Using system analysis methods to search for coolant leaks in order to develop an automated information system for dispatch control of a heat generating enterprise

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Abstract. The modern variety of methods for diagnosing the condition of a heat conduit requires a systematic approach and structuring. The methods classification based on the IDEF0 methodology for analyzing the technical conditions of the pipeline and the requirements for their implementation are proposed. Modern methods and technologies for searching coolant leaks are considered, the use of which is possible outside of hydraulic tests and changes in transportation technology. The proposed options for expanding existing software and hardware are considered and trends and prospects for their future development are identified.

1. Introduction
According to the Ministry of Energy of the Russian Federation for the period until 2018, the depreciation of fixed assets of heat supply rose up to 70 percent. Losses in heating networks increased from 14 to 20 percent. The causes of heat loss include imperfection of metering systems, technical leaks caused by emergency situations, damage, wetting of heat-insulating material in the sections of highways and ambient temperature [1,2]. As a result, a negative economic effect, a violation of the technological process of transportation and the quality of thermal energy. The energy strategy of the Russian Federation for the period until 2030 defines a long process of technical re-equipment and modernization of the heat and power complex (FEC). At the moment, one of the ways to increase the efficiency of the fuel and energy complex is to solve the problem of developing and implementing operational methods for localizing emergency sections of highways. It is also noted that the conduct of mandatory hydraulic tests carries a number of negative effects on the functioning of the heat supply system. The development of non-destructive testing means can reduce the duration of work and the load during the crimping of the nodes of the heating network.

2. Statement of the problem
The criterion for the efficiency of a production heat and power enterprise is the observance of technological processes and their continuity. With regard to the transportation of thermal energy – technology, quality, delivery time are strictly defined at the level of legislative acts and regulatory documents, which is why a critical requirement for diagnostic methods of energy networks will be the ability to work effectively without interference in technological processes.

When considering methods for diagnosing heating networks, it is customary to use the following classification [3,4]:

- Methods based on hardware solutions. These include hardware implementations of non-destructive testing methods, including means for converting physical quantities, analogue-to-digital conversion, and a signal processing unit. The main practical application was received by the methods of acoustic emission, echo, vibration diagnostics and thermal imaging.
• Methods based on software solutions. Systems based on data analysis algorithms, data SCADA-systems;
• Expert methods based on the individually-professional qualities of technical personnel.

At the current level of information technologies, the presented classification does not reveal all the features offered by the market and the scientific community of solutions and approaches. Modern means of storage, processing and transmission of information offer great computational capabilities and open up new prospects for the use of complex mathematical models and methods for solving the problems of coolant losses during its transportation. The introduction of intelligent technologies significantly expands the possibilities of using existing hardware solutions used at energy companies.

3. Experiment Results
The process of diagnosing the state of heat transfer systems is presented in the IDEF0 methodology in figures. 1 and it is reduced to 3 main stages.

Figure 1. Pipeline diagnostics in the IDEF0 methodology.

• Conversion and registration of physical parameters of the diagnostic object. The main requirements are operating ranges, sensitivity, noise reduction, noise immunity of recording instruments - sensors.
• Conversion and storage of data.
• Methods of data analysis.

The general characteristics of leak detection systems and requirements during their implementation can be formed using the top-level decomposition diagram of the IDEF0 methodology presented in figure 2.
Entrance – type of recorded physical quantities: Acoustic signals, vibration level, temperature, pressure, flow rate, etc.
Mechanisms – The method of conversion of physical quantities - determines the registration method, the quality of the received data. When introducing the system into the production process is an important economic and high-cost component. It is described by cost criteria for scalability, maintenance, and service lifecycle.
ADC is a method of analog-to-digital conversion. Describe by the criteria of bit depth and discretization. The quality of digitized information will directly affect the applicability and effectiveness of mathematical processing methods.
Mathematical methods – determine the applied intelligent technologies and methods of data analysis.
Control. Defines security restrictions for connecting physical quantity converters and computing resources of a data analysis system.
Development and implementation in production of instrumental solutions (physical quantity converters), such as modern high-tech physical quantity converters - pressure, humidity, flow sensors, acoustic, vibration, etc. are a direct extension of the functionality of non-destructive testing hardware platforms (acoustic methods, vibration diagnostics, thermal imaging, etc.). In turn, the emergence of new effective instrumental solutions determines the requirements for the implementation of software methods.
Such solutions are presented in the form of thermoelectric heat flow sensors or autonomous vibration sensors [5]. The latter offer great opportunities for the automation of early prediction and monitoring systems in real time.
The instrumental solutions also include the technology of laying the pipeline with polyurethane foam insulation and an integrated cable of the operational-remote control system (SODK). This system allows monitoring the state of the network over the entire length of the heating network. The technology involves the use of a signal cable to measure insulation moisture by means of monitoring
resistance changes. Despite the high prospects of SODK, the violation of the technology of manufacturing, transportation, installation of pipelines with PU foam insulation is criticized, which can minimize the effectiveness of this technology. In addition, the principle of humidity monitoring used does not accurately localize the accident site. Further development of the technology can be carried out in the implementation of a hardware-software complex with the use of additional humidity sensors along the network section [6], which will help to solve the problem of accurately determining the location of damage to the pipeline.

