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Digital Twin of Urban Heat Networks: Optimization of Energy Systems

Abstract: The paper discusses the concept and importance of the digital twin of a heat network for modern energy systems. A digital twin is a virtual representation of a real heat network, which allows system operators to efficiently manage and optimize heat supply operations. The advantages of using digital twins are in predicting network efficiency and reducing energy losses. The main stages of creating a digital twin of heat networks are given, as well as the required functionality for thermal-hydraulic calculations. As an example, the process of creating a digital twin for the heating network of Pavlodar city is described.

Keywords: digital twin, heat network, efficiency optimization, thermal-hydraulic calculations.

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Introduction

Nowadays, the importance of efficient energy management cannot be overemphasized (Zhapbasbayev et al., 2021; Kolesnikov et al., 2021; Ilmaliyev et al., 2022). This is especially relevant for those regions of Kazakhstan where winters are cold and heating networks play an important role in providing heat and hot water to homes, businesses, and infrastructure in cities and towns. The energy efficiency of heating networks is a pressing issue in Kazakhstan, especially due to the rising costs of energy resources. The introduction of more environmentally friendly and efficient technologies can be a priority to reduce emissions and improve the sustainability of the systems.

Currently, the situation with heat networks in Kazakhstan is characterized by several challenges. Firstly, there is a high degree of wear and an increased risk of accidents in heat networks. According to official data for the current year, heat networks are worn out by 57% on average in the country (On approval…, 2023), and in the northern regions of the country the situation is even more critical. Secondly, the growth of the urban population, intensive housing construction, and development of large and small enterprises puts additional load on the existing heating network, which in turn requires more optimal distribution of heat among consumers.

In addition, the problems of irrational utilization of heat energy pose significant challenges for ensuring a reliable and efficient heat supply. Limitations in control and monitoring systems can make it difficult to optimize the operation of heat networks and make rational decisions. In this regard, the development and implementation of digital twins will be a useful tool for the management, monitoring, and operation of heat supply systems. A digital twin is a virtual model of a real object, system, process, or environment created using modern information technologies (Javaid et al., 2023; Aheleroff et al., 2020; Guerra-Zubiaga et al., 2021; Assawaarayakul et al., 2019). A digital twin is an accurate or approximate representation of the physical characteristics and functionality of an object or system in a virtual environment. It gives a digital representation of a material object, can simulate various processes that can take place in production, and predict their operation in different conditions based on real data. Having sufficient information, the digital twin can recommend necessary solutions (Vachálek et al., 2017; Pires et al., 2019). The software, based on reliable data, determines the operating conditions of physical objects, their states in real time (Uhlemann et al., 2017; Pires et al., 2018).

The digital twin can be used to stress-test of thermal network processes, simulating the best possible operation under emergency conditions. The process of creating a digital twin begins with experts analyzing the mechanics of the physical system and its operational factors to develop a mathematical model that correctly describes the original system (Durão et al., 2018; Aheleroff et al., 2021; Negri et al., 2017; Pang et al., 2021). The digital twin software receives raw data from sensors connected to the physical system. The sensors collect important operational data so that the software can simulate what is happening in real-time in the physical system.

The digital twin software is created by collecting real-time data from real heat network objects. This data is then used to create a digital replica to help better understand and analyze real-world objects or systems (Schroeder et al., 2020; Rolle et al., 2020). The main advantage of the digital twin is that it provides real-time data that can help in learning, analyzing, and understanding how objects and systems function. It allows users to analyze, simulate, and optimize the performance of a physical object throughout its lifecycle

The digital twin of a heat network includes information on the network structure, equipment conditions, heat distribution, and other important parameters. Analysis of the conducted research allows us to conclude that the application of a digital twin in a heat network brings the following benefits: ensuring the reliability of the district heating supply; improving the quality of operational and dispatch management and dynamic stability of the property complex. The digital twin allows heat network operators to allocate resources more efficiently, identify potential problems and vulnerabilities in the heat network, thus contributing to accident prevention and improved service, and optimize system operations, resulting in reduced fuel consumption and greenhouse gas emissions.

