Current Issues of Russian and Mongolian District Heating Systems and Scientific and Methodological Lines for Solving Them

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Abstract — **Against the background of the commonality of issues facing district-heating systems (DHSs) in Russia and Mongolia, the prospective strands to overcome them through the widespread adoption of modern methods of mathematical modeling and information technologies are addressed in this paper. A brief description of the long-term experience of cooperation between the Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) and the scientific and energy enterprises of Mongolia in the field of computer technologies for the analysis and development of operating parameters of the DHS is given. The study shows that this experience is in line with the current global trends in the modernization of district heating systems based on their digitalization and smartization. The concept of intelligent (smart) DHSs, their advantages, as well as the issues arising on the way of the DHS transformation into cyber-physical self-controlled systems are revealed. The results of the analysis of the state-of-the-art scientific and methodological developments and software in the field the DHS analysis and control smartization are discussed. The main results obtained at the ESI SB RAS in the formulation of the DHS adaptive control problems and the creation of a single information space are presented along with the methods for resolving specific issues of analysis, identification of models, and DHS optimization. Additionally, the paper focuses on the software developed at the ESI SB RAS to meet new conditions and requirements in three main applications: as a tool for automating calculations when developing adjustment measures to normalize and improve the energy efficiency of operating conditions; as a tool for integrating heterogeneous information resources into a single space; and as a platform for the development and adoption of the DHS computer simulation methods in practice of operational dispatch control.**

Index Terms: **district heating systems, functioning issues, digitalization, smartization, computer modeling.**

I. Introduction

Modern district heating systems (DHSs) in the cities of Russia and Mongolia are unique in scale and complexity of engineering and technical structures of large dimensions. The DHSs in Russia still have no analogues in other countries in terms of their quantity and total capacity [1]. Such systems include heat sources of various types (CHP, boiler houses) operating for common extended and looped heat networks; pumping stations; central and individual heat points with various sets and schemes for connecting local heat consumption systems, and other control units. Many district heating systems are technologically organized according to a hierarchical principle to ensure multi-stage control of heat supply at heat sources, central or individual heat points, directly at heat-consuming installations (in heating, ventilation and hot water systems). They are characterized by multi-loop heat networks; spatial separation; variability in structure, operating parameters, and conditions of operation.

The main line in the development of the Mongolian energy sector is thermal power industry, with 95.7% of electricity generated at thermal power plants [2], which are concentrated in three large cities (Ulaanbaatar, Erdenet, and Darkhan). The largest DHS is located in the country's capital, Ulaanbaatar. In recent years, Ulaanbaatar's DHS has experienced a shortage of thermal energy due to the

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Table 1. Software for Modeling Heat Networks

No.	Name	Country	Organization
1	ICE "ANGARA-HN"	Russia, Irkutsk	ESI SB RAS
2	ZuluThermo	Saint Petersburg, Russia	Politerm LLC
3	IGS "CityComTeploGraf"	Russia Moscow	"CityCom"
4	GICC "TeploExpert"	Russia, Ivanovo	Teplotex LLC
5	TERMIS	France, Rueil-Malmaison	Schneider Electric
6	NEPLAN Heating/Cooling	Switzerland, Zurich	NEPLAN AG
7	NetSim	Sweden, Stockholm	Vitec Software Group AB
8	STANET	Germany	STANET
9	PSIControl	Germany	PSI SOFTWARE AG
10	Wanda	Netherlands	Deltares
11	PSS Singal	Germany	Siemens

increase in population. This requires an increase in capacity, adjustment of heat consumption systems, automation of individual heat points, and installation of metering units.

The commonality of the district heating problems in Russia and Mongolia is determined by the following main circumstances: 1) severe climatic conditions comparable in terms of daily and annual fluctuations in outdoor temperature and duration of heating period; 2) similar principles of the DHS construction and organization of operation; 3) transition to a market economy and related tightening of requirements for energy efficiency and energy saving.

The common problems also include general aging of the main equipment and poor provision with control, measuring and monitoring equipment. As a result, there is a low degree of DHS controllability, reliability, and efficiency; increased accident rate; high thermal energy losses and energy consumption, and interruptions in energy supply to consumers. On the one hand, work on the adoption of technical means for measuring, automatically recording and regulating thermal energy has been intensified recently. On the other hand, this increases the variability of operating conditions of the district heating systems and significantly complicates the control processes.

The improvement in the reliability, cost-effectiveness, and quality of DHS operation requires a set of measures related to both technical re-equipment of DHS and the adoption of modern information and computing technologies for the analysis and optimization of DHS operation at almost all stages of decision-making: development of heat supply diagrams, design, reconstruction, operation, and dispatch control.

For more than 30 years, the ESI SB RAS has been actively cooperating with scientific and energy enterprises of Mongolia in the field of heat supply [3–5]. Interaction was also organized with the Mongolian University of Science and Technology on the basis of the Department of Thermal Power Engineering to train Mongolian specialists to use software and computing systems for DHS modeling, which were developed at the ESI SB RAS. Since 2014, within the framework of a cooperation agreement with the National Dispatching Center of the Energy System of Mongolia, the two countries have worked to adopt computer technologies for the analysis and development of the operating conditions of district heating system, and concepts for controlling them, given new requirements, equipment, and technologies.

This paper, based on a brief description of the experience of this cooperation and an analysis of the current state and main trends in digitalization and smartization of DHS in other countries, characterizes the most promising areas for the DHS renovation, as well as the scientific and methodological groundwork available at the ESI SB RAS in this area.

II. Experience in Application of Computer Technologies to Provide DHS Operation in Russia and Mongolia

As noted, a significant enhancement in the DHS efficiency becomes impossible without the use of modern information technologies and applied software. This is evidenced by a fairly developed market for foreign and domestic software for computer modeling of district heating systems (Table 1).

The analysis of this market shows [6] that the currently existing software mainly automates typical problems of modeling the DHS operating conditions. At the same time, these software products are as a rule closed in terms of functions, data, and methodological support. These circumstances significantly limit the possibilities of their integration with other information or computing resources, and do not allow developing the information and computing space in the absence of developers, applying mathematical models and methods hidden from the user, and guaranteeing the adequacy and reliability of calculation results. Table 2 presents the results of the analysis of the most common software applied to date for solving non-traditional, but significant problems (analysis and provision of controllability, observability, adaptability, optimal functioning) that arise with the DHS smartization.

Table 2. Correspondence of the Existing Software Capabilities to New Requirements

No.	Software	Import-Export	Open data format	Hydraulic calculation	Thermal calculation	Non-stationary conditions	Controllability	Provision of observability	Damageability	Observability	Adaptability	Forecasting	Optimality	Integrability	Analytic functions
1	ICS ANGARA-HN	+/-	+	+	+				+/-				+/-	+	+/-
2	Zulu Thermo	+/-	+/-	+	+									+/-	+/-
3	IGS “CityComTeploGraf”	+/-	+	+	+				+/-					+/-	+/-
4	GCC TeploExpert	+/-		+	+										+/-
5	TERMIS	+	+	+	+	+						+/-	+	+	+
6	NEPLAN Heating/Cooling	+	+	+	+				+/-			+/-	+/-	+	+
7	NetSim	+/-	+/-	+	+								+/-		+/-
8	STANET	+	+/-	+	+								+/-		+/-
9	PSIControl	+	+/-	+	+		+/-				+/-	+/-	+/-	+/-	+/-
10	Wanda	+/-	-	+	+	+							+/-		+/-
11	PSS Singal	+	+	+	+		+/-		+/-		+/-	+/-		+	+/-

