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DIAGNOSTICS OF OIL LEAKS CAUSED BY MALICIOUS DAMAGE TO THE LINEAR PART OF OIL PIPELINES: INNOVATIVE SOLUTIONS FOR THE OIL INDUSTRY

Summary. *The purpose of the study is to develop an experimental model of the oil leak detection system along the controlled section of the pipeline. The leak detection system should prevent not only material damage caused by attackers but also major disasters. Preliminary analysis of leak detection methods and principles of operation of hardware and software security diagnostics of the state of pipe transport networks has been considered. A method of studying experimental data and presenting results has been developed. Different literature sources have been analyzed, these literature sources provide information about real cases of pipeline system diagnostics and leak or defect detection. The software and hardware part of the control systems for conducting checks along the control part of the pipeline have been developed. It has been established that the proposed system has advantages in terms of the "quality–price" ratio, speed, and durability over existing systems using methods based on negative pressure waves. The prospect of further research in this direction is the determination of damage and losses for the oil industry as a result of malicious damage to the linear part of oil pipelines.*

Key words: *oil industry, oil leak detection system, negative pressure wave method, registration of mechanical effects on the pipeline, losses, innovative solutions.*

Introduction. In the field of pipeline transport, it is necessary to include: ensure reliable and safe functioning; to support the defense capabilities of the state; coordinate scientific research, search, design and construction, expert and other engineering works and services; to promote the reconstruction and modernization of existing facilities, equipping them with modern, efficient equipment, automated accounting and control systems, etc.; compliance with environmental safety of pipeline transport [1]. The high cost of oil and oil products, the constant high demand for them, as well as the considerable length of the oil pipeline, caused a surge in such a negative phenomenon as the removal of these products from the oil transportation system. Among all the variety of criminal offenses committed in the oil and gas industry, the main place is occupied by the theft of oil and oil products [1], which are committed during their transportation through main pipelines, by damaging the latter [2]. In addition, the equipment of the main pipelines has been operated for more than 40 years, that is, the term of operation of this transport system has expired. Therefore, the development of methods for predicting oil losses in accidents, the introduction of measures to reduce and prevent cases of depressurization of pipelines, the introduction of a leak detection system into the production process, the reduction of oil loss volumes, and the minimization of material and financial costs for the localization and elimination of emergencies will serve to increase the efficiency of a functioning system of trunk oil pipelines, their environmental and technical safety. Accordingly, the research of methods and means of detecting leaks along the controlled section of the oil pipeline is an urgent problem.

Review of information sources. A review of literary sources allows us to state that the most effective way to control the technical condition of the linear part of oil pipelines is intra-pipe diagnostics [3; 4]. Let's highlight the methods based on pressure/flow monitoring. It uses leak detection techniques that monitor routine production data such as inlet and outlet pressure and flow rate. Any deviations from the operating conditions are analyzed to determine whether these deviations may be an indication of a leak.

A leak monitoring method was proposed, it was supposed to be based on wavelet analysis that detects singularities in reflected pressure waves in case of an anomalous event (Z.-D. Xu, C. Zhu, L.-W. Shao) [5]. Wavelet transform algorithm and wavelet thresholding algorithms [5] were used in combination with a negative pressure wave (J. Li, Q. Zheng, Z. Qian, X. Yang) [6] to achieve high accuracy when calculating the leak location. Standard pressure transmitters are not reliable in the presence of low-quality signals and small pressure changes. To overcome this limitation [6], the use of a dynamic pressure transducer was demonstrated, it has higher sensitivity and positioning accuracy for rapidly variable leak detection.

A fuzzy clustering algorithm (P. D. Ndalila, Y. Li, C. Liu, A. H. A. Nasser, E. A. Mawugbe) [7] on noise absorption data was used to detect leaks and defects and achieved an accuracy of up to 95 % in field tests. In a study of the performance of a vibroacoustic pipeline monitoring system based on the principles of negative pressure wave (NPW) (K. Ling, G. Han, X. Ni, C. Xu, J. He, P. Pei, J. Ge) [8] and statistical (M. Marino, F. Chiappa, G. Giunta) [9] analysis, the sensitivity and performance of the system were improved and a localization accuracy of approximately 25 m at a distance of up to 35 km from the sounding point was obtained. The problem of leak detection from the perspective of fluid mechanics [9] was studied and the change in pressure at the inlet and the total flow rate at the outlet as indicators were considered. It was found that the change in inlet pressure is sensitive to both the size of the leak and the location of the leak.