Let's list the main advantages of implementing a digital twin of the heating network:

1. Improved Heat Network Management: Operators can quickly respond to changes in demand and operational conditions, minimizing downtime and reducing expenses.
2. Increased Efficiency: Optimization of heat network operations leads to reduced heat losses during transmission and distribution, resulting in cost savings.
3. Greater Transparency: A digital twin provides real-time access to data on the state of the heat network, enabling rapid problem detection and resolution.

Thus, the purpose of creating a digital twin of the heating network is to optimize the management of the heating network, improve reliability and safety, as well as to save resources and reduce environmental impact.

Concept and operating principle of the digital twin of heat network

The control of heat networks is a complex multi-parameter problem, as the process modeling must consider the operation modes of pumps, boiler houses in heat and power plants (HPP), heat points, regulation of network gate valves, etc.

In addition, heat network parameters such as heat loads, average temperatures during cold periods, pipe characteristics, and pump operation during long-term operation are subject to changes from year to year and from season to season. Therefore, it is important to carry out periodic modeling and regular verification of the heat network operation modes. This is necessary because modes that were previously safe may turn out to be emergency or energy-costly the following year.

Based on the integrated data, a mathematical model of the heating network is created; the model allows for various analyses and simulations, predicting the behavior of the system under different conditions and evaluating its efficiency.

The digital twin continuously receives the raw data of the heat network in real-time. This data includes information on heat flow, temperature, pressure, and other parameters. Further, using the obtained data, the condition of the heating network is analyzed, potential problems, leaks, and inefficiencies can be identified and emergency situations can be addressed.

A database is being created and integrated into the digital twin, forming a unified virtual representation of the heat network. This includes geometric parameters (pipes, nodes, substations), thermal characteristics (heat losses, temperature regimes), operational parameter data, etc. Based on the analysis results, the digital twin can offer optimal solutions for heat network management. This may include recommendations for equipment regulation, heat redistribution, and even planning investments for system modernization.

The digital twin can also be used to predict the future state of the heat network under various scenarios of load changes, climatic conditions, and other factors. This aids in long-term planning and decision-making. The application of geoinformation technologies in centralized heating systems is driven by several factors, such as the clarity of information representation, the ability to use a graphical base (map of a city, district, settlement), ease of overlaying the heat network scheme onto the city map with its linkage to existing buildings and structures, quick input of the initial data required for engineering calculations, and the convenience of analyzing the results obtained from the calculations.

Architecture and main elements of the digital twin

The main elements of the digital twin for a heat network include:

1. Location Data: This includes the coordinates of pipelines, nodes, and substations within the heat network, typically integrated with a Geographic Information System (GIS).
2. Network Topology: Information about the structure and connections between different elements within the heat network.
3. Thermal Characteristics: Data regarding heat losses, temperature regimes, and other thermal properties.
4. Mathematical Model: This describes the physical processes occurring within the real heat network and may encompass equations for heat exchange, hydraulic calculations, and other mathematical models.
5. Algorithms: These utilize data and models for monitoring, diagnostics, forecasting, and optimization of heat network operations.
6. Graphic Interface: A user-friendly interface that allows operators and engineers to interact with the digital twin, visualize data, and receive reports and notifications.
7. Simulation and Virtualization Tools: These enable testing and analysis of various scenarios involving changes to heat network parameters.
8. Database: This stores all parameters related to heat network objects, as well as historical data on heat supply system operations for subsequent analysis and reporting.

Heat network parameters

Objects within the heat network (HN) can be viewed as nodes and edges in an undirected graph of the network. Among the nodes of the HN are heat chambers (HC), central heating points (CHP), pumping stations (PS), heat and power plants (HPP), pipe branching points, and pipe parameter change points. The edges of the HN graph represent sections of pipes between nodes, where the flow rate of the heat transfer medium and pipe parameters remain constant in terms of length.

The parameters of the HN are categorized into the following groups:

- Structure of Connection of HN Objects.
- Parameters of Pipe Sections.
- Parameters of Pumping Stations.
- Parameters of Heat and Power Plants.
- Parameters of Heat Chambers.

For HN, a clear structure of connecting HN components must be defined, which describes the hydraulic connections between network nodes. The connection of network nodes should be accomplished through network edges, which correspond to the respective sections of pipes.