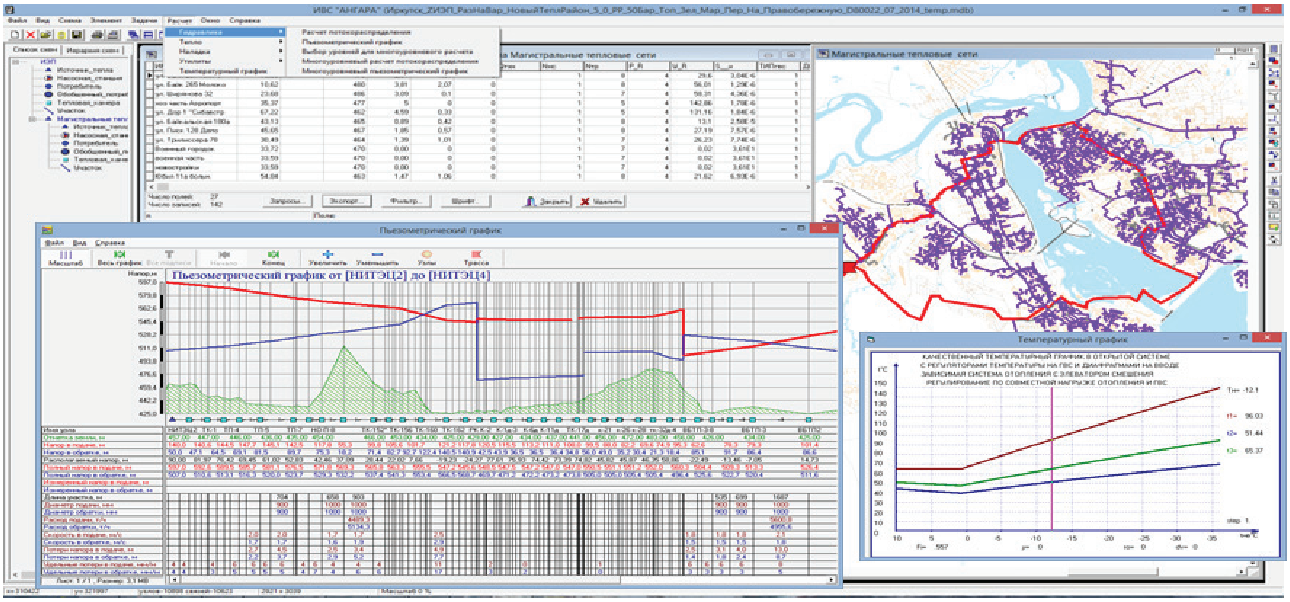


Fig. 1. Interface of the ANGARA-HN software.

Based on the theory of hydraulic circuits, a scientific area developed at the ESI SB RAS, the Institute has accumulated unique experience in creating methodology and software for calculating and optimizing pipeline systems (PLSs) [8].

Since 2000, the proprietary information computing environment (ICE) "ANGARA" has been created and developed here as a universal platform for modeling PLSs of various types and purposes [17, 18]. This ICE automates the processes of setting up the information computing environment of the user, including that without the participation of developers. The use of this environment within a single graphical interface provides many opportunities for PLS computer simulation, information analysis, interpretation of initial data, and calculation results [19].

The most important properties of the ICE areas follows:

- Data are stored in an open form in the format of modern relational DBMS (both local and network ones), there is possibility of expanding the database (DB) structure by the user, organizing interaction with other information systems, and flexibly integrating into a single information space (SIS) of the enterprise;
- Support for multi-level models of pipeline systems is provided to decompose a single design diagram on any basis (territorial, technological, departmental) and harmonize the calculations of individual parts;
- There is a possibility of multi-layer presentation of information according to the network diagrams and terrain plan, including data exchange between layers and computational models, which enables the intersystem interaction between models of different types of pipeline systems during their modeling;
- Support for the processes of end-to-end modeling is ensured, in which once created electronic model can be used in different stages of decision-making: design, reconstruction, operation, dispatch control, training.

The latest version of the ANGARA ICE has a multilingual interface (Russian, English, and Chinese), which can be adapted to any other language.

To automate modeling of the DHS operating conditions, the ESI SB RAS developed the information computing system (ICS) ANGARA-HN [20–22], which is an integration of the ANGARA ICE and the software (Fig. 1). The ICS allows hydraulic and thermal calculation; analysis of feasibility of operating parameters; search for the places of rationally sectioning the heat network; calculation of the parameters of throttling devices to maintain the required operating parameters for the consumer; calculation and construction of temperature and piezometric graphs, and others.

The main distinctions of the ANGARA-HN software are related to its capability to provide the hierarchical single-line or two-line representation of heat network diagrams, their single- or multi-level, detailed or aggregate modeling, and increase in the composition of calculation tasks without reprogramming existing ones on a single information basis. Methods and algorithms for modeling the operating conditions, which are implemented in the ANGARA-HN ICS [23–35] have been extensively tested in the district heating systems of many Russian cities (Moscow, St. Petersburg, Urengoy, Yekaterinburg, Petropavlovsk-Kamchatsky, Irkutsk, Angarsk, Bratsk, Baikalsk, Cheremkhovo, Zheleznogorsk-Ilimsky, etc.) and cities of other countries (Mongolia (Ulaanbaator, Darkhan), Ukraine (Dnepropetrovsk), China (Beijing), and others). This appeared to be possible thanks to long-term close cooperation with many design and operating organizations, research institutes and universities (OJSC Irkutskenergo, OJSC Irkutskteploenergo, grid companies of Irkutsk,

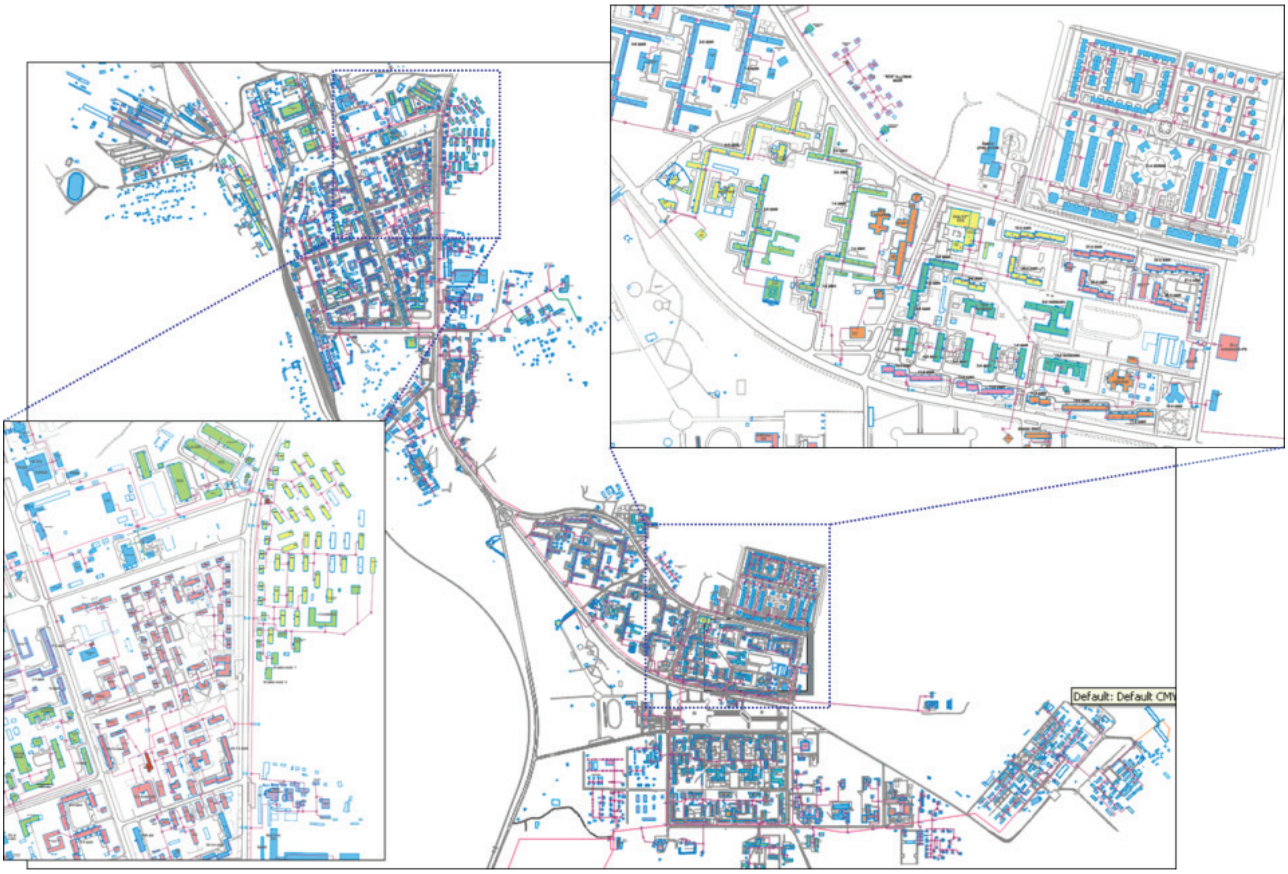


Fig. 2. Heat networks of the city of Darkhan against the backdrop of urban development.