Another multiphase flow study (C. J. Thiberville, Y. Wang, P. Waltrich, W. C. Williams, S. I. Kam) [10] also proved that upstream pipeline pressure is a critical indicator for leak detection, even when the size of the leak is small and downstream flow velocity acts as the dominant leak indicator. To detect two-point leaks based on fluid and pipe parameters in parallel piping systems (M. A. Adegboye, A. Karnik, W.-K. Fung) [11], a method was proposed based on the analysis of flow parameters with a combination of CFD modeling and experiments by determining the relationship between pressure drop, leak location, and flow velocity.

A single leak detection mechanism cannot exclusively monitor the entire pipeline network due to certain limitations in the application of each method and due to the properties of the oil transported through the pipeline. There are many scenarios for a leak in a pipeline, such as multiple leaks, the location of the leak, and the size of the leak (A. A. Vladimirsky, I. A. Vladimirsky; V. Y. Grudz) [12; 13]. It is worth noting that the fusion of two methods based on different operating principles allows the detection of leaks with higher accuracy.

Most external methods detect and determine the location of the leak with greater accuracy, but they cannot determine the rate of the leak.

Many companies provide services for non-destructive testing and technical diagnostics of main oil pipelines for pumping oil.

Among them there are world-famous companies [14–19]: 1) ICP DAS (USA); 2) the Japanese company Yokogawa; 3) Schneider Electric; 4) Enduro; 5) BJB Company; 6) Pipeline Inspection Company; 7) GE Oil&Gas PII; 8) Inline Services and Pipeline Cleaners; 9) Ukrtransnafta; 10) ROSEN; 11) "Elesi".

For example, the Elesi company has developed its leak detection system based on the pressure-flow method, which involves the installation of pressure and flow sensors. The basis of the system's operation is the principle of recording the release of wave fluctuations of pressure/flow along the controlled section of the pipeline. When a leak occurs, a combination of two methods is used: a modified method of negative pressure waves and an interference method for separating the nature of pressure fluctuations. As a part of the mathematical model and pressure signal processing algorithms at the middle and upper level of the system, methods of noise compensation, which appear due to the operation of the pump and taking into account the location of the leak, are implemented.

Design characteristics of the system for this facility: the minimum value of the detected leak is $2\,\frac{m^3}{h}$; detection accuracy: ±500 m; detection time no more than 5 min.

This system has certain disadvantages. In particular, the primary sensors need to be placed at distances of no more than 30 km, the leak detection time is long enough for such distances. One of the disadvantages is also the high cost of this system in general for the pipeline, caused by the small range of placement of sensors and the integration of the SCADA Infinity software complex. At the moment, the Japanese company Yokogawa is also one of the leading companies in the world in providing services related to the leak detection system along the pipeline section. The development of Yokogawa's leak detection system was prompted by the Japanese Government's ban on transporting products by pipeline without detecting leaks and defects in the pipeline section to protect the environment. This system has certain advantages, but it also has disadvantages.

The advantages are the reduction of the load on the environment due to the avoidance of soil pollution, the amount of detected leakage is low, compared to its analogs, also, the wireless pressure and temperature sensors are implemented. Since the system was developed primarily to preserve the environment, that is, to control a large number of parameters, it is also quite expensive. The characteristics of this system are as follows: the minimum value of the detected leak is $1\ \frac{m^3}{h}$; detection accuracy: ±300 m; detection time no more than 3 min.

The main disadvantages of the system are the difficult integration into the automation of the pipeline operation since the modules developed by the Yokogawa company must be installed for the system to function, and the high cost of the installed modules.

Concluding the review, it can be noted that, in general, a large number of methods (N. V. S. Korlapati, F. Khan, Q. Noor, S. Mirza, S. Vaddiraju) [20] can be used as a basis for the technology of detection and localization of leaks. To navigate this population, scientists provide various classifications. One of these classifications is based on the division into external methods, internal (A. Rai, J.-M. Kim) [21] or computational (computer-based) methods (B. Koman, O. A. Balitskii, V. Yuzevych) [22], and control methods taking into account internal stresses (M. A. Adegboye, W.-K. Fung, A. Karnik) [23].