The parameters for pipe sections include the following data for both forward and return pipes:

- Length of the pipe section.
- Internal and external diameters of the pipe.
- Roughness of the inner pipe wall.
- A list of local resistance objects with corresponding coefficients or the value of the total local resistance coefficient.
- Thickness and type/grade of pipe insulation (or insulation thermal conductivity coefficient).
- Thermal conductivity coefficient of the surrounding soil (for underground pipe installation).
- Elevation points of the pipe axis and ground surface.
- Factory-tested maximum pressure rating.
- List of pipe defects. For each defect, its location along the pipe section and its maximum pressure should be specified.
- Year of commissioning.

PS and HPP are considered sources of pressure supply into the network and include the following data:

- List and schematic diagram of pump unit connections.
- Presence of a pressure-reducing valve at the station's outlet.
- Presence of a Variable Frequency Drive (VFD). When a VFD is present, it needs to be linked to the corresponding pump units.
- Parameters of each pump unit (PU).

The parameters for each PU within a PS or HPP should include the following data:

- Passport relationship between head and flow rate of the pumped water.
- Passport relationship between the pump's efficiency and the flow rate of the pumped water.
- Passport operating range for the flow rate of pumped water.
- Passport value of rotor rotation frequency.
- Nominal power of the electric motor.
- Electric motor efficiency at nominal load.
- Rotor rotation frequency of the electric motor.

For HPP, which is considered as a source of heat transfer medium, the parameters should include, in addition to the previously mentioned ones, the following data:

- Number of heat outputs.
- Efficiency of boiler units or turbine units (depending on the type of heater in the HPP).
- Type of combustible fuel.

For HC and CHP, which are considered as consumers of the heat transfer medium, and are assumed to be connected to the corresponding distribution network (one or several district networks), and where the pressure in the respective network can be regulated by valves in the HC or CHP, located at the inlet of the supply and return pipelines of the distribution network (DN), the parameters for HC and CHP should include the following data:

- Maximum height of buildings connected to the DN with the specified HC or CHP.
- Dependency of the heat transfer medium consumption by the connected DN on the available pressure after the valves in the node.
- Dependency of local resistance on the degree of opening of the valve on the supply pipeline of the DN.
- Dependency of local resistance on the degree of opening of the valve on the return pipeline of the DN.
- Additionally, for each HN object in the city, tariffs for electricity from power plants and HPPs, as well as tariffs for combustible fuel at HPPs, should be determined.

Data Collection and Analysis for the Heat Network

The creation of a digital twin for the heat network begins with the development of a virtual replica of the network using data regarding its structure, parameters, geographical location, and other characteristics. These data can be obtained from relevant organizations that manage or own urban heat networks, and they can also be collected through sensors, Geographic Information Systems (GIS), thermal imaging, satellite imagery, and other sources.

The digitization of the urban heat network will be carried out using the following initial data, as illustrated in Fig. 1: characteristics of pipelines; and heat supply objects.

Data collection and analysis for the heat network allows system operators to manage and monitor its operations more effectively, identify issues at early stages, and optimize processes to enhance the reliability and efficiency of the heat supply system. To collect data, the following steps are necessary:

- Placement of sensors and probes at various points within the heat network to monitor various parameters such as temperature, pressure, heat flow, and equipment efficiency.
- Use of automatic data collection systems that regularly read information from sensors and transmit it to a central server.
- Creation of GIS maps of the heat network, including information about the location of pipes, nodes, and other infrastructure elements.
- Implementation of monitoring and control systems that enable operators to monitor the heat network's performance in real-time and respond to potential problems.
- Data processing using specialized software platforms and algorithms for analysis and interpretation.
- Conducting regular inspections and surveys of the heat network to identify potential problems.
- Analysis of heat consumption data by various consumers and assessment of system efficiency.
- Presentation of data in the form of graphs, charts, and reports for ease of interpretation and decision-making.
- Use of data to optimize the heat network's operations and predict future changes in consumption and heat network parameters.
- Application of machine learning algorithms for data analysis.

Next, we carry out problem identification, i.e., we need to identify potential problems in the operation of the heating network, such as leakages, inefficiencies, and overloads by analyzing the data.

The next step is to assess the efficiency of the heat supply system, as well as its energy utilization factor. It is necessary to compare the actual performance with the designed performance.