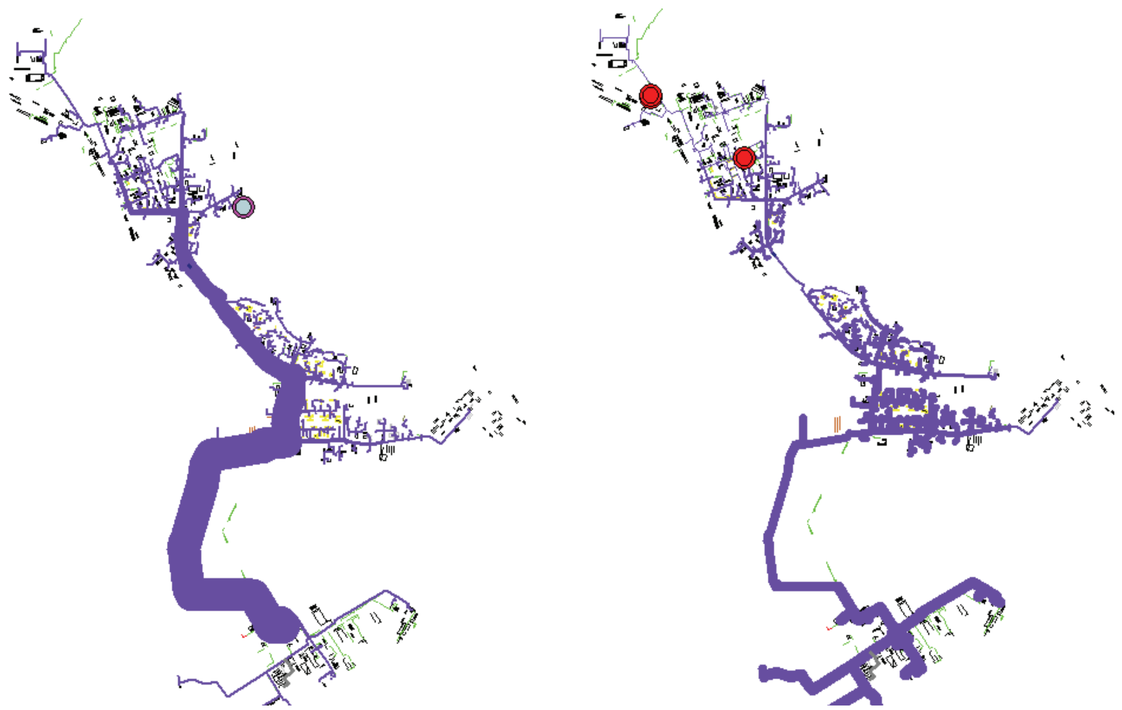


Fig. 3. Analysis of the current state of the heat network in Darkhan, a) distribution of flows (line thickness is proportional to the flow in the supply pipeline), b) distribution of available pressures (line thickness is proportional to the available pressure).

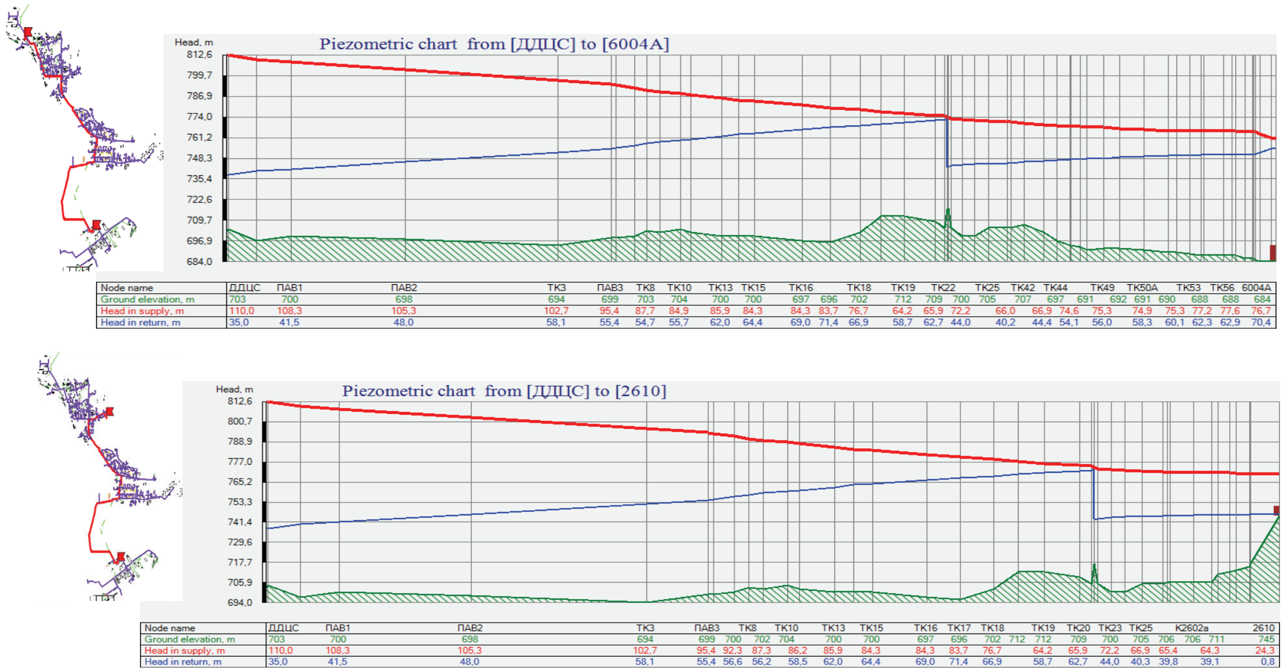


Fig.4. Piezometric graphs of the heat network in the city of Darkhan to the characteristic consumers in terms of available pressure (a) and pressure in return pipeline (b).

OJSC Siberian ENTC (Departments of heat networks and advanced design), Irkutsk State Technical University, PJSC "KamchatskEnergo" (branches "Kamchatskye CHPPs" and "Communal Energy"), OJSC "Gazprom Promgaz," Research Institute of OJSC "VTI," "TEP-Engineering," OJSC "Center of Power Engineers of the Urals," OJSC "DneprVNIPIenergoprom," Urengoy State District Power Plant, National Dispatch Center of Power Systems of Mongolia, Darkhan Heat Network Enterprise, Mongolian University of Science and Technology, and others).

In the vast majority of cases, the use of the software made it possible to identify and, to a large extent, implement a great potential for energy saving, and improve the quality of heat supply to the consumer by reducing the circulating water flow, make-up water flow, water discharges by the residential sector, unproductive heat losses, electricity consumption for pumping and chemical water treatment of coolant, fuel consumption, and others.

The experience of cooperation between the ESI SB RAS and scientific and energy enterprises of Mongolia in the field of heat supply has more than 30 years of history, mainly in the area of the adoption and application of the software developed by the Institute for DHS simulation (modeling). Over this period, several generations of such software have changed. Back in 1992, the interactive computing software "DISIGR," introduced for personal computers running with DOS, was used by Mongolian specialists to calculate the operating conditions of the district heating systems in some cities in Mongolia. In 2000, the software ARMTTS, which combined computational tasks with a graphical database, was handed over to Mongolian colleagues. In 2010, the Windows version of the ANGARA-HN was transferred to and since then it has been maintained at the Department of Thermal Power Engineering of the Mongolian University of Science and Technology, at the National Dispatching Center for Energy Systems of Mongolia, and at the JSC "Darkhan Heat Network." Figure 2 shows an example of fragments of the graphical database of the DHS in Darkhan. The analysis of operating conditions of these heat networks allowed detecting their weaknesses (Figs. 3, 4) and developing adjustment measures.

III. Trends and Strands in Overcoming Existing Issues

In recent decades, the processes of renovation and modernization of district heating systems have been intensified all over the world through the adoption of new equipment and materials; systems for control, monitoring and measurement; computers; remote control systems for collecting and processing the measurements, and methods of mathematical and computer modeling for analysis and decision-making on control. The aim of these transformations is primarily associated with the digitalization and smartization of DHS.

The generalization of the experience of these transformations, as well as the goals and experience of the smartization of electric power systems, made it possible to formulate the concept of smart (intelligent) DHS (IDHS) as a fundamentally new platform, within which it becomes possible to effectively coordinate the interests, requirements, and capabilities of all parties involved in the processes of thermal energy generation, transportation, distribution, and consumption [6, 33, 34]. The consumer is assigned the role of an active equal participant influencing the amount of heat consumed, its quality and prices. The main features of the IDHS are:

1) A single information (digital) space, as the main backbone factor responsible for the observability of the processes of production, distribution, and consumption for all participants in these processes;
2) A high level of controllability as the main way to harmonize the requirements of consumers and the capabilities of producers (suppliers);
3) Dynamic pricing stimulating consumers to change their usual consumption schedules;
4) High proportion of digital, information, and telecommunication technologies; methods of mathematical modeling and optimization in real-world scenarios in the context of monitoring, control, and decision-making.

The main means of implementing the IDHS are not only energy-efficient basic and maneuverable control equipment but also mainly advanced information, telecommunication, and computer technologies. Intelligence is associated with the transfer of the main functions of analysis, forecasting, decision-making, and implementation to software. The greater the number of such functions, which previously required engineering education, experience and qualifications of specialists, are assigned to computer systems, the more "intelligent" DHS is.