Internal leak detection methods work based on a model or algorithmic principle that declares control of flow parameters in real-time.

External leak detection methods work on the non-algorithmic principle of physical detection of leaking oil using special external sensors (S. Kumar Vandrangi, T. Alemu Lemma, S. Muhammad Mujtaba, T. N. Ofei) [24].

Visual or inspection methods do not monitor flow parameters in real-time. Instead, they are scheduled at regular intervals and performed by humans or trained canines for visual inspection on land, robots for inspecting underwater pipelines, and aerial inspection devices (A. B. Lukonge, X. Cao) [25] for aerial surveillance.

Although there is a wide range of leak detection methods available, the goal of detecting and locating leaks is usually achieved by a combination of external, visual [26], and internal methods [27].

Along with that, it is also worth noting the scientific research: N. Repianskyi, T. Rak [28], H. Fu, L. Yang, H. Liang, S. Wang, K. Ling [29], T. Toosi, M. Sirola, J. Laukkanen, M. Van Heeswijk, J. Karhunen [30], L. Yuzevych, R. Skrynkovskyy [31], V. Lozovan, G. Pawlowski, M. Yasinskyi and other scientists [32].

All these aspects are also presented and published in a scientific article by scientists: A. Obshta, Y. Biliak, V. Shugai [33].

Based on the review of literature sources [1–33] and products of leading companies manufacturing leak detection systems, it can be stated that research on this topic remains relevant, as advances in computer technology allow for the development and implementation of more effective pipeline leak detection algorithms.

Setting Objectives. The purpose of the study is to develop an experimental model of the oil leak detection system along the controlled section of the pipeline. The leak detection system (LEDS) should prevent not only material damage caused by attackers but also major disasters.

It is necessary to create software and hardware that will be able to carry out constant monitoring to detect leaks. The system should have the following properties: high sensitivity; high accuracy of leak location detection; ensuring control of long pipelines; the ability to work in all pipeline modes; high degree of reliability, reliability, and efficiency of the obtained results; to be safe in operation.

The main task is to reduce the length of the defect segment to save the time of going through a long distance to find an actual defect. The reduced resulting length should be no more than ±300 m.

The mathematical model of leak detection is based on the basic equations of hydraulics: mass movement of oil under pressure, continuity and state. Iterative methods can be used to calculate the coordinate of the leakage point. These methods are the basis for the development of a computer system.

Results and discussion. An experimental leak detection system has been developed, which is not inferior to the characteristics of detecting the location and volume of the detected leak and is much cheaper than similar systems operating in Ukraine.

The leak detection system is a distributed control system consisting of a large number of modules for different purposes. Some of the modules function on dedicated servers, some on the workstations of company employees, and some on the workplaces of security service employees. Dedicated servers may be required for modules such as the database and sometimes for information analysis modules.

At the same time, a multiprocessor system was used to ensure the speed of the system and to calculate the results of the detection of the leakage point, the estimation of the magnitude of the leakage reading, and data transmission. In this case, the shared memory MIMD multiprocessor architecture is used. Data in such a system that was recorded by one processor becomes publicly available to others. Accordingly, it is not necessary to spend a lot of time on data transfer. For such an architecture, software writing is simplified, and several computational threads are created, which ensures faster data processing [33].

The general structure of data collection by the leak detection system and transmission to the central control center is shown in Fig. 1 [33].