Finally, the data should be used to predict future heat demand and changes in the heat network parameters, which will allow planning of long-term measures.

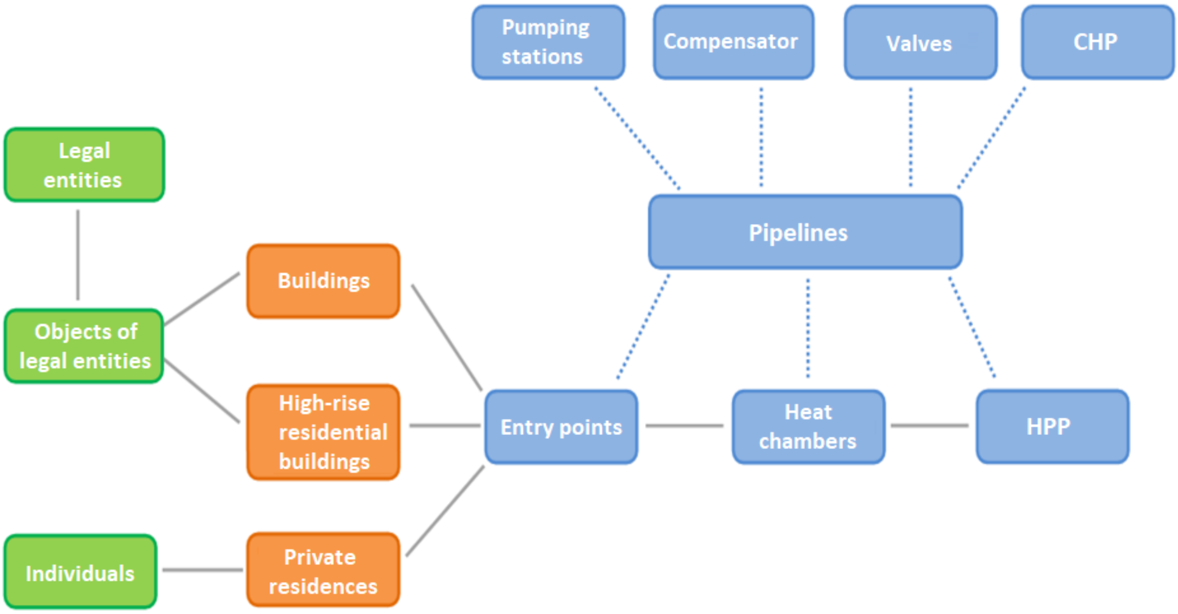


Fig. 1. Objects of the Urban Heat Network for Digitization

Types of calculations performed by the digital twin

The digital twin program will perform the following types of calculations:

1) adjustment calculation of the heat network;
2) verification calculation of the heat network;
3) calculation of heat losses;

4) calculation of hydraulic shock;
5) calculation of the reserve capacity of the heat network section.

The purpose of adjustment calculation is to ensure that all consumers connected to the district heating network receive the necessary amount of thermal energy and network water at an optimal operating mode of the centralized heating system as a whole.

As a result of the adjustment calculation, the following are determined: the identification numbers of elevators, the diameters of nozzles and throttling devices (for consumers, CHPs, and cluster washers), as well as the locations for their installation.

The calculation is carried out considering various schemes for connecting consumers to the heat network and the degree of automation of the connected heat loads.

The purpose of verification calculation is to determine the actual consumption of the heat transfer fluid at various sections of the district heating network and at consumers, as well as the amount of thermal energy received by the consumer at a given water temperature in the supply pipeline and available head at the heat source. In this process, it is possible to analyze the hydraulic and thermal operation modes, as well as to forecast changes in the internal air temperature of consumers. Calculations can be conducted with various input data, including emergency situations, such as the shutdown of individual sections of the district heating network, transfer of water and thermal energy from one source to another through one of the pipelines, and others.

Verification calculations allow for the calculation of any accidents or incidents on the district heating network pipelines and the heat source. The results of the calculation include flow rates and pressure losses in the pipelines, pressures at network nodes, including available pressures at consumers, the temperature of the heat transfer fluid at network nodes (considering heat losses), indoor air temperatures at consumers, flow rates, and water temperatures at the inlet and outlet of each heating system. When multiple heat sources are connected to one network, the distribution of water and thermal energy between the sources is determined.