The most widespread in the issue of localization of the place of leaks in pipeline valves was the contact acoustic diagnostic method. At the same time, software-based solutions based on data mining are developed on its basis. Artificial neural networks are used to automate the process of linear diagnostics and localization of emergency sections [7,8]. Methods of time-frequency correlation analysis have been developed [8]. Solutions are proposed to reduce the number of false positives of systems using the acoustic monitoring method by aggregating several data mining methods. In this case, systems of automatic control and metering of energy can be a relevant solution.

A promising direction is also the application of the method of vibration diagnostics. Experimental studies [9] of monitoring water supply systems suggest that it is possible to develop automated systems for early prediction of leakage by monitoring vibration. The initial results were based on the calculation of standard deviations of the acceleration vectors. As in the case of the acoustic method, the further development of the method of vibration diagnostics and its automation comes down to an effective software implementation of filtering and analysis of signals (data).

Effective use of infrared (thermal) aerial photography in regions with a dry climate is noted when searching for leaks in water supply and sanitation systems [10]. Based on IR thermography, leak classification algorithms are proposed. The approach is based on the concept of digital image processing [11]. Despite the insignificant study and scientific interest in this area, solutions for passive monitoring of the state of the pipeline are being developed [12,13]. In addition, infrared aerial photography can be effectively used to search for funnels and soil failures, pavement due to blurring by sources of leakage of heat and water supply systems [14].

Lately, the concepts of energy distribution and metering in “Smart Grids” [15], which include a complex for monitoring the state of equipment of the fuel and energy complex, have been actively developed. The general principle of operation of sensor networks is presented in Fig. 3. Development of modelling techniques for topologies of wireless sensor networks capable of working in various communication standards [16]. At the same time, questions of preliminary information filtering and optimization of operating modes are considered in order to solve the problems of energy consumption of wireless systems [17,18]. Based on wireless information transfer systems, solutions are proposed for detecting emergencies in a small segment [18]. As part of a subnet consisting of several physical sensors with wireless transmitters installed, information is collected. Using the methods of supporting vector methods, naive demonic computing and the K-nearest neighbour, a decision is made on the state of the fuel and energy complex node.
Figure 3. Sensor Network Diagram.

It is worth noting that network solutions are extremely effective for the rapid collection of status information and the use algorithms that work in real time. In the practical application of non-destructive testing equipment, the best result is achieved by applying several methods. In fact, this is due to the aggregation and processing of information of various types.

In the context of the proposed classification, we consider the method of the time-frequency correlation analysis in the problems of determining the coordinates of leaks in pipelines [8] Tab. 1.

| Table 1. Evaluation of diagnostic methods. |
|-------------------------------------------|
| Input                           | Conversion methods | Mechanism            | Control         |
| Acoustic signal                  | Contact, linear    | High resolution      | Safety conditions |
|                                | ADC                | Mathematical methods | GOST            |
|                                | Time-frequency correlation |                   | High            |

4. The discussion of the results

The application of the proposed classification based on the IDEF0 methodology allows you to structure diagnostic methods. A description of the applied technological processes, an assessment of the cost of each stage of work, and identification of critical areas.

The methodological approach can serve as the basis for the formation of an economic justification for the introduction of new technologies and an assessment of the possibility of modernizing the existing diagnostic processes used at energy enterprises.

Note that most of the developed technologies are based on the analysis of vibro-acoustic processes. Thus, their implementation requires equipping the heat conduit assemblies with additional specialized equipment in the form of physical converters. Which is a technically effective solution, but it is not economically feasible. The costs of installation, maintenance and maintenance can significantly exceed the financial benefits received after the introduction of new technology. The solutions offered on the basis of thermal imaging are not capable of real-time diagnostics. In addition, they strongly depend on the state of the environment, the depth of the pipeline, the quality of thermal insulation, and other factors.
Methods with the ability to freely scale, not requiring the introduction of specialized tools, will be cost-effective. These include software solutions, the mathematical methods of which are based on processing data from automated means of energy control and accounting.

