Determining the Place of Depressurization of Underground Pipelines (Gas Pipelines): New Solutions in Industry based on Thermal Image Analysis Using Computer Vision

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Abstract. An analysis of the analytical ratios of the mathematical model, which characterizes the development processes of a corrosion cavern on the surface of an underground metal pipeline, which is placed in the environment of moist soil with an electrolyte solution, is performed. A neural network method for estimating the main informative parameters for determining the place of gas depressurization on the surface of an underground pipe and an expression for calculating the change in gas pressure around a crack after its formation have been developed. The principles of determining the limit values of the parameters of the "pipe-cathodic protection" system are formulated, considering the metal's quality and strength criteria at the top of the cavern.

Depressurization causes fluid to flow from the pipeline to the surface. Thermal imaging devices make it possible to detect the place of damage to the pipeline based on the temperature properties of the surrounding objects. Thermal imaging can be used to analyze the location of a fluid leak or warn of it using computer vision. Thus, preventing an accident or even a catastrophe in the pipeline. In the work, the colour gamuts of the thermal image in the places of depressurization are considered, and the regularities of detecting damaged sections of the pipeline are established.

Keywords: depressurization of gas pipelines; gas; corrosion; computer vision; image mining.

INTRODUCTION

Ensuring the high operational reliability of Ukraine's main gas pipelines (MG) is quite important [1]. Airtightness can be attributed to the essential criteria for the efficiency of Ukraine's gas transportation system (GTS), which characterizes its operational reliability. Here it is necessary to emphasize the problem of tightness of the MG's linear part (LP) [2, 3].

Depressurization (loss of tightness of the housing or any system) of pipelines (MG) is accompanied by leakage and ignition of gas [1, 2, 3, 4]. In most cases of accidental destruction of the MG, gas ignition occurs at the site of damage [5]. This can lead to negative phenomena, which are accompanied by fires and explosions and often threaten people's lives [2].

The scale of the impact on the environment and the nature of gas combustion depend on the following main factors (parameters) [4]:

1) pipeline diameter (MG) and gas working pressure;

2) soil density and properties of the original soil massif;

3) mutual (position) arrangement of the axes of the pipe ends.

The leading cause (more than 50%) of incidents (depressurization, accidents and failures) at MG is corrosion of pipe metal [1, 2, 6].

Based on the above, in particular [2], and taking into account the information in works [7, 8, 9, 10, 11], it can be considered: one of the urgent issues is the identification of the place of gas leakage from pipelines that are located in various environments (in particular, in the open air, in water and wet soil), and its quick and high-quality sealing.

Depressurization is associated with the formation of pitting corrosion. Over time, the cavern expands, and its depth increases. At a certain value of the depth of the corrosion crack, a limit state occurs at the top of the cavern, and a crack is formed. In that place, depressurization occurs, accompanied by a change in gas concentration inside the pipe in the vicinity of a crack-type defect.

High temperatures in such places of depressurization may be associated with certain damages to this area. When analyzing a thermal image, it is possible to identify potential locations of leakage or depressurization.

The article aims to identify and determine the place of depressurization of underground and surface pipelines based on the analysis of thermal images using computer vision methods.

Among the main tasks in this work, the following can be distinguished:

– to form the main dependencies of informative parameters for determining the place of gas depressurization on the surface of an underground metal pipe;

– to analyze the places of depressurization of pipelines based on thermal imaging using computer vision methods.

MATERIALS AND METHODS

Depressurization of the pipeline in a particular area leads to liquid leakage to the earth's surface. The temperature at the place of damage can be pretty high. With the help of thermal imaging devices, it is possible to detect areas of breakthrough and leakage of substances or liquids.

Thermal imaging images usually contain a specific range of colours that signal the temperature level of surrounding objects. Blue and black highlight things in the photo at low temperatures, yellow and green colours for medium temperatures, and red and purple colours and their shades for places with the highest temperature. Thus, a pixel recognition approach can be applied to detect the damaged location of the pipeline. Pixels are the minor parts of an image that make up the size of the image and contain the colours.