Calculation of heat losses of a heat network is an important part of designing and assessing the efficiency of a heat supply or heating system. This calculation makes it possible to determine the amount of heat that is lost in the process of heat transfer through heat networks and structures. Knowing the heat losses allows us to optimize the system and save resources.

The goal of this calculation is to determine the normative heat losses through the insulation of the pipelines over the course of a year. Heat losses are calculated annually, broken down by each month, considering the operation of the district heating pipelines during different periods (summer and winter).

The results of the calculation can be viewed both as a summary for the entire district heating network and for each individual heat source and each Central Heating Plant (CHP). It can also be analyzed according to different owners of district heating sections.

Calculating thermal losses helps assess the efficiency of the heating system and can be valuable in making decisions regarding system modernization or optimization to save energy and resources.

The purpose of hydraulic regime calculation is to determine the various temporal states of the heat supply system (distribution of pressure, temperature, and flow rates) and the actual thermal load received by the consumer nodes of the heat supply system when the operation mode of the pumping stations (PS) or heat and power plants (HPP) is changed or when the parameters of the regulating valves in the consumer nodes of the heat supply system are altered. Thus, in both cases, a non-stationary transient process is considered from the initial established state of the heat supply system to a new state. In the case of simulating a transient regime, it is assumed that changes in the operation mode of the PS, HPP, or valves occur relatively smoothly. In the case of simulating a hydraulic shock, it is assumed that changes in the operation mode of the PS, HPP, or valves occur very abruptly (e.g., sudden pump shutdown in the heat supply system), which can lead to the occurrence of a hydraulic shock in the pipes of the heat supply system.

The methodology for calculating the heat network pipe section reserve depends on many factors, including the condition of the network, its parameters, and the availability of data.

To perform this calculation, all available data about the pipelines are required, including their technical specifications (diameter, wall thickness, material), installation date, and previous historical data on repairs and replacements.

Data regarding the condition of the pipes resulting from in-pipe diagnostics is necessary to assess the level of corrosion and wear. The assessment may involve determining the remaining wall thickness and the assumed corrosion rate.

Based on the corrosion and wear assessment data, as well as the current condition of the pipelines, the remaining life can be determined for each pipeline section. This can be expressed in terms of years, load cycles, or percentage of wear.

It is essential to identify the pipeline sections where the remaining life is the lowest and where there is the highest risk of failure or deterioration.

Remaining life refers to the duration of safe operation of the pipeline under permissible parameters from the current moment until its projected ultimate condition. The forecasting of the remaining resources of the pipeline is based on the results of the technical condition assessment, the study of mechanical properties and microstructure of the material, an evaluation of the actual load on the main load-bearing elements of the pipeline, and hydraulic (pneumatic) testing with a trial pressure.

Monitoring the condition of heat networks is crucial for ensuring their efficient operation and for responding to changes and emergencies promptly. The implementation of a real-time monitoring and control system allows operators to react to fluctuations and incidents immediately.

The digital twin should include a specialized module for viewing various historical measurements. In this module, historical data can be viewed in two modes:

- Viewing changes in historical data over time for the selected period of HN operation, i.e. the data of selected measurements are displayed as curves on a graph with the abscissa axis being the time scale.
- Viewing the status of the HN along its length for a specific date: the data is displayed either as points on a graph with the abscissa axis being the pipeline route kilometer or as a colored map of the HN.

These capabilities enable operators to gain insights into the past performance of the HN, identify trends, and assess its current condition. It also provides a valuable tool for troubleshooting and making informed decisions to optimize the operation and maintenance of the district heating system.

Optimizing the operation of heat networks

A digital twin of HN can help optimize its operation, performance, and efficiency in real-time, leading to significant economic and environmental benefits.

To optimize the operation of a district heating system, it is necessary to integrate the software with various information systems, such as SCADA (Supervisory Control and Data Acquisition), and ensure regular access and data updates to keep the information up to date.

Using the digital twin, various scenarios of the HN operation can be modeled, including changes in load, temperature distribution, equipment control, and more. By analyzing the results of modeling, optimal solutions can be determined to improve the efficiency and reliability of the system.