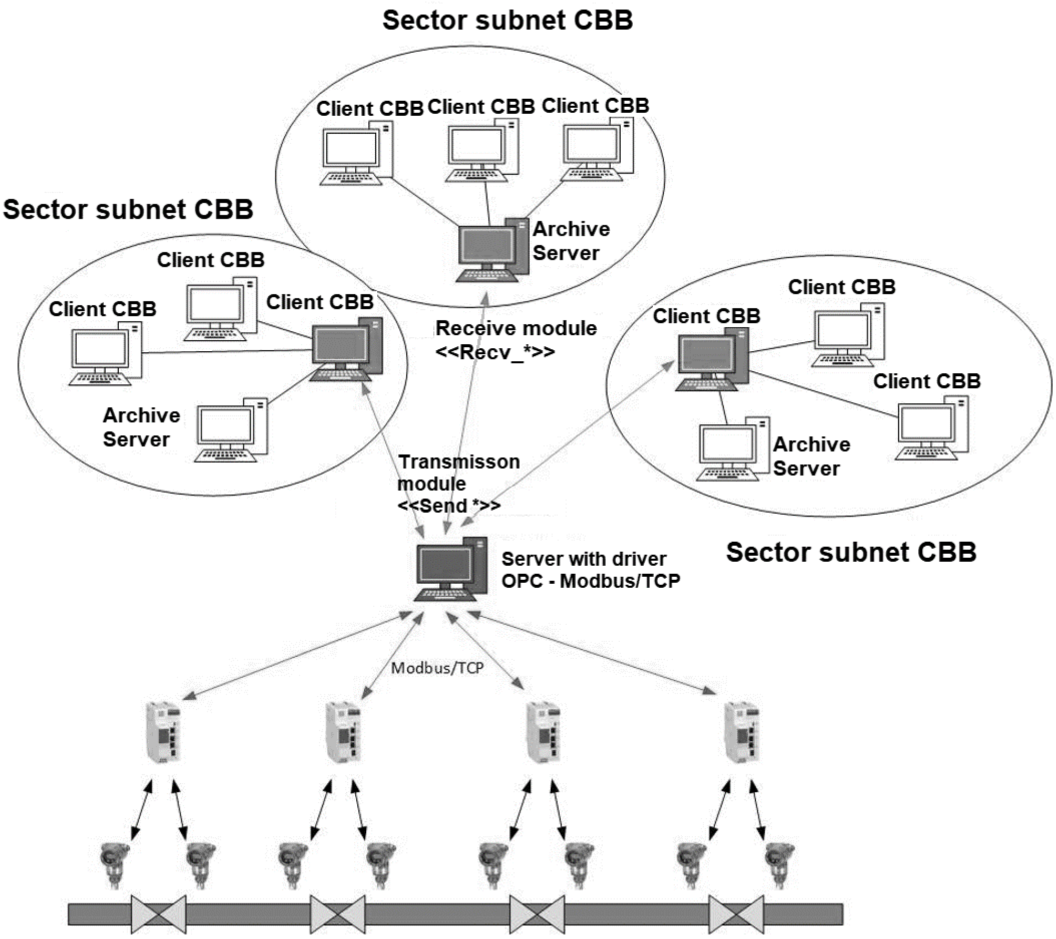

Fig. 1. General structure of data transfer

Source: [33]

Our software was developed similarly to client-server architecture (N. Repianskyi, T. Rak) [28], which is placed on servers in the data center and performs a centralized collection of information from all automation cabinets and synchronizes their work. Synchronization accuracy is no more than 10 ms. The periodicity of data collection from all primary converters is no more than 50 ms.

The data transmission algorithm has the following form (A. Obshta, Y.

Biliak, V. Shugai) [33]: 1) Pressure sensors are connected to the programmable logic controller (PLC); 2) the PLC receives data from the pressure sensors and stores the data in the PLC memory in the corresponding buffer every 50 ms. The buffer has a set of such data for 5 s; 3) polling of all PLCs is performed by the system polling server using a specialized OPC-Modbus/TCP driver using the Modbus/TCP protocol. The polling period of one PLC should not exceed 5 s; 4) on the survey server side, a software module is launched to transmit data received on a specific oil pipeline, which reads operational data of the OPC-Modbus/TCP driver and transmits it to a specific IP address; 5) on the archive server side, a software module is launched, which receives data from the survey server and stores the data in the appropriate directory for the archive; 6) the local client reads data from the network directory of the archive server. On the local client, the main application and the graph viewer are launched. Oil spill processing and decision-making are performed by the local client. When an event occurs, a corresponding event appears on the main screen with an indication of the area, the location of a possible oil leak, and a sound message appears.