Various representations are used to represent colours in computer graphics. One of the most popular is red-green-blue (RGB). The combination of these three colours can be used to determine the shade of a colour. Moreover, the most significant values of each of the components can be 255. In addition, colours can be recorded in cyan-magenta-yellow-black (CMYK), hue-saturation-lightness (HSV), and other representations.

The software application for pipeline damage detection includes three main parts: visualizing the damage of a part of the pipeline, highlighting the damaged area, and calculating the percentage of damage relative to the image size. The Java programming language is used to develop a program for detecting depressurizations and their further analysis.

Results are visualized using the library for developing desktop graphical interfaces in the javax.swing application. In addition, java.awt library is used to work with image pixels.

The first step in the program's algorithm is to obtain the width and length of the image in pixels. This data is needed to read the pixel colours of the image in an iterative process along each XY axes. The next step is to check the availability of colours:

1. The first condition to check the red colour of the image pixels: red >=200 and green <=50, and blue <=50. If this condition is met, the current pixels of the image is redrawn in red, and the number of such pixels is calculated for further percentage calculation and storage of XY coordinate data further to highlight the damaged area with a red rectangle.

2. The second condition is to determine the purple colour of the pixels: red >=170 and green <=50, and blue >=170. Moreover, all these actions described in the first condition are performed. This condition is separated due to the peculiarity of some thermal imaging images associated with highlighting in purple colour, not only objects with high temperature.

3. The third condition for contour selection: 10 < red <=225 and 10 < green <= 225 and 10 < blue

<= 225. Since existing colours can be used for visual perception, these colours remain in the image.

4. The fourth condition for using white colour to draw accompanying objects. This condition is performed if the RGB colour combination is not performed in the conditions above.

In addition to highlighting each pixel in red, the lateral parts of the damage can be selected to save the XY coordinates and mark them on the image in the form of a rectangle with the area of the damage.

RESULTS AND DISCUSSION

Formation of the main dependencies of information parameters for determining the place of depressurization on the surface of the underground pipeline

The work [2] proposed a method for determining the place of gas leakage from the pipeline (MG). At the same time, it is noted that with the help of A. Avogadro's law and the barometric formula, the dependence of gas pressure on the concentration of its molecules is obtained – formula (1):

$$p = nkT \ , \tag{1}$$

where n – is the number of gas molecules per unit volume; k – Boltzmann constant; T – absolute temperature. Using the procedure of measuring gas concentration at different points according to formula (1), the pressure distribution field around the leak site is determined [2].

It is found that the gas concentration is most accurately determined using the spectral method of analysis [2]. It has been established that this method can be used for MG and gas distribution pipelines in different environments (open air, water, and underground areas).

For underground gas pipelines (MG), there is practically no transport movement of the medium, while the differential equation of a point source is reduced to the Laplace equation in the form of the formula (2):

$$\alpha\nabla^2 p^2 = -\frac{f}{\rho\beta^*}, \ \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial y^2}, \tag{2}$$

where α – coefficient of piezoconductivity of the soil $\left(\alpha = \dfrac{k}{\mu\beta^*}\right)$, m/s²; k – permeability of the porous medium, m²; μ – absolute viscosity of the medium, Pa·s; $\beta^* = m\beta_p + \beta_c m$ – composite coefficient of volume elasticity; β_p, β_c – volume elasticity coefficient of liquid and solid material; m – porosity of the medium; ∇^2 – the Laplace operator; f – internal source function, km/m³·s – formula (3) [2]:

$$f(x, y, z) = \lim_{\substack{\Delta V \to 0 \\ \Delta t \to 0}} \frac{\Delta G}{\Delta V \Delta t}. \tag{3}$$

The initial pressure at all points of an infinite flat porous medium is the same and equal p_0, and at a point with coordinates (x_0, y_0, z_0), there is a constant source of intensity q (kg/m·s) [2]. Then the function f looks like a formula (4):

$$f = q\delta(x - x_0)\delta(y - y_0)\delta(z - z_0), \tag{4}$$

where $\delta(x\text{-}x_0)$, $\delta(y\text{-}y_0)$, $\delta(z\text{-}z_0)$ – Dirac delta functions [2].

