://doi.org/10.1016/j.ijthermalsci.2022.107624

[4] Rabiu, A., Na, W.-H., Akpenpuun, T. D., Rasheed, A., Adesanya, M. A., Ogunlowo, Q. O. et. al. (2022). Determination of overall heat transfer coefficient for greenhouse energy-saving screen using Trnsys and hotbox. Biosystems Engineering, 217, 83–101. doi: http://doi.org/10.1016/j.biosystemseng.2022.03.002

[5] Li, J., Xie, X., Li, S., Zhang, Q. (2022). Reliable potential and spatial size of virtual cathode obtained by an emissive probe with accurate filament temperature in a vacuum. Vacuum, 200, 111013. doi: http://doi.org/10.1016/j.vacuum.2022.111013

[6] Modest, M. F., Mazumder, S.; Modest, M. F., Mazumder, S. (Eds.) (2022). Fundamentals of Thermal Radiation. Radiative Heat Transfer Academic Press, 1–29. doi: http://doi.org/10.1016/b978-0-12-818143-0.00009-2

[7] Guan, H., Xiao, T., Luo, W., Gu, J., He, R., Xu, P. (2022). Automatic fault diagnosis algorithm for hot water pipes based on infrared thermal images. Building and Environment, 218, 109111. doi: http://doi.org/10.1016/j.buildenv.2022.109111

[8] Zhou, S., O'Neill, Z., O'Neill, C. (2018). A review of leakage detection methods for district heating networks. Applied Thermal Engineering, 137, 567–574. doi: http://doi.org/10.1016/j.applthermaleng.2018.04.010

[9] Schmid, J., Bicat, D., Elfner, M., Bauer, H.-J. (2021). Improved in-situ calibration applied to infrared thermography under high angles of view. Infrared Physics & Technology, 119, 103952. doi: http://doi.org/10.1016/j.infrared.2021.103952

[10] Reddy, K. S., Veershetty, G., Srihari Vikram, T. (2016). Effect of wind speed and direction on convective heat losses from solar parabolic dish modified cavity receiver. Solar Energy, 131, 183–198. doi: http://doi.org/10.1016/j.solener.2016.02.039

[11] Bruno, R., Ferraro, V., Bevilacqua, P., Arcuri, N. (2022). On the assessment of the heat transfer coefficients on building components: A comparison between modeled and experimental data. Building and Environment, 216, 108995. doi: http://doi.org/10.1016/j.buildenv.2022.108995

[12] Burmeister, L. C. (1993). Convective heat transfer. John Wiley & Sons inc.

[13] Eckert, E. R. G., Drake, Jr. R. M. (1987). Analysis of Heat and Mass Transfer. Washington: Hemisphere Publishing Corp.

[14] Incropera, F. P., Dewitt, D. P., Bergman, T. L., Lavine, A. S. (2007). Fundamentals of heat and mass transfer. John Wiley & Sons, Inc, 1070. Available at: https://hyominsite.files.wordpress.com/2015/03/fundamentals-of-heat-and-mass-transfer-6th-edition.pdf

[15] Turner, W. C., Malloy, J. F. (1981). Thermal Insulation Handbook. New York: McGraw Hill, 50.

[16] ASTM C 680 – 89 Standard Practice for Determination of Heat Gain or Loss and the Surface Temperatures of Insulated Pipe and Equipment Systems by the Use of a Computer Program. Available at: http://nawabi.de/project/hrsg/ASTM-C680.pdf

[17] EN ISO 12241:1998 Thermal insulation for building equipment and industrial installations – Calculation Rules. Available at: https://www.iso.org/standard/21345.html

[18] Huntley, H. (1967). Dimensional analysis. Dover, 158

[19] Kostov, P. S., Nikolov, Ch. I., Atanasov, K. T., Kalchev, S. V. (2014). Possible to determine of the heat losses in supports by using a thermal cameras. XIX International Conference, I, 186–190. Available at: http://copepm.eu/documents/tom_1.pdf

[20] Chakyrova, D., Andreev, A. (2021). Exergoeconomic analysis and optimization of a waste tires pyrolysis, Journal of Chemical Technology and Metallurgy, 56 (6), 1234–1248. Available at: https://dl.uctm.edu/journal/node/j2021-6/15_20-17p1234-1248.pdf

[21] Doseva, N., Chakyrova, D. (2019). Thermoeconomic analysis of biogas engines powered cogeneration system. Journal of Thermal Engineering, 5 (2), 93–107. doi: http://doi.org/10.18186/thermal.532210

[22] Velichkova, R., Stankov, P., Simova, I., Markov, D., Angelova, R., Pushkarov, M., Denev, I. (2021). Integrated System for Wave Energy Harvesting. Proceedings of the 2021 6th International Symposium on Environment-Friendly Energies and Applications. doi: http://doi.org/10.1109/efea49713.2021.9406234

[23] Penkova, N. Y., Mladenov, B. M., Krumov, K. S. (2019). Finite elements analysis of mass transfer and mechanical processes in ceramic ware at convective drying. IOP Conference Series: Materials Science and Engineering, 595 (1), 012003. doi: http://doi.org/10.1088/1757-899x/595/1/012003

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