The Schneider Electric Modicon M340 module is used as a processor module. It supports Modbus TCP protocol operation and has an internal RAM of 4096 KB. Modicon M340 does not create environmental pollution (noise, emissions), which requires special precautions in standard use. The consumed electricity depends on the conditions in which the product is sold and used. The electrical power consumed by the Modicon M340 ranges from 10 W to 50 W. In active mode, it is 21.6 W. The cons of this module include its low operating temperature, which should be in the range from 0 °C up to 60 °C. In the case of its use in field conditions, it has to be additionally protected from weather conditions. The proposed system uses a 4-core Intel processor, namely Celeron N3160. All its characteristics meet the needs of the system. The processor belongs to the generation of Braswell processors, it has an operating frequency of 1.6 GHz, a level two cache of 2 MB, and a maximum core temperature of no more than 90 °C. The processor has a built-in Intel HD Graphics (Braswell) video card, which has 8 GB of video memory, and a maximum video core frequency of 640 MHz [33].

RAM SODIMM DDR3L has also been used. 2 modules of 4 GB are integrated. The OP used has a frequency of 1600 MHz and a supply voltage of 1.35 V. Asus Z10PE-D8 WS was used as a motherboard because it fits all the nodes listed above and is optimal in size. This board supports the connection of eight RDIMM/LR-DIMM/NVDIMM DDR4-1333//2133 RAM modules and the selected processor. The input/output interfaces required for the system are also used, i.e., COM-ports: 2, RS 232/422/485: 2. These nodes are assembled in an industrial protective unit that will ensure the operating temperature from -25 to 60 °C [33].

To ensure continuous operation and stability of the system, the Windows Embedded operating system was used, this made it possible to ensure autonomous operation of the application since this system has a mechanism for intercepting system messages and allows to create devices without a monitor, mouse, and keyboard. It is also possible to enable the Enhanced Write Filter (EWF) and File Based Write Filter (FBWF) components. EWF allows to protect the system partition from writing and prevent interference with the embedded system. FBWF enables protection of individual files and folders and thus leaving access to the folders to which you want to write files while protecting the system folder [33].

An RS-232 to RS-485 converter, namely the I-7520, was used to increase the speed and range of data transmission, as well as to use the ICP DAS ADC to ensure smooth operation. The characteristics of the converter from RS-232 to RS-485 are given below.

Although widely used, RS-232 has limited transmission speed, range, and network capabilities. RS-485 standards overcome these limitations by using differential voltage lines for data and control signals that transparently convert RS-232 signals to an isolated RS-485 signal without the need for hardware or software changes [33].

Characteristics of the ICP DAS I-7520 converter [26]: 1) input DC supply voltage: +10 V ~ +30 V; 2) power: 1.2 W; 3) data transfer rate: 300 ~ 115200 bps; 4) operating temperature -30 ~ +75 °C; 5) humidity: 10 ~ 90 %; ports: 1 x RS-232, 1 x RS-485 output. Features of the ICP DAS I-7520 converter [26]:

- Automatic RS-485 Direction Control;
- ESD Protection for the RS-232/422/485 Data Line;
- 3000 VDC Isolation Protection on the RS-232 side;
- Transmission Speed of up to 115200 bps.

ICP DAS model I-7080 pulse converter was also used [34]. Features of the ICP DAS I-7080 converter [34]:

- 2 Counter/Frequency Inputs;
- Supports 32-bit Counter;
- Isolated or Non-isolated Input;
- Programmable Alarm Output, Digital Filter and Threshold Voltage Level;
- Maximum Frequency of up to 100 kHz;
- Built-in Dual Watchdog.

The ICP DAS I-7017 ADC has all the necessary characteristics for system operation. It also has a fairly large range of operating temperature and humidity, which is an indisputable advantage over its analogs for use in field conditions. Features of the ICP DAS I-7017 converter [27]:

- 8 Differential, or 6 Differential and 2 Single-ended Analog Inputs;
- Voltage and Current Inputs;
- High Resolution: 16-bit;
- Open Wire Detection for 4 ~ 20 mA;
- Built-in Dual Watchdog.

The diagram of the leak detection system along the controlled section of the pipeline is shown in Fig. 2 [33].