Taking (4) into account, equation (2) has the form – formula (5):

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \delta(x - x_0)\delta(y - y_0)\delta(z - z_0), \tag{5}$$

where $u = p^2(x, y, z)$.

Boundary condition $u_{(-\infty,+\infty)} = u_0 = p_0^2$ [2].

The general solution of the Laplace equation is given by Green's formula [12, 13], which is obtained in the form of the formula (6):

$$u(x, y, z) = p^2(x, y, z) = \\ = \frac{1}{2\pi}\int\int_{-\infty}^{\infty} \frac{z}{\left[(x-\xi)^2 + (y-\eta)^2 + z^2\right]^{3/2}} f(\xi\eta)\, d\xi d\eta, \tag{6}$$

where ξ, η – coordinates of the point where the gas concentration is measured.

By specifying the values of the coordinates in formula (6), the values of the function u are determined, according to which the isobars in the soil are constructed and, accordingly, obtain the coordinates of the point on the outer surface of the pipeline, where the probable source of gas pollution or the place of depressurization of the gas pipeline is located.

For a section of an underground metal pipeline, considering the system probing procedure using an electromagnetic field, it is advisable to apply neural networks similar to the articles where acoustic technologies are used [14, 15].

Since the network implements a continuous function of the goal, with its help, a method of predicting the value of the potentials in special areas on the surface of the pipeline, in which the condition regarding the polarization potential (PP) is violated, is proposed U_P [16]. The main criterion for protecting the pipeline against corrosion is the limit value of the potential difference between the metal and the ground electrolyte, called the polarization potential [16].

The problem of predicting the resource of an underground metal pipeline is reduced to an optimization problem using neural networks and computer modelling methods [17], as well as the quality criterion for the "MG – installation of cathodic protection" system [18, 19].

Similarly, as in works [18, 20, 21, 22], the strength criterion is used, as well as the multiplicative qualitative quality criterion for the MG section, which will be presented in the form of a formula (7):

$$Z_1 = \prod_{i=1}^{m} k_i = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot k_6 \cdot k_7 \cdot k_8 \cdot k_9 \Rightarrow \max , \qquad (7)$$

where k_1 – commercial gain ratio; k_2 – coefficient of the level of competitiveness (competitiveness) of underground metal pipelines; k_3 – coefficient of reliability of MG; $k_4(D_f)$, $k_5(p_S)$, $k_6(\sigma_{ve})$, $k_7(K_S)$, $k_8(T_S)$, $k_9(U_P)$ – coefficients that characterize defectiveness D_f, strength p_S, limit of corrosion fatigue $\sigma_{ve}(N_P)$, the effect of coating on corrosion resistance K_S, period of trouble-free operation T_S (durability) structures (pipes); compliance with the optimal range of polarization potential U_P on determining the place of depressurization of underground pipelines.

The ratio (1)–(7) is the basis of a new mathematical model for modelling a dangerous area's behaviour on the MG's surface and the stages of its development with the help of a neural network. The hazardous area initially looks like a spot. Then, in the process of corrosion, the location turns into a cavern. A crack appears at its top at a specific cavern's size, and depressurization occurs. Depressurization will correspond to the limit values of two determining parameters, $u(x, y, z)$, Z_1, which characterize the critical situation of gas leakage and are determined from ratios (6) and (7).

Determination of depressurization locations and analysis of results based on thermal imaging using computer vision methods

Modern information technologies make it possible to assess, forecast, and obtain detailed analyses based on images or other information. One of the examples is the use of computer vision to detect cracks, which is used in work [23]. There are many thermal imaging images of pipeline damage on the Internet.