The transition to the ISCT platform will require dealing with a whole host of scientific, legal, technical, technological, economic, informational and other issues, including the need to revise the existing practice of design, operation and dispatching control of DHS.

The main issues to be faced can be briefly summarized as follows.

1. *In design*. Traditionally, DHS is designed for one so-called design behavior of maximum load, which follows from the requirement of firm supply to the consumer under any other conditions. However, the system operates in this condition only a small fraction of its total operation time. Under highly uneven consumption (especially with active behavior of the consumer) and low controllability of DHS, this approach leads to an overestimation of investment in development and operating costs. The current design practice does not provide the controllability of the DHS as a whole, and there are no requirements and standards for the controllability of the DHS at all. At best, standard schemes for local automation of individual structures (sources, pumping stations, heating points, etc.) are used. Accordingly, the designed district heating systems are poorly adapted to efficient operation in a variety of possible conditions.
2. *In operation.* The traditional norms for the DHS operation regulate the repair work in accordance with the standard service life of the equipment, i.e., a planned and preventive system is applied. At the same time, with the progressively growing general aging of this equipment, on the one hand, the implementation of these standards becomes unrealistic, and, on the other hand, meeting these standards is not rational. The actual service life of the equipment, depending on the specific conditions of its use, may differ from the normative one by several times, both up and down. The transition to the system of operation according to the actual state, as more efficient, is poorly supported scientifically, methodologically, and normatively.
3. *In control*. The lack of full-scale information-and-measuring systems (IMS) until now has been the main constraint on the development and implementation of advanced concepts of process control, which require the presence of feedback (observability and identifiability of DHS). For this reason, the dominant concept until now has been the simplest concept of control "according to the regulations." According to this concept, control decisions are made on indirect grounds (according to the forecast of outdoor air temperature, return water temperature at sources, etc.) and the consequences of control (the extent to which consumers are provided with heat, feasibility of the conditions, and their optimality) remain partially or completely unobservable, i.e., the feedback principle, as the basis for reliable and sustainable control, is not ensured.

The analysis of these issues allows formulating the following key objectives that arise on the way of the DHS smartization.

1. *In design.* 1) ensure the operational efficiency of the designed and reconstructed DHS, given the use of new concepts and control technologies; 2) develop controllability and observability regulations and standards; 3) synthesize control and information-and-measuring systems.
2. *In operation.* 1) switch to the practice of planning repairs based on the actual state of the equipment; 2) apply methods of active identification, technical diagnostics and damage analysis; 3) optimize plans for repair and restoration work, given the actual state of the equipment, damage statistics and damage to consumers.
3. *In control.* 1) transition to a new concept of controlling district heating systems as dynamic and stochastic objects operating under uncertainty about the internal state and external impacts [33–36]; 2) optimally plan and control the main (operational), post-accident and «repair» conditions; 3) continuously monitor the actual state of the DHS; 4) overcome departmental or corporate disunity of technologically connected parts of the DHS and related systems.

Summarizing what has been said, it is worth stating that the core direction of resolving the traditional contradiction between the requirements for the DHS efficiency and reliability on the way to their smartization involves the enhancement of their controllability based on the mathematical modeling methods. The primary issue that arises here is the need to develop the principles for creating a single digital space, methods and technologies for real-time monitoring of the DHS parameters and states, and the external environment.

IV. Current State of Scientific and Methodological Developments in the Field of Mathematical Modeling of Heat Supply Systems

The analysis of the current state of scientific and methodological developments and software designed to make the processes of DHS control in Russia and other counties [6] intelligent identifies three major classes of tasks: analysis, identification of models, and optimization of operating conditions.

The tasks of analysis (simulation of DHS conditions) arise at almost all stages of decision-making on control, but for different purposes. To design district heating systems, one should analyze the reliability and feasibility of their operation in non-design conditions; during reconstruction, it is necessary to analyze the throughput and identify "bottlenecks" in operation under expected future loads; to plan operation for the upcoming heating season – to develop and justify measures to adjust heat networks; in the case of dispatching control – to analyze and justify control decisions. The models and methods for modeling operating conditions (hydraulic, thermal, stationary, and non-stationary) have been the subject of an extensive literature, a lot of experience has been gained, and the developed methods have become widespread. It is worth noting, however, that this experience is limited in terms of new needs of intelligent DHS, such as the analysis of the cybernetic properties of DHS (controllability, identifiability, efficiency, and others) based on the creation of "digital twins" of DHS for testing new concepts, rules, and algorithms of optimal control. These tasks require considering real conditions of DHS operation: the dynamics of behaviors, the stochastic nature of external disturbances, and the uncertainty about information on the internal state of the equipment. To jointly take into account these factors, further development of methods for mathematical modeling of DHS is necessary. In this regard, the generalized [37] and object-oriented [40] models and methods for calculating the flow distribution, which are developed at the ESI SB RAS, appear to be promising, as they factor in arbitrary equipment (including new one) of DHS and the probabilistic nature of flow distribution [41] affected by stochastic external environment in the case of uncertain information on the actual characteristics of the system components.

The tasks and methods of identifying the DHS vary markedly, which is explained by the variety of goals pursued: 1) identification of equipment characteristics (parametric identification) 2) identification of states (state estimation); 3) damage identification (technical diagnostic tests), and others. In this case, the question inevitably arises whether these goals can be achieved based on available measurements. Therefore, the DHS identification is a complex task that includes two main areas: 1) analysis and synthesis of information-measuring systems (placement/composition, parameters, rate of inquiry of measuring instruments) to ensure the DHS identifiability; 2) development of methods for processing large volumes of measurement information in order to achieve the identification goals set. A review of literature [6] shows that: 1) the synthesis of measurement systems for DHS is still at the initial stage of awareness and development; 2) the parametric identification is mainly reduced to the "calibration" of the DHS electronic models, which involves ensuring the agreement between modeling results and measurements at a limited number of network points, where standard measuring instruments are installed; 3) the first works appear in the field of real-time state estimation of DHS based on the results of measurements, including those coming from heat meters at consumers (steady-state hydraulic and temperature conditions are considered); 4) there is a revival of interest in leak detection based on the joint use of measurements and coolant flow models. Identification of pipeline systems as an independent problem was first formulated [7, 9] and systematically studied [42, 43] in the papers of the ESI SB RAS. In particular, the focus was on the optimal planning of operating conditions, the composition of measurements and processing the results of tests of the pipeline systems for hydraulic and heat losses [40].

The above review of the literature on the tasks and methods for DHS optimization [6] indicates high demand for them at almost all levels of decision-making on control (design, operation, operational control) and, accordingly, a growing number of publications. This testifies to the increasing urgency of the DHS optimization problems, as well as their complexity, the presence of many unsolved problems, and the lack of effective general-purpose methods suitable for wide practical application. This situation is explained by some objective factors: 1) large dimensionality and non-linearity of models of DHS operating conditions; 2) many technological requirements and restrictions; 3) a variety of methods and combinations of control (continuous and discrete), restrictions on the places of their application and magnitude; 4) multi-criteria nature of the majority of emerging problems; 5) the need to take into account the dynamics and stochastics of external conditions, and others. The ESI SB RAS proposed a new hierarchical approach to optimization of the DHS hydraulic conditions and automation of the development of adjustment measures [45]. The main capabilities of this approach and the methods developed within its framework [46, 47] are: 1) their applicability to DHS of almost any dimension; 2) a guarantee of a global solution to be obtained without iterative coordination of solutions at different levels (main and distribution networks); 3) distribution of different optimality criteria (economic, technological, environmental, etc.) and types of control