5. Conclusions

General trends in the development of methods for diagnosing the state of pipeline valves are reduced to the possibility of collecting information on physical indicators of nodes and on-line machining. There are a number of main areas of development of diagnostic technologies and the search for an emergency section of the heat pipe:

- instrumental solutions for the conversion of physical quantities;
- hardware complexes of linear diagnostics;
- software solutions built on the basis of intelligent technologies;
- sensor networks.

The scientific literature focuses on the software-based method for leak detection, big data processing, and the use of intelligent technologies. From a practical point of view, the introduction of software methods is more economical than the hardware of the fuel and energy complex. For the most part, the basic unit of analysis and application of software solutions is the physical parameters of the heat supply units, while the possibility of developing intelligent methods based on automated energy metering systems remains unattended.

References

[1] Berardi U and Naldi M 2017 The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance Energy and Buildings 144 262–75
[2] Khoukhi M 2018 The combined effect of heat and moisture transfer dependent thermal conductivity of polystyrene insulation material: Impact on building energy performance Energy and Buildings 169 228–35
[3] Zhang D J 1996 Designing a Cost Effective and Reliable Pipeline Leak Detection System Pipeline Reliability Conference 11
[4] Adegboye M A, Fung W-K and Karnik A 2019 Recent Advances in Pipeline Monitoring and Oil Leakage Detection Technologies: Principles and Approaches Sensors 19 2548
[5] Okosun F, Cahill P, Hazra B and Pakrashi V 2019 Vibration-based leak detection and monitoring of water pipes using output-only piezoelectric sensors Eur. Phys. J. Spec. Top. 228 1659–75
[6] Lidén P and Adl-Zarrabi B 2017 Non-destructive methods for assessment of district heating pipes: a pre-study for selection of proper methods Energy Procedia 116 374–80
[7] El-Zahab S, Asaad A, Mohammed Abdelkader E and Zayed T 2017 Collective thinking approach for improving leak detection systems Smart Water 2 3
[8] Avramchuk V S and Goncharov V I 2013 Time-Frequency Correlation Method for Improving the Accuracy in Detecting Leaks in Pipelines Advanced Materials Research
[9] Martini A, Troncossi M and Rivola A 2015 Automatic Leak Detection in Buried Plastic Pipes of Water Supply Networks by Means of Vibration Measurements Shock and Vibration 2015 1–13
[10] Shakmak B and Al-Habaibeh A 2015 Detection of water leakage in buried pipes using infrared technology; A comparative study of using high and low resolution infrared cameras for evaluating distant remote detection pp 1–7
[11] Adedeji K, Hamam Y, Abe B and Abu-Mahfouz A 2017 Leakage Detection and Estimation Algorithm for Loss Reduction in Water Piping Networks Water 9 773
[12] Bach P and Kodikara J 2017 Reliability of Infrared Thermography in Detecting Leaks in Buried Water Reticulation Pipes IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing PP 1–15
[13] Wang J, Tchapmi L P, Ravikumar A P, McGuire M, Bell C S, Zimmerle D, Savarese S and Brandt A R 2020 Machine vision for natural gas methane emissions detection using an infrared camera Applied Energy 257 113998

[14] Lee E J, Shin S Y, Ko B C and Chang C 2016 Early sinkhole detection using a drone-based thermal camera and image processing Infrared Physics & Technology 78 223–32

[15] Ai-Roomi A R and El-Hawary M E 2018 New Heat Energy Trading Concepts for the Next Generation Smart Grids 2018 IEEE Canadian Conference on Electrical Computer Engineering (CCECE) 2018 IEEE Canadian Conference on Electrical Computer Engineering (CCECE) pp 1–6

[16] Matsuo K, Elmazi D, Liu Y, Sakamoto S and Barolli L 2015 A multi-modal simulation system for wireless sensor networks: a comparison study considering stationary and mobile sink and event J Ambient Intell Human Comput 6 519–29

[17] Mustafa H and Chou P H 2012 Embedded Damage Detection in Water Pipelines Using Wireless Sensor Networks 2012 IEEE 14th International Conference on High Performance Computing and Communication & 2012 IEEE 9th International Conference on Embedded Software and Systems 2012 IEEE 14th Int’l Conf. on High Performance Computing and Communication (HPCC) & 2012 IEEE 9th Int’l Conf. on Embedded Software and Systems (ICESS) (Liverpool, United Kingdom: IEEE) pp 1578–86

[18] Mysorewala M 2019 Time and Energy Savings in Leak Detection in WSN-Based Water Pipelines: A Novel Parametric Optimization-Based Approach Water Resour Manage 33 2057–71