Integrating real-time control with the digital twin allows for rapid response to changes in the system. Automated algorithms can be used to optimize system operations, such as load management and heat distribution.

Furthermore, data from the digital twin can be used to forecast future states of the system and predict potential failures. Diagnostic algorithms can automatically detect and warn of potential issues.

Data analysis and optimization of the district heating system enable more efficient and cost-effective operation, ensuring high reliability and meeting the needs of users.

Creation of a digital twin of the district heating system for the city of Pavlodar

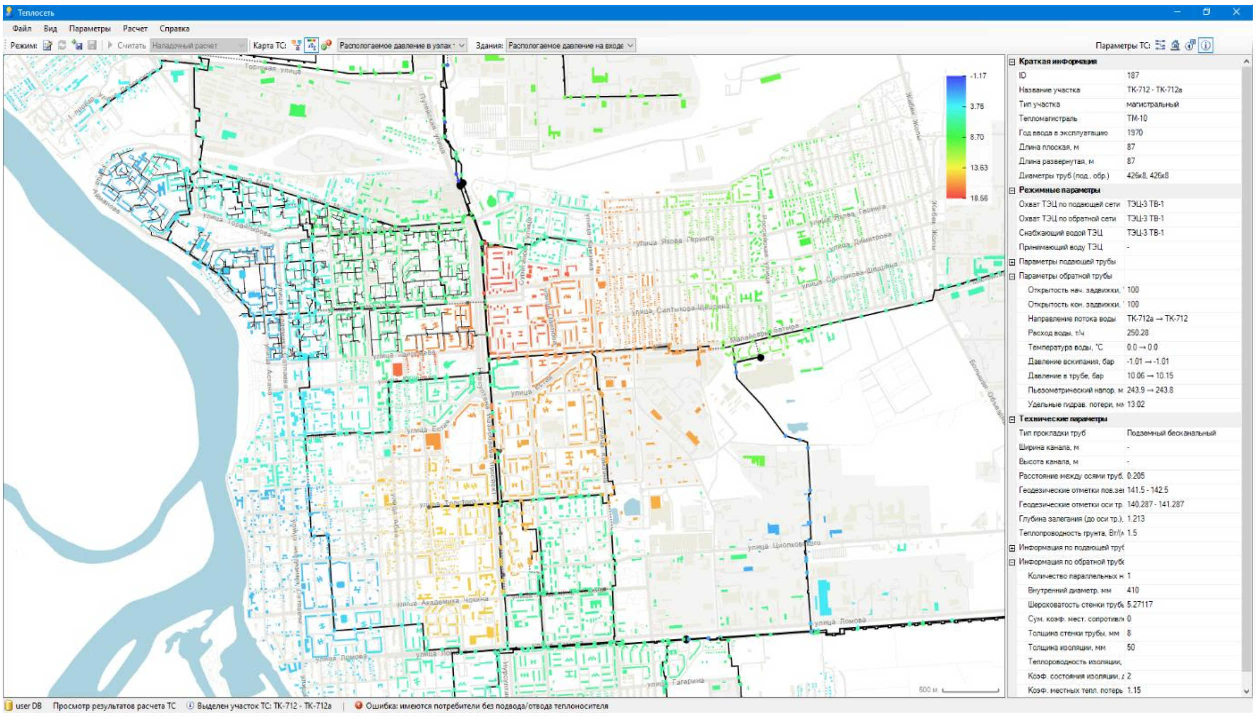
We are currently developing a digital twin of the heating network of Pavlodar city. The following steps have been taken:

- Data collection, including information about the distribution of pipelines, heat consumption, equipment characteristics, and more. At this stage, maps of the city's heating network have been digitized (Fig. 2), including 44 main heating networks, 587 network nodes (thermal chambers, pump stations, CHP, HPP outlets, branching, and pipe transition points), 623 sections of heating pipelines along the city streets, and 900 local pipe resistances.
- Creation of a data input interface (Fig. 3), modules for conducting thermal-hydraulic network calculations, a result viewing interface, and a database.

The following data have been entered into the database of the Digital Twin:

- Parameters of pipeline sections: pipe diameters and lengths, inner wall roughness, local pipe resistances, insulation thickness and type, burial depth, maximum allowable pressures, list of pipe defects, and elevation marks.