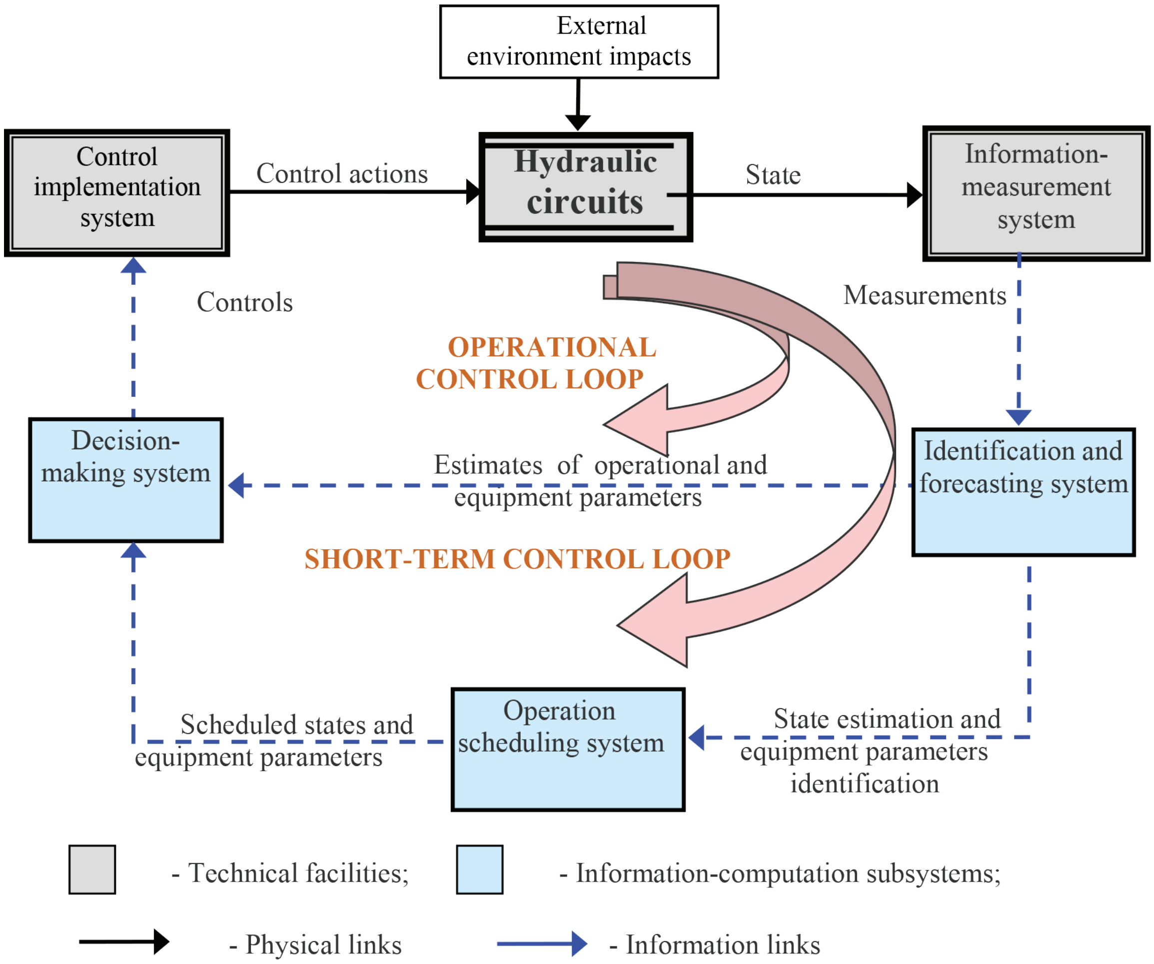


Fig. 5. Loops of causal relationships for controlled DHS.

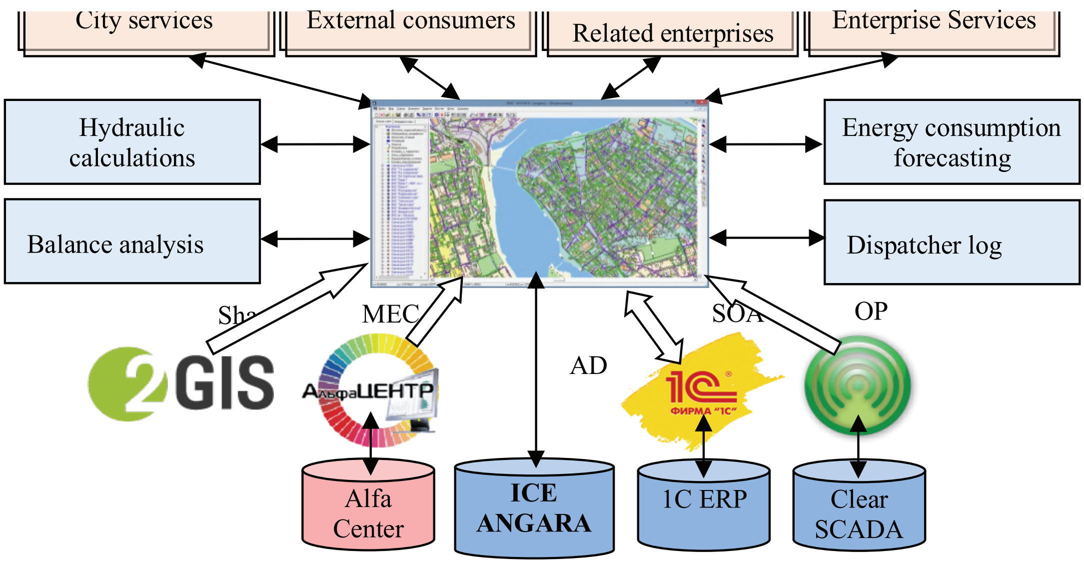


Fig. 6. ICE "ANGARA" as the core of the Single Digital Space of the enterprise.

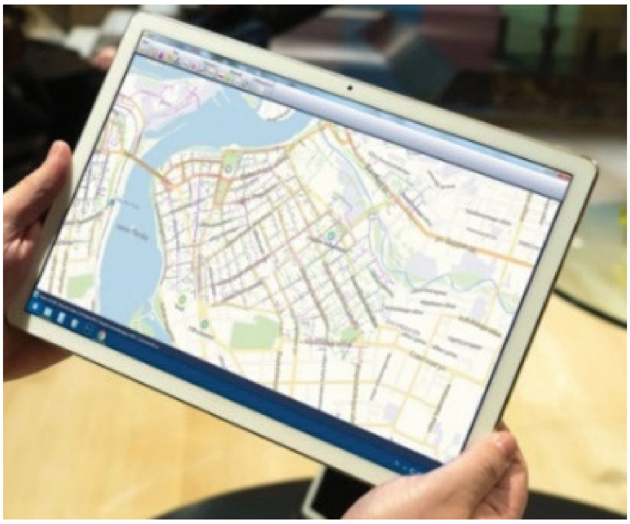


Fig. 7. Graphical interface of the "ANGARA" MIS.

(continuous, discrete, Boolean) according to different levels of the hierarchy; 4) consideration of any technological constraints on operating parameters; 5) consideration of all existing control methods (unit commitment, throttling, frequency control, and others); 5) high performance due to the possibility of conducting parallel calculations.

V. Idea and Technologies of the New DHS Control Concept

An analysis of international experience in the development of district heating technologies shows that at present there are all the necessary prerequisites for the transition to a new advanced concept of compromise adaptive control of DHS operation in the state space with feedback [33, 35–38].

The concept of compromise control means here the need for dynamic coordination of supply and demand between suppliers and consumers, as well as coordination with related systems, through the efficient use of available technical capacities and a flexible tariff policy. Accordingly, in addition to the traditional calendar-time (operation planning, operational control) and territorial-organizational (technological, interdepartmental and intersystem hierarchy) levels of control of operating conditions, it is assumed that there is a level of technical-economic coordination of pricing policy.

The state space is understood as the space of operating parameters (pressures, flow rates, temperatures), the relationship between which satisfies the physical laws of flow distribution, which suggests the use of appropriate mathematical and electronic models. Thus, the DHS control object can be classified as cyber-physical. The qualitative difference between such systems is that they rely not only on the main equipment but also on information and computing resources that directly determine their performance indices.

Adaptive feedback control is understood as the possibility of adapting the models used (through their identification) to changes in the characteristics of the DHS equipment and external impacts based on the monitoring and measurement of the operating parameters and manifestations of the external environment.

Figure 5 shows a stylized flow diagram of the DHS as a cyber-physical system. The main objects of this system are: 1) technical means (the main equipment of the DHS, measurement and control subsystems); 2) information and computing means (for identification of the current DHS state and its projection, optimal operation planning, and operational control).

As seen, this is a full-scale cybernetic system with feedback, and its subsystems are in constant physical, technical, and informational interaction. Different loops of control are associated with the need to factor in its calendar-time nature for decision-making.

The primary problem on the way to the adoption of this concept is associated with a significant increase in the amount of information available for the processes of monitoring and optimal control, and its solution can be found through the creation of a single information (digital) space (SDS) as the basis for coordinating decisions on process control and pricing policy [48]. Such a space, in turn, suggests: 1) integrating the process control and commercial accounting systems into a single information measuring systems (IMS); 2) using new high-speed telecommunication technologies, methods for collecting and processing large amounts of information; 3) providing information to consumers and other participants involved in heat supply processes; 4) creating unified corporate, interdepartmental, territorial (for example, urban) information-measurement systems, which will not only synchronize control decisions but also significantly reduce the cost of these systems themselves.