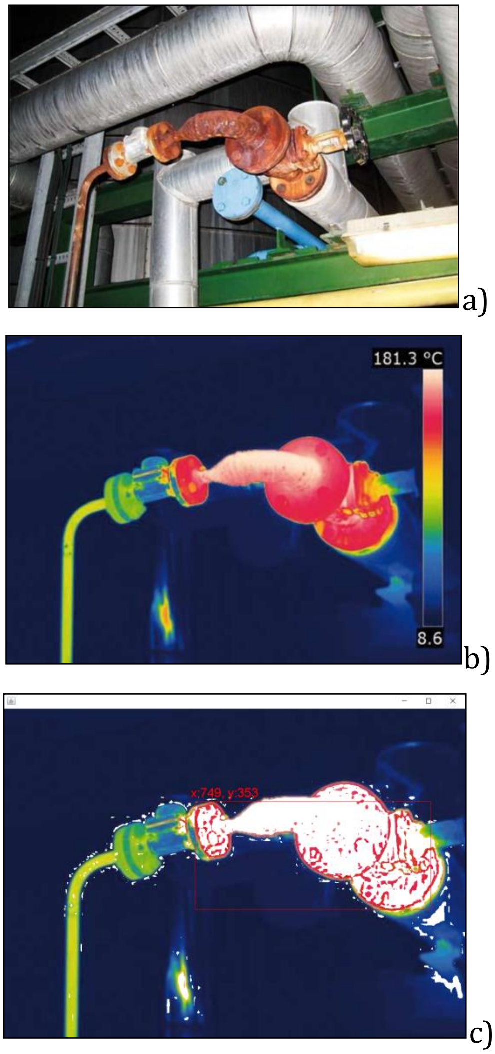
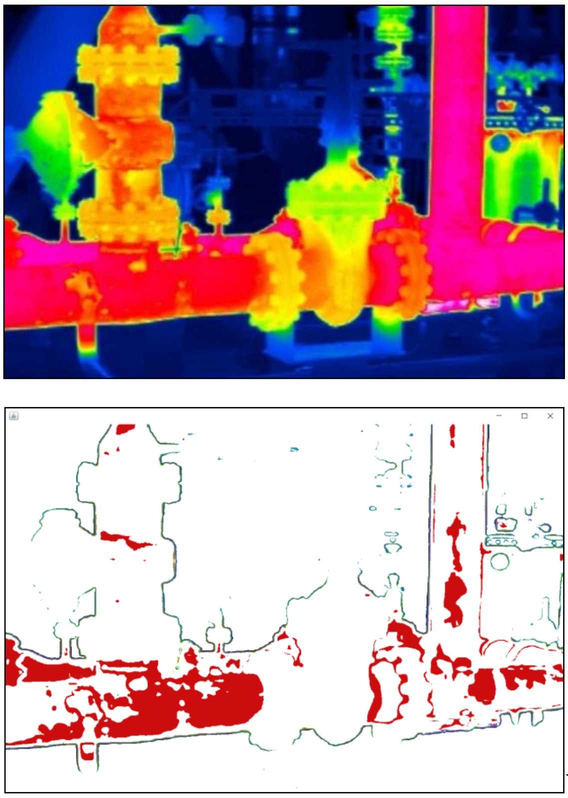


Figure 1 – The process of analyzing a damaged pipeline: a) – the original image of the pipeline [24], b) – the thermal image of the pipeline [25], c) – the processed image of the pipeline

The analysis process uses a thermal imaging device, as in Figure 2b, relative to the original Figure 2a. As seen in Figure 1b, processing the damaged pipeline image can be performed using the selection of specific colours in the thermal imaging image. The textural elements of the image in which the red is the most saturated stand out best. Thus, it can be concluded that the temperature of these elements in such areas is the highest. According to the pixel analysis of the red areas, the percentage of the damaged pipeline is equal to 0.016 of the total image size. The XY coordinates in the image are the centre of the selected rectangle.