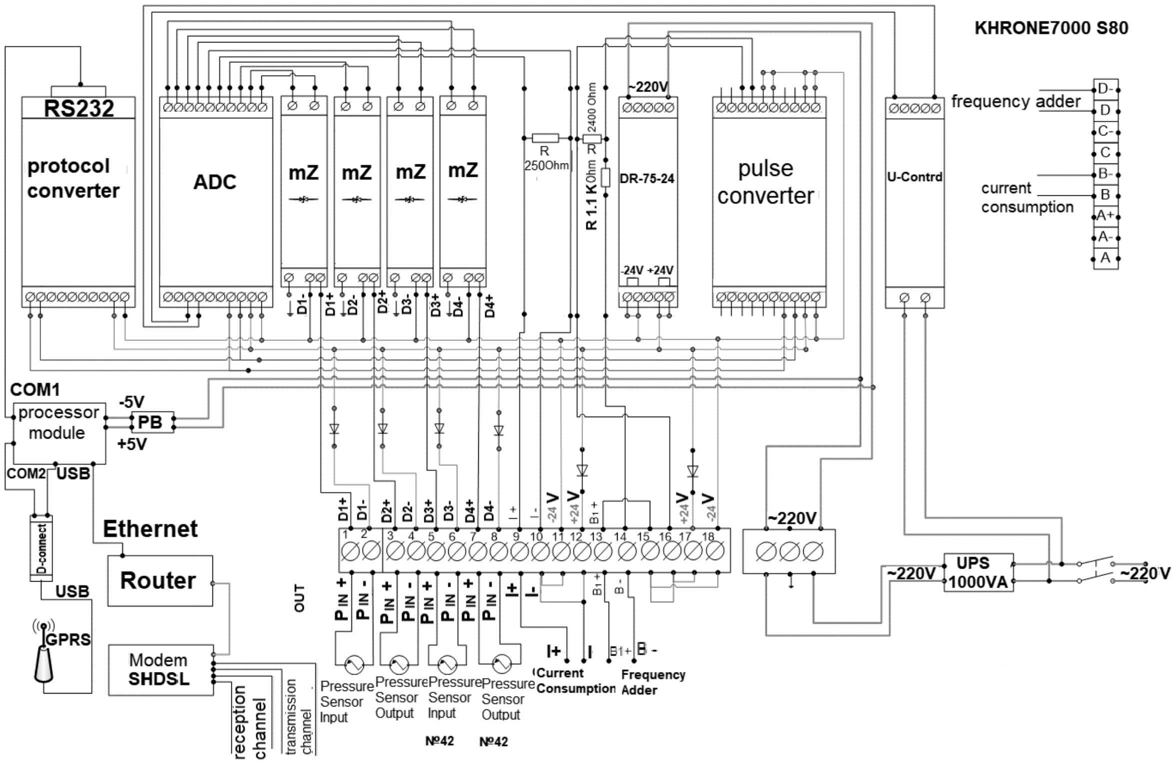

Fig. 2. Functional diagram of the control station of the leak detection system along the controlled section of the pipeline

Source: [33]

The developed experimental leak detection system along the pipeline section differs from existing analogs in architecture and leak detection algorithm. A software for this system using C++ is developed. The program ensures the necessary speed and correct operation of the leak detection system. It was possible to develop a program that can fully control all processes that occur in the system and memory.

The following occurs in the program part of the system [33]:

On the client of the defect detection system, a specialized algorithm of the parametric system is implemented, which analyzes the data of the oil pipeline section for the specified time from 25 s to 30 min, depending on the client's settings (25 s, 7.5 min, 15 min, 30 min). A larger value of the period is better for stable stationary pumping of oil without a mode change.

The program in real time calculates the change in pressure at each sensor and displays the wave of the change in pressure along the section of the oil pipeline. Algorithms for averaging the initial and final pressure values are used to reduce the impact of oil pipeline noise.

For a specific section of the oil pipeline, the values of boundary lines are selected to determine leaks. This parameter depends on the noise of the oil pipeline and the influence of other noises.

The transition of the spline beyond the first limit line indicates that a possible oil leak has occurred. The location of this leak will be determined by the minimum point of the spline.

The transition of the spline beyond the second boundary line immediately indicates a possible oil leak.