We developed and tested a technology for creating such a space [49] based on the ANGARA ICE (at the "Vodokanal" company in the city of Irkutsk) (Fig. 6). This technology, in contrast to the known ones, does not involve the establishment of a new information system, but provides integration of existing (or attracted) local information resources (cartography, electronic models, SCADA systems, billing, dispatch logs, etc.) into a single information system. Such a technology provides: 1) completeness, reliability and consistency of information; 2) operational availability of information, both to all interested services and specialists of the enterprise, and to external consumers (city services, related companies, subscribers, etc.) in local or global computer networks; 3) end-to-end support of computational and analytical problems solved at various temporal and territorial levels of control on a single information basis.

In view of the significant scale of the DHS, the problem of the DHS accessibility via wireless communication channels from mobile devices ("smartphone" or "tablet") arises for the enterprise specialists involved in its maintenance at an arbitrary point of the operated facility,

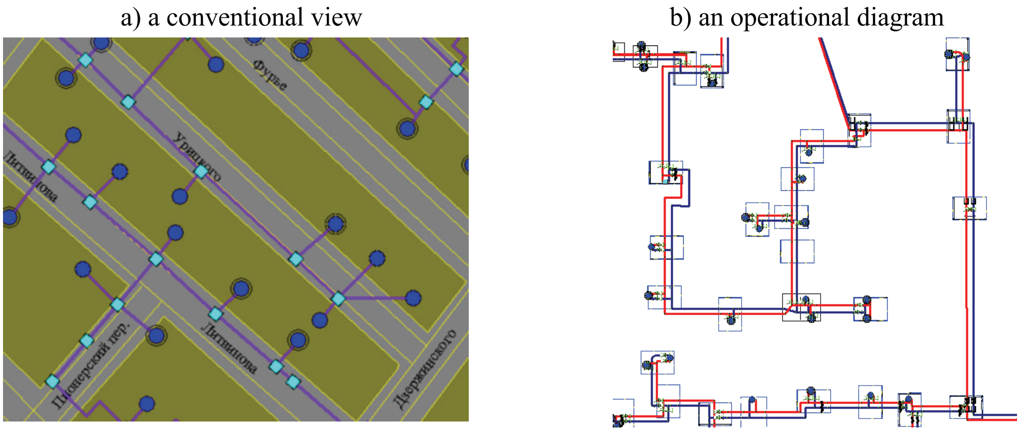


Fig. 8. Representation of the graphic diagram of the heat network in the «ANGARA-DHN» software.

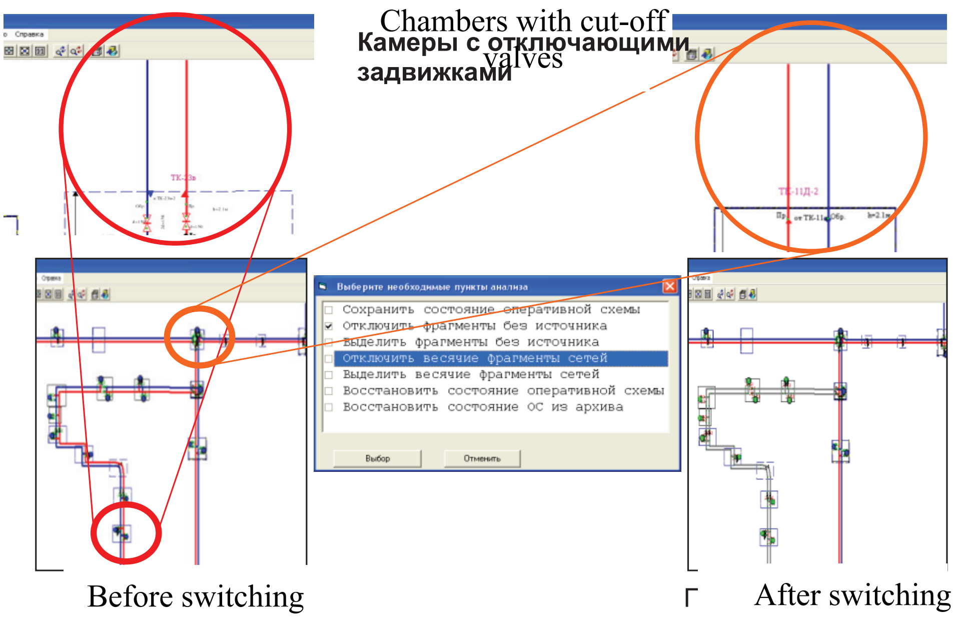


Fig. 9. Search for switches and display of switched off sections on the operational diagram.

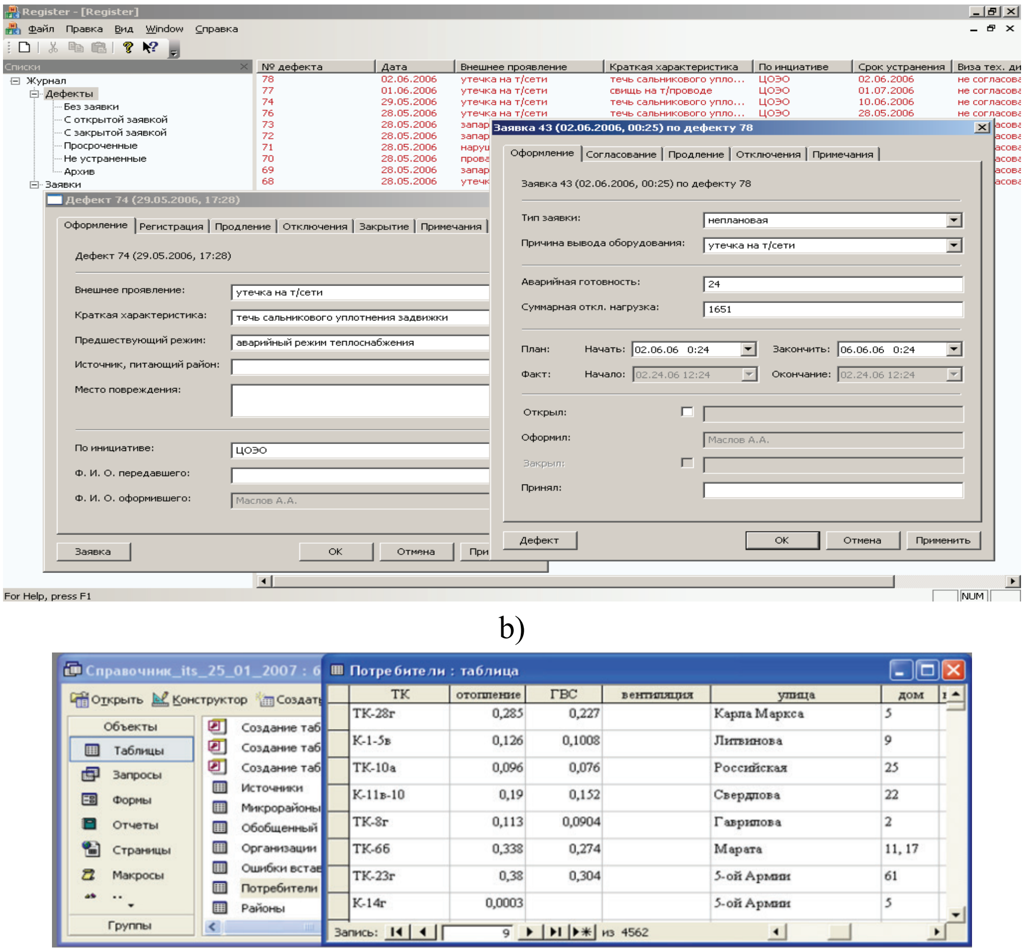
which requires the development of dedicated software. Some works focus on these problems, from the standpoint of the development of both mobile communications [50] and technologies for transmitting large amounts of data on them [51]. To overcome these problems, the ANGARA mobile information system (MIS) was developed, which works on mobile devices under the Windows operating system (Fig. 7). The program is implemented based on .NET Framework and provides users with a basic set of functions: searching, editing, displaying pipeline systems against the background of downloaded satellite maps of the area, logging operations, and automatically synchronizing the data with the SDS of an enterprise.

Solving the problem of information security of the DHS optimal control processes creates the necessary ground for the development and practical application of a whole range of new topical tasks relying on the application of methods of mathematical and computer modeling of the DHS. These are: continuous monitoring and forecasting of consumption and operation parameters; automatic provision of adequacy of electronic models to real-world characteristics of DHS equipment; calculation of optimal parameters for the thermal energy supply from sources; prompt detection of accident sites and development of recommendations for their elimination; optimization and correction of hydraulic and temperature conditions; control of telemetry reliability; maintenance of electronic logs of switching, defects and damages, applications for repair and restoration work, orders and instructions, and many others [52–57].