- Network pipeline connection structure: the location of heating network objects, pipe locations, and connections.
- Pump station parameters: a list and location of pump units, head and efficiency curves of rotors, and parameters of pump motors.
- HPP parameters: a list and location of pump units, head and efficiency curves of rotors, motor parameters, parameters of boiler units and turbo units, and the number of heat outputs.
- Thermal chamber parameters: the relationship between heat carrier flow and available chamber head, the minimum required static head for high-rise buildings.



Режим: Нападочный расчет | Карта ТС: Распологаемое давление в узлах | Здания: Распологаемое давление на входе

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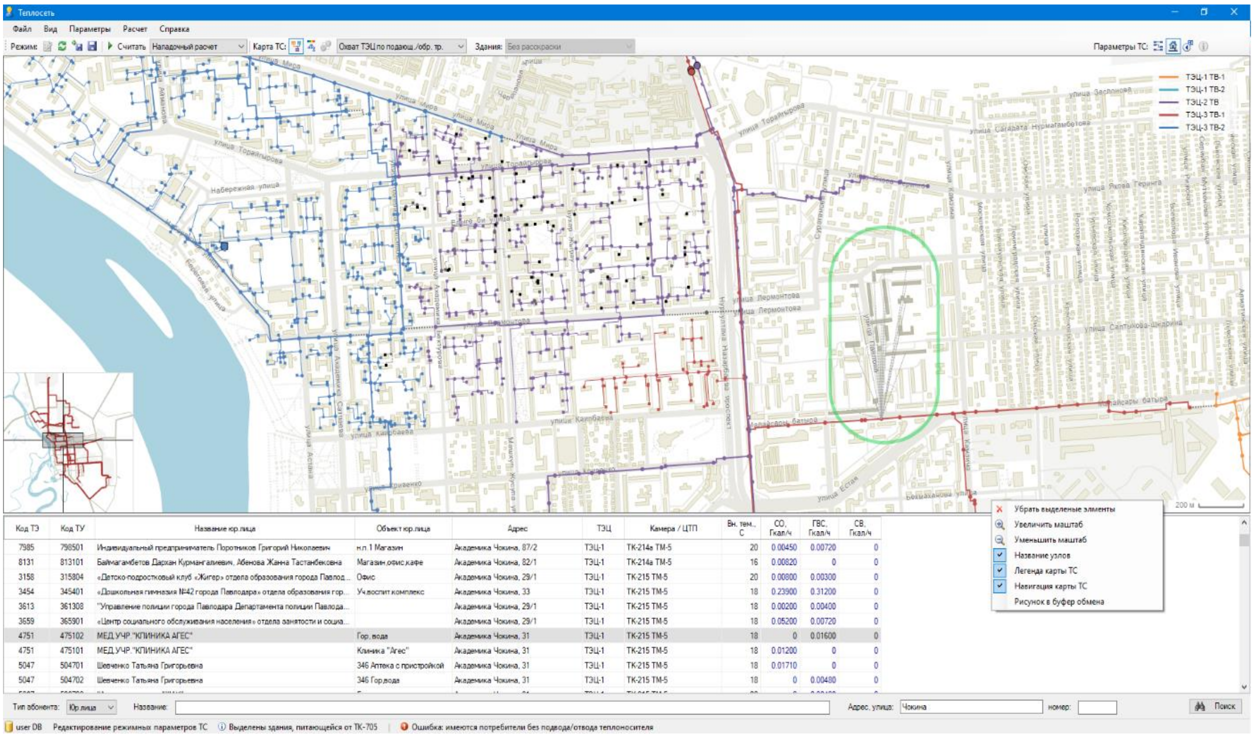
ID	187
Название участка	ТК-712 - ТК-712а
Тип участка	магистральный
Тепломагистраль	ТМ-10
Год ввода в эксплуатацию	1970
Длина плоская, м	87
Длина развернутая, м	87
Диаметры труб (под., обр.)	426x8, 426x8
Режимные параметры	
Охват ТЭЦ по подающей сети	ТЭЦ-3 ТВ-1
Охват ТЭЦ по обратной сети	ТЭЦ-3 ТВ-1
Снабжающий водой ТЭЦ	ТЭЦ-3 ТВ-1
Принимающий воду ТЭЦ	-
Параметры подающей трубы	
Параметры обратной трубы	
Открытость нач. задвижки,	100
Открытость кон. задвижки,	100
Направление потока воды	ТК-712а → ТК-712
Расход воды, т/ч	250.28
Температура воды, °С	0.0 → 0.0
Давление вскипания, бар	-1.01 → -1.01
Давление в трубе, бар	10.06 → 10.15
Пьезометрический напор, м	243.9 → 243.8
Удельные гидрав. потери, мм	13.02
Технические параметры	
Тип прокладки труб	Подземный бесканальный
Ширина канала, м	-
Высота канала, м	-
Расстояние между осями труб.	0.205
Геодезические отметки пов.зе	141.5 - 142.5
Геодезические отметки оси тр.	140.287 - 141.287
Глубина залегания (до оси тр.),	1.213
Теплопроводность грунта, Вт/(	1.5
Информация по подающей труб	
Информация по обратной трубе	
Количество параллельных н	1
Внутренний диаметр, мм	410
Шероховатость стенки трубы	5.27117
Сум. коэф. мест. сопротивл	0
Толщина стенки трубы, мм	8
Толщина изоляции, мм	50
Теплопроводность изоляции,	
Коэф. состояния изоляции,	2
Коэф. местных тепл. потерь	1.15

user DB Просмотр результатов расчета ТС | Выделен участок ТС: ТК-712 - ТК-712а | Ошибка: имеются потребители без подвода/отвода теплоносителя

Fig. 2. Digital Twin Interface



Режим: Нападочный расчет | Карта ТС: Охват ТЭЦ по подающ./обр. тр. | Здания: Без раскраски

Код ТЭ	Код ТУ	Название юр.лица	Объект юр.лица	Адрес	ТЭЦ	Камера / ЦТП	Вн. тем., С	СО, Гкал/ч	ГВС, Гкал/ч	СВ, Гкал/ч
7985	798501	Индивидуальный предприниматель Поротников Григорий Николаевич	н.п.1 Магазин	Академика Чокина, 87/2	ТЭЦ-1	ТК-214а ТМ-5	20	0.00450	0.00720	0
8131	813101	Баймагамбетов Дархан Курмангалиевич, Абенова Жанна Тастанбековна	Магазин,офис,кафе	Академика Чокина, 82/1	ТЭЦ-1	ТК-214а ТМ-5	16	0.00820	0	0
3158	315804	«Детско-подростковый клуб «Жигер» отдела образования города Павлод...	Офис	Академика Чокина, 29/1	ТЭЦ-1	ТК-215 ТМ-5	20	0.00800	0.00300	0
3454	345401	«Дошкольная гимназия №42 города Павлодара» отдела образования гор...	Уч.воспит.комплекс	Академика Чокина, 33	ТЭЦ-1	ТК-215 ТМ-5	18	0.23900	0.31200	0
3613	361308	"Управление полиции города Павлодара Департамента полиции Павлода...		Академика Чокина, 29/1	ТЭЦ-1	ТК-215 ТМ-5	18	0.00200	0.00400	0
3659	365901	«Центр социального обслуживания населения» отдела занятости и социа...		Академика Чокина, 29/1	ТЭЦ-1	ТК-215 ТМ-5	18	0.05200	0.00720	0
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4751	475101	МЕД.УЧР."КЛИНИКА АГЕС"	Клиника "Агес"	Академика Чокина, 31	ТЭЦ-1	ТК-215 ТМ-5	18	0.01200	0	0
5047	504701	Шевченко Татьяна Григорьевна	346 Аптека с пристройкой	Академика Чокина, 31	ТЭЦ-1	ТК-215 ТМ-5	18	0.01710	0	0
5047	504702	Шевченко Татьяна Григорьевна	346 Гор.вода	Академика Чокина, 31	ТЭЦ-1	ТК-215 ТМ-5	18	0	0.00480	0

Тип абонента: Юр.лица | Название: | Адрес, улица: Чокина | номер:

user DB Редактирование режимных параметров ТС | Выделены здания, питающейся от ТК-705 | Ошибка: имеются потребители без подвода/отвода теплоносителя

Fig. 3. Data Input Interface