Each leak must be checked by the trend viewer program, or through the "playback" that is in the main SBB program (for this, another SBB program is launched – automatically in the mode for viewing archive data).

In the "playback" mode, it is possible to change both the time settings and the viewing speed. The maximum speed allows you to view hourly data per minute [33].

An example of the main program is shown in Fig. 3.

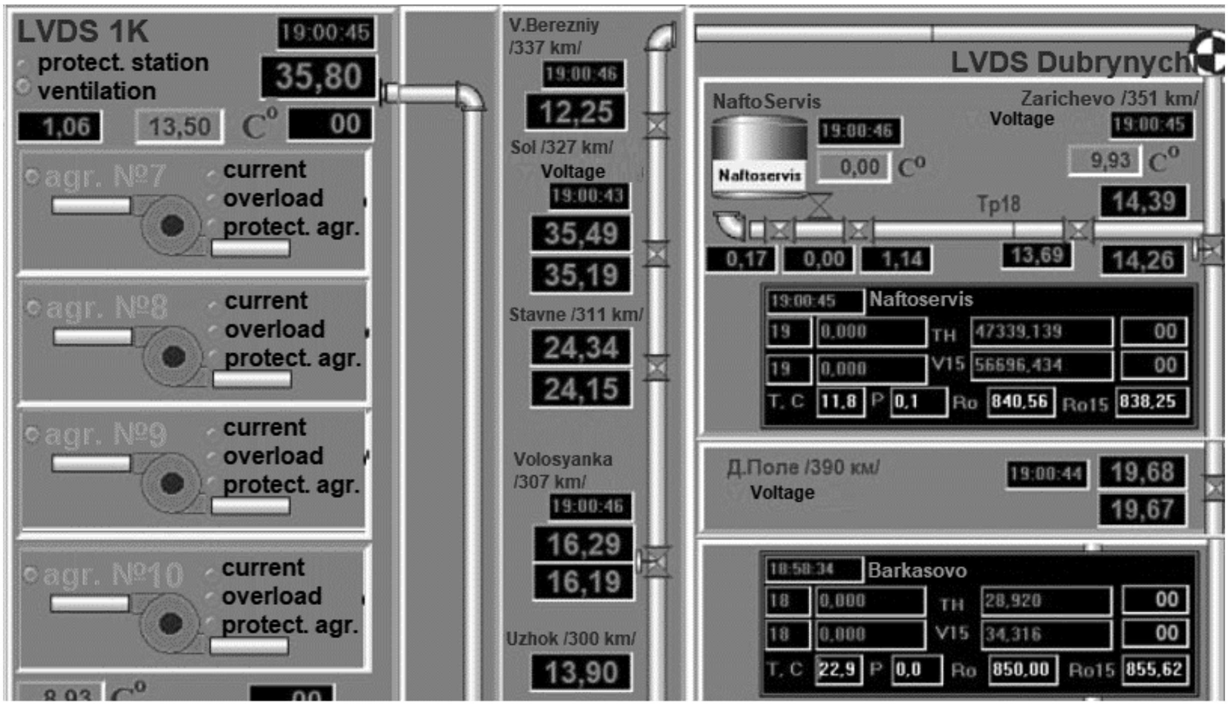

Fig. 3. Presentation of the results of the detection of pipeline section leaks in normal mode

This program displays the values of the pressures before and after the valve at each control point. At some points, flow meters are installed to determine the flow of oil when a leak is detected. If a certain station fails, it will be provided with an additional power source, and a message will be displayed above the pressure data.

Certain aspects presented above, as well as calculation and evaluation of system test results presented in a scientific article by A. Obshta, Y. Biliak and V. Shugai "Cyber-Physical System for Diagnostic Along the Controlled Section of the Oil Pipeline" [33].

Conclusions. Based on the research results, the article presents the development of an experimental model of the oil leak detection system along the controlled section of the pipeline. It has been established that the proposed system has advantages in terms of the "quality–price" ratio, speed, and durability over existing systems using methods based on negative pressure waves. As a result of the tests, it was established that the proposed operational control system for detecting oil product leaks along the pipeline section can be used in the field of main pipeline protection system.

The prospect of further research in this direction is the determination of damage and losses for the oil industry as a result of malicious damage to the linear part of oil pipelines.

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