The ESI SB RAS has developed a pilot version of the ANGARA ICS intended for the use in dispatching control (the ANGARA-DHN software). It allows:

1. displaying heat network diagrams, both in single-line (on the urban development plan) and in two-line representation (operational diagram) (Fig. 8);
2. combining the requirements for compactness and details of the operational diagram (display of primary

a)



b)

Fig. 10. Interfaces of electronic log of defects and switching points (a) and the reference book on contractual loads (b).

components: pumps, valves, measuring instruments, etc.);

3. supporting multi-level operational diagrams in conjunction with single-line diagrams on the terrain plan;
4. searching for switching points to bring the network component into repair and display disconnected sections on the operational diagram (Fig. 9);
5. conducting operational hydraulic calculations using decomposition, reduction and disaggregation methods, and direct measurement data;
6. assessing the feasibility of operating conditions for the district heating system according to the process conditions of the equipment operation;
7. graphically interpreting “bottlenecks” and places where the requirements for feasibility of operating conditions are not met on diagrams and piezometric graphs;
8. integrating with dispatching electronic logs of defects and switching (Fig. 10), reference books on contractual and current loads of consumers (Fig. 11), and measurement systems.

VI. Conclusion

1. Russia and Mongolia have a long history of fruitful cooperation in building and modernizing DHSs, which has all the grounds for its further development. An analysis of the current energy efficiency and energy saving issues, as well as global trends in the transformation of heat supply technologies, shows that the main way to overcome them lies in the «digitalization» of district heating systems and “smartization” of their control.
2. The main goal of these processes is to build a new generation of DHSs as cyber-physical self-controlled systems, which, not only rely on the main equipment, but are also carriers of information and computing resources that directly affect the DHS efficiency, reliability, and quality. At the same time, the analysis of existing scientific, methodological, and software developments indicates that the scientific and methodological framework, which can be used as the basis for the DHS smartization is currently still in the process of formation, and the existing DHSs are not yet adapted to solving new problems emerging along this way.

3. The paper presents the main results in the field of DHS smartization, which have been obtained at the Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences. In particular, a new concept of adaptive control of the DHS operating conditions, as well as constructive statements and methods for solving new problems of analysis, identification of models, and optimization of DHS operation are proposed. Accordingly, the primary objective of implementing the proposed concept is to provide full-scale feedback with the DHS, as an object of control, in the form of a single information (digital) space.
4. The software developed at the ESI SB RAS is described against the background of a brief review of the most common software products used in Russia and other countries to support electronic DHS models. This software has been widely tested on many real-world DHSs in Russia and Mongolia and continues to evolve with a focus on new conditions and requirements. The considered software includes 1) ICC "ANGARA-HN," as a means to automate calculations for the analysis, development, and justification of adjustment measures to normalize heat supply to the consumer and improve the energy efficiency of operating conditions; 2) a new version of the ICS "ANGARA," as a tool to integrate heterogeneous information resources into a Single Digital Space; 3) ICC "ANGARA-DHN," as a pilot platform to develop the methods of DHS computer simulation and adopt them in the practice of operational dispatch control.

References

[1] I. A. Bashmakov, "Energy efficiency enhancement in heat supply systems. Part 1. Problems of Russian heat supply systems," *Energy saving*, no. 2, pp. 46–51, 2010. (In Russian)

[2] E. G. Gasho, H. Enkhzhargal, L. Batmand, G. Bayarsaikhan, S. Monkhbayar, *Modernization of heat supply systems in Mongolia*. [Online]. Available: https://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=4221/.

[3] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, "Experience in the development and application of information and computing systems for calculating large heating systems and organizing their operation," in *Proceedings of the International Scientific Conference "Energy and Market Economy,"* Ulaanbaatar, Mongolia, 2005, pp. 323–329.

[4] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Current problems of heat supply system control and methodological directions for their solution," in *Proceedings of the International Scientific Conference on Energy Industry Development and Ecology*, Ulaanbaatar, Mongolia, 2010, pp. 145–148.

[5] V. V. Tokarev, N. N. Novitsky, Z. I. Shalaginova, "Calculation technology and experience in using the ANGARA-HN information-computing complex (ICC) in the development of operating behaviors for heat supply systems in large cities," in Proceedings of the Science and Practice Conference on Improvement in planning the district heating system operation, Ulaanbaatar, Mongolia, 2014, pp. 53–64.

[6] N. N. Novitsky, Z. I. Shalaginova, A. V. Alekseev, et al, "Current state, trends and tasks of smartization of heat supply systems (review)," *Thermal Engineering*, no. 5, pp. 65–83, 2022.

[7] A. P. Merenkov, V. Ya. Khasilev, *Theory of hydraulic circuits*. Moscow, Russia: Nauka, 1985, 278 p. (In Russian)

[8] E. V. Sennova, V. G. Sidler, *Mathematical modeling and optimization of expanding heat supply systems*. Novosibirsk, Russia: Nauka, 1985, 222 p. (In Russian)

[9] *Mathematical modeling and optimization of heat, water, oil, and gas systems*, A.P. Merenkov, Ed. Novosibirsk, Russia: Nauka, 1992, 407 p. (In Russian)

[10] E. V. Sennova, M. G. Sukharev, V. K. Averyanov, et al. *Hydraulic circuits. Development of theory and applications*, Novosibirsk, Russia: Nauka, 2000, 273 p. (In Russian)

[11] V. K. Averyanov, A. V. Alekseev, M. I. Alekseev, et al, *Pipeline energy systems: development of mathematical modeling and optimization methods*. Novosibirsk, Russia: Nauka, 2008, 311 p. (In Russian)

[12] A. A. Atavin, N. N. Novitsky, M. G. Sukharev, et al. *Pipeline energy systems: Mathematical and computer technologies for smartization*. Novosibirsk, Russia: Nauka, 2017, 384 p. (In Russian)

[13] *Hierarchical modeling of energy systems*, N. I. Voropay, Ed. Novosibirsk, Russia: Academic Publishing House "Geo," 2020, 314 p. (In Russian)

[14] A. V. Alekseev, O. A. Grebneva, N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Mathematical models and methods for assessing and realizing the energy saving potential in the control of heat supply systems," in *Research and Development of the Siberian Branch of the Russian Academy of Sciences in the field of energy efficient technologies*. Novosibirsk, Russia: Research Institute of Molecular Biology and Biophysics, 2009, pp. 38–49. (In Russian)

[15] N. N. Novitsky, A. V. Alekseev, O. A. Grebneva, A. V. Lutsenko, V. V. Tokarev, Z. I. Shalaginova, "Multilevel modeling and optimization of large-scale pipeline systems operation," *Energy*, vol. 184, pp. 151–164, 2019.

[16] Z. I. Shalaginova, V. V. Tokarev, "Development of methods for modeling thermal-hydraulic conditions in time to assess the quality of heat supply system performance," in *Proceedings of XVII All-Russian Scientific Seminar "Mathematical Models and Methods for Analysis and Optimal Synthesis of Developing Pipeline and Hydraulic Systems,"* Irkutsk, Russia, 2020, pp. 63–76. (In Russian)

[17] A. V. Alekseev, N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, "Principles of development and software implementation of the information-computing environment for computer modeling of pipeline and hydraulic systems," in *Methods of Research, Control and Optimization of Pipeline Systems in the Energy Sector: Collected papers*. Novosibirsk, Russia: Nauka, 2007, pp. 221–229. (In Russian)

[18] A. V. Alekseev, N. N. Novitsky, "Computer technology "ANGARA" for the integration of information and computing space in the modeling of pipeline systems," *Scientific Bulletin of NSTU*, no. 2, pp. 26–41, 2017. (In Russian)

[19] N. N. Novitsky, A. V. Alekseev, V. V. Tokarev, "Integrated development and application of information technologies for automating the processes of analysis and development of operating conditions of engineering systems for heat and water supply," *Proceedings of Universities. Investments. Construction. Real Estate*, vol. 8, no. 4, pp. 139–161, 2018. DOI: 10.21285/2227-2917-2018-4-139-161. (In Russian)

[20] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, O. A. Grebneva, S. Yu. Barinova, "Information and computing complex "ANGARA-HN" for automating the calculation and analysis of operating conditions for the control of large multi-loop heat supply systems," *Proceedings of ISTU*, vol. 22, no. 11 (142), pp. 126–144, 2018. (In Russian)

[21] V. V. Tokarev, A. V. Alekseev, N. N. Novitsky, et al, "Development of the information and computing complex "ANGARA-HN" for automating the development of operating conditions of heat supply systems," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. Irkutsk, Russia: ESI SB RAS, 2018, pp. 345–365. (In Russian)