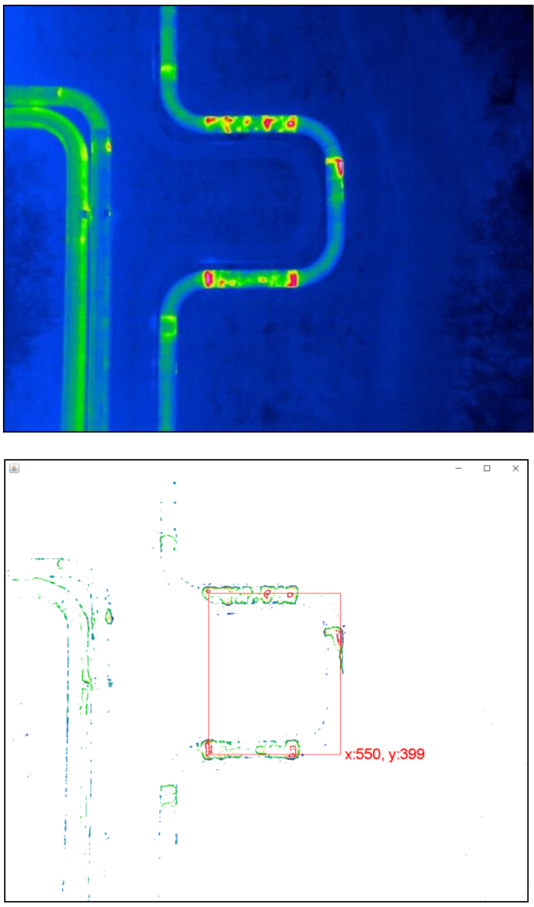


a)

b)

Figure 2 – Detection of pipeline damage in the room:
a) – the thermal image of the pipeline [26],
b) – the processed image of the pipeline

From Figure 2a, it can be seen that most of the pipe is under high temperatures. Potential breakout locations may be in areas with purple and red colours. It is problematic to determine such places visually from the picture. Most areas are smoothed out in a combination of red and purple colours. With the help of colour separation, it is possible to see potential places of depressurization in Figure 2b. Under the same conditions, the processed image contains 8.42% of the pipeline's red areas according to the image's size. Moreover, red spots can be equated to potential damage.



a)

b)

Figure 3 – A damaged pipeline from the aerial survey:
a) – thermal imaging image of the pipeline [27],
b) – the processed image of the pipeline

Figure 3a shows an aerial photo taken from a quadrocopter of a part of the pipeline [27]. As a result, in Figure 3b, the analysis under unchanged conditions highlights the primary damage to the pipeline. As one assumption, it could be depressurization or other types of defects. The red areas in the image are 0.02% of the total image size.

In addition, a specific section of the junction of several pipelines is considered, and the place with the highest temperature is determined.

The highest temperature is observed at the junction of several pipelines in Figure 4a. The developed program determines the location of depressurization or damage at the central point with coordinates (629, 417). The percentage value of the probable damage from the image can be equal to 0.37, considering the amount of red area in the image to the total picture size.

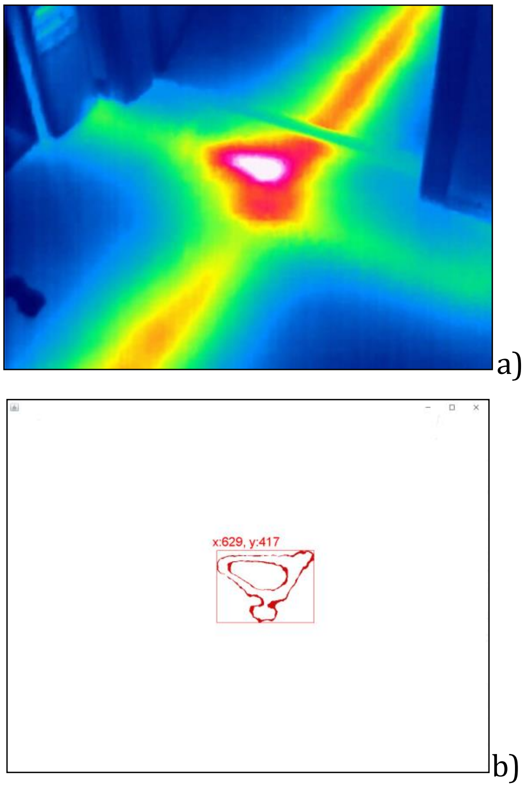


Figure 4 – A damaged pipeline at the junction of several pipes: a) – thermal imaging image of the pipeline [28], b) – the processed image of the pipeline

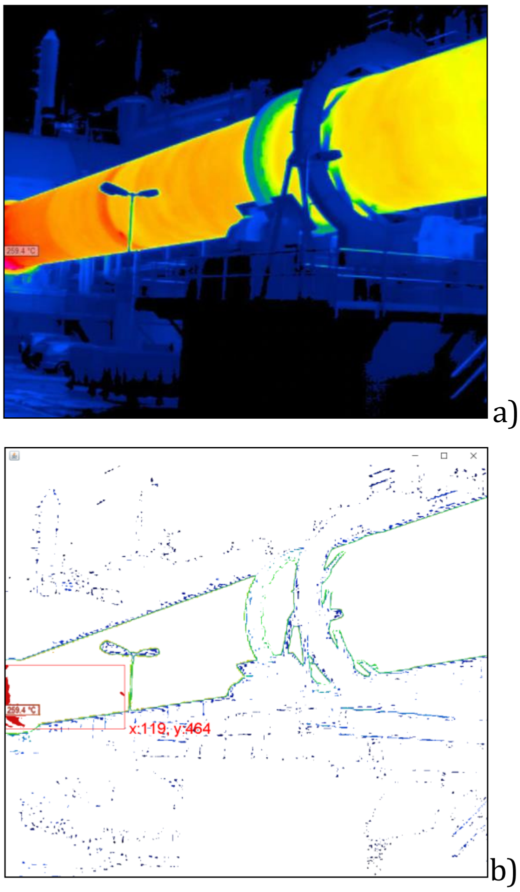


Figure 5 – Pipeline at an industrial facility: a) – thermal imaging image of the pipeline [29], b) – the processed image of the pipeline

In the more industrial section of the pipeline, the highest temperature is observed in the extreme section in Figure 5a. In addition to the potential damage location, several areas are identified that could cause the metal pipe to depressurize. The total damage in Figure 5b is 0.13% of the area with high temperatures to the full image size.

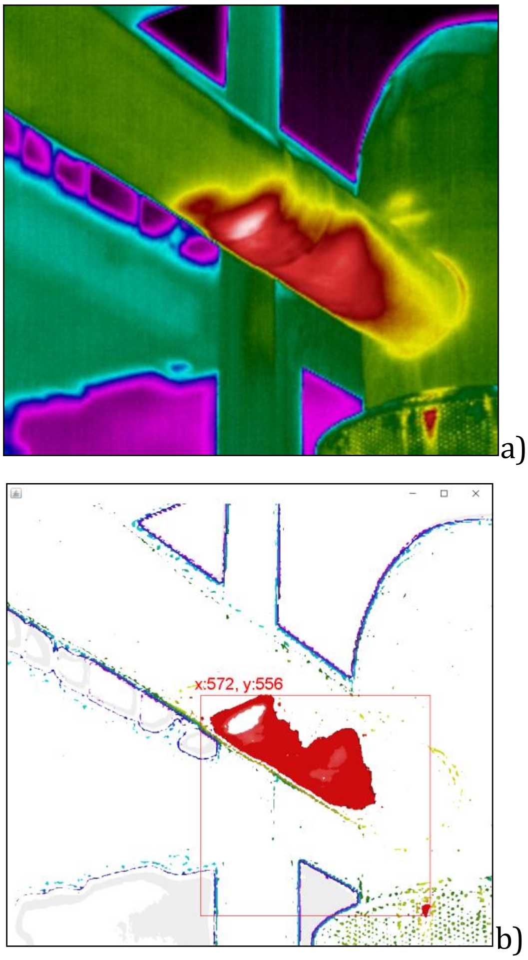


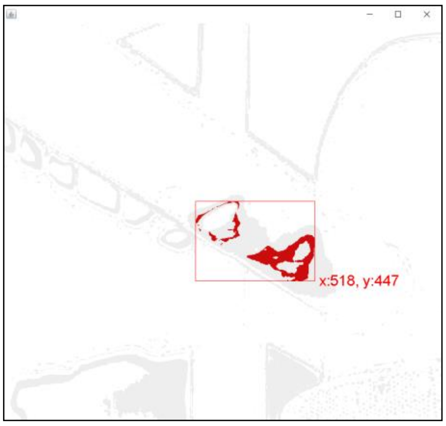
Figure 6 – Analysis of the damaged pipeline: a) – the thermal image of the pipeline [30], b) – the processed image of the pipeline

Figure 6a shows the input image with damage; Figure 6b shows the processed image with identified locations of pipeline damage. In this case, the second condition is excluded to focus attention only on the potentially dangerous area. In this case, the percentage of the damaged red zone to the total image size is 0.81.

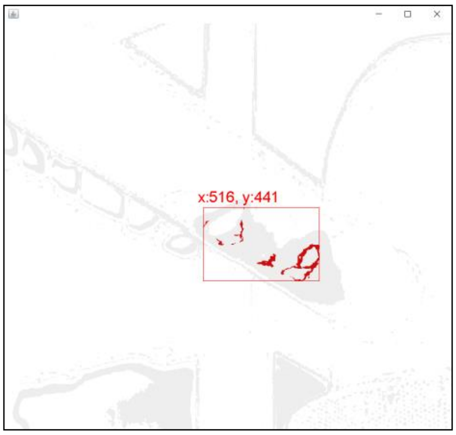
Using Figure 6a, it is possible to analyze the change in the shade of colour by the size of the detected damage. At the same time, unnecessary contours can be made grey by removing the third condition from the program algorithm.

a)

b)



c)



d)

Figure 7 – Analysis of a damaged pipeline with different shades of damage colour: a) – red = 100 and green = 70 and blue = 70, b) – red = 150 and green = 100 and blue = 100, c) – red = 200 and green = 50 and blue = 50, d) – red = 210 and green = 50 and blue = 50

Figure 7a highlights the crack coverage area, which is the largest and is equal to 5.6% of the image size. Moreover, it constantly decreases with the change of colour in condition 1 of the described algorithm.

When changing the colour to RGB (150, 100, 100), the selected damage area is reduced to 4.3% of the image size, and when RGB (200, 50, 50) – 0.8% of the image size. The contours of potential damage stand out visually better in Figure 7d for the RGB (210, 50, 50) combination. In this case, the damaged area is 0.246% of the image size. Therefore, it can be assumed that the coordinates of the centre decrease according to the smaller number of points for a more saturated colour.

In investigating depressurization, an analysis is performed based on six thermal images using computer vision. The XY coordinates of the centre of damage are determined relative to images with selected areas of increased temperature based on data on the location of pixels in the picture.

Thermal imaging can show microcracks and other defects that are often overlooked but can be highlighted on objects using computer vision.

The following regularities are noticed. The place with the most significant saturation of a red colour can be considered the central damage place.

At the same time, the places highlighted in purple should be considered because, according to the temperature scale on some thermal images, these areas have an even higher temperature.

The main place of burning during depressurization can be placed with white colour on the thermal imaging image. In addition, the percentage of pixels highlighted in red relative to the total size of the thermal image can be considered to estimate the damaged area.

Formulated dependences of strength criteria and other information indicators can also be considered when examining the pipeline's damaged area.

CONCLUSIONS

1. An analysis of the analytical ratios characterizing the gas leakage and the quality of the system “main pipeline – installation of cathodic protection” is performed. Also, a set of informative parameters for determining the place of gas de-

pressurization on the surface of an underground metal pipe and an expression for evaluating the change in gas pressure after cracks have formed. In addition, a neural network method has been developed for predicting the stages of the transition of a corrosion cavern into the limit state, the appearance of a crack at the top of the cavern, and the transition of a crack into a critical state.

2. The places of degassing of pipelines are analyzed based on thermal imaging using computer vision methods. The main dependencies are described when the locations and area of damage are determined based on processed images. At the same time, more saturated colour can be used to detect a more precise placement of damage to the pipeline.

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