[22] N. N. Novitsky, V. V. Tokarev, Z. I. Shalaginova, A. V. Alekseev, "Principles of implementation and directions of software development for calculating the heat supply systems," in *Information and Mathematical Technologies in Science, Technology and Education. Proceedings of the X Baikal All-Russian Conference*, Irkutsk, Russia, 2005, pp. 285–293. (In Russian)

[23] N. N. Novitsky, Z. I. Shalaginova, V. V. Tokarev, O. A. Grebneva, "Technology for the development of operating conditions of large heat supply systems based on the methods of multilevel thermal-hydraulic modeling," *Proceedings of RAS. Power Engineering*, no. 1, pp. 12–24, 2018. (In Russian)

[24] V. V. Tokarev, Z. I. Shalaginova, "Experience in the application of new technologies for the organization of operating conditions of large heat supply systems," *Proceedings of ISTU*, vol. 59, no. 12, pp. 240–248, 2011. (In Russian)

[25] V. V. Tokarev, Z. I. Shalaginova, "Development of a methodology for multi-level adjustment thermal-hydraulic calculation of heat supply systems and its implementation as part of the ICC "ANGARA-HN"," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. Irkutsk, Russia: ESI SB RAS, 2010, pp. 300–314. (In Russian)

[26] Z. I. Shalaginova, V. V. Tokarev, "Applied problems and methodological approaches to planning and implementation of operating conditions in district heating systems," *Thermal Engineering*, vol. 66, no.10, pp. 714–729, 2019.

[27] Z. I. Shalaginova, V. V. Tokarev, O. A. Grebneva, A. V. Lutsenko, "Technologies for mathematical and computer modeling to automate the process of operational states development for heat supply systems," *E3S Web of Conferences*, vol. 209, ID 02026, 2020.

[28] V. V. Tokarev, Z. I. Shalaginova, "Development of operating conditions of district heating systems with quality regulation," *E3S Web of Conferences*, vol. 102, ID 03011, 2019.

[29] V. V. Tokarev, A. V. Alekseev, Z. I. Shalaginova, "Efficiency increasing by development of district heating systems operational modes using graphical analysis," *E3S Web of Conferences*, vol. 102, ID 04003, 2019.

[30] Z. I. Shalaginova, "Estimating the energy saving potential from adjustment works in heat supply systems on the basis of modeling their thermal-hydraulic operating modes," *Thermal Engineering*, vol. 61, no. 11, pp. 829–835, 2014.

[31] Z. I. Shalaginova, "Methods for analyzing operational controllability and their application for estimating the quality of heat supply systems," *Thermal Engineering*, vol. 59, no. 5, pp. 408–413, 2012.

[32] Z. I. Shalaginova, V. V. Tokarev, "Applied problems and methodological approaches to planning and implementation of operating conditions at district heating systems," *Thermal Engineering*, vol. 66, no. 10, pp. 714–729, 2019.

[33] N. N. Novitsky, "Intelligent pipeline systems as a new object of application of the theory of hydraulic circuits," in *Proceedings of the Conference "Energy of Russia in the XXI century. Innovative Development and Management,"* Irkutsk, Russia, 2015, pp. 378–389. (In Russian)

[34] N. N. Novitsky, M. G. Sukharev, et al, "Methodological problems of pipeline system smartization and directions for the development of the theory of hydraulic circuits for solving them," in *Pipeline energy systems: Mathematical and computer technologies of smartization*. Novosibirsk, Russia: Nauka, 2017, pp. 167. (In Russian)

[35] N. N. Novitsky, Z. I. Shalaginova, A. V. Alekseev, et al,

"Smarter Smart District Heating," *Proceedings of the IEEE*, 2020. DOI: 10.1109/JPROC.2020.2990490.

[36] N. N. Novitsky, "Mathematical modeling of hydraulic chains as cyber-physical object," *E3S Web of Conferences*, vol. 216, 2020.

[37] N. N. Novitsky, "Development of methods of the theory of hydraulic circuits for solving problems of heating systems control," *Thermal Engineering*, no. 12, pp. 38–43, 2009.

[38] N. N. Novitsky, "Development of methods of the theory of hydraulic circuits for the analysis and synthesis of the properties of pipeline systems as objects of control," in *Pipeline Systems of Energy: Mathematical Modeling and Optimization*. Novosibirsk, Russia: Nauka, 2010. pp. 58–75. (In Russian)

[39] N. Novitsky, E. Mikhailovsky, "Generalization of Methods for Calculating Steady-State Flow Distribution in Pipeline Networks for Non-Conventional Flow Models," *Mathematics*, vol. 9, no. 8, pp. 796, 2021. DOI: 10.3390/math9080796.

[40] N. N. Novitsky, E. A. Mikhailovsky, "Object-oriented modeling of hydraulic circuits," *Proceedings of ISTU*, no. 7, pp. 170–176, 2012. (In Russian)

[41] N. N. Novitsky, O. V. Vanteeva, "Modeling of flow distribution stochastics in hydraulic circuits," *Proceedings of RAS. Power Engineering*, no. 2, pp. 145–154, 2011. (In Russian)

[42] N. N. Novitsky, *Estimation of the parameters of hydraulic circuits*. Novosibirsk, Russia: Nauka, 1998, 214 p. (In Russian)

[43] N. N. Novitsky, "Elements of the theory and methods of network identification of pipeline systems," *Proceedings of RAS. Power Engineering*, no. 6, pp. 87–97, 2000. (In Russian)

[44] O. A. Grebneva, N. N. Novitsky, "Optimal planning and processing of the results of testing heat networks for hydraulic and heat losses," *Thermal Engineering*, no. 10, pp. 62–67, 2014.

[45] N. N. Novitskiy, A. V. Alekseev, O. A. Grebneva, A. V. Lutsenko, V. V. Tokarev, Z. I. Shalaginova, "Multilevel modeling and optimization of large-scale pipeline systems operation," *Energy*, vol. 184, pp. 151–164, 2019.

[46] N. N. Novitsky, A. V. Lutsenko, "Discrete-continuous optimization of heat network operating conditions in parallel operation of similar pumps at pumping stations," *Global Optimization*, vol. 66, no. 1, pp. 83–94, 2016.

[47] A. V. Lutsenko, N. N. Novitsky, "Optimization of hydraulic conditions of radial district heating systems with pumping stations," *Energy Systems Research*, 2019, vol. 2, no. 1(5), pp. 34–41, 2019.

[48] A. Alekseev, N. Novitsky, "The concept and technology of a unified digital space organizing of an operational enterprise as a necessary condition for the intelligent automation of pipeline systems," *IOP Conference Series: Materials Science and Engineering*, vol. 667, ID 012003, 2019.

[49] A. V. Alekseev, N. N. Novitsky, "Information and computing spaces integration for operating enterprises of pipeline systems using "ANGARA" computer technology," *E3S Web of Conferences*, vol. 39, ID 04001, 2018.

[50] C. Shen, M. Yun, A. Arora, H.-A. Choi, "Efficient Mobile Base Station Placement for First Responders in Public Safety Networks," *Lecture Notes in Networks and Systems*, vol. 70, pp. 634–644, 2020.

[51] R. Siddavaatam, I. Woungang, S. K. Dhurandher, "Efficient Data Transmission Technique for Big Video Files over HetNet in Emerging 5G Networks," *Advances in Intelligent Systems and Computing*, vol. 926, pp. 713–724, 2020.

[52] N. N. Novitsky, V. V. Tokarev, "Modeling of operating conditions of heat networks in tasks of dispatching control," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 352–361. (In Russian)

[53] Z. I. Shalaginova, "Adaptation of temperature graphs of central control to the operation of heat supply systems based on thermal-hydraulic modeling," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 372–385. (In Russian)

[54] N. N. Novitsky, A. V. Alekseev, "Methods for calculating feasible hydraulic conditions of pipeline networks," in *Pipeline energy systems: Operation and expansion planning*. Novosibirsk, Russia: Nauka, 2004, pp. 361–372. (In Russian)

[55] N. N. Novitsky, V. V. Tokarev, "Consideration of a variety of flow directions when modeling a steady nonisothermal flow distribution in hydraulic circuits," in *Modern methods of optimization and their applications to energy models*. Novosibirsk, Russia: Nauka, 2003, pp. 178–188. (In Russian)

[56] V. V. Tokarev, N. N. Novitsky, "Investigation of the problems of calculating the actual conditions of heat networks according to measurement data," in *Mathematical models and methods of analysis and optimal synthesis of developing pipeline and hydraulic systems*. St. Petersburg, 2006, pp. 47–50. (In Russian)

[57] N. N. Novitsky, V. V. Tokarev, "Calculation of steady-state thermal-hydraulic operating conditions of heat networks based on a limited number of measurements," *Thermophysics and Aeromechanics*, vol. 14, no. 2, pp. 289–298, 2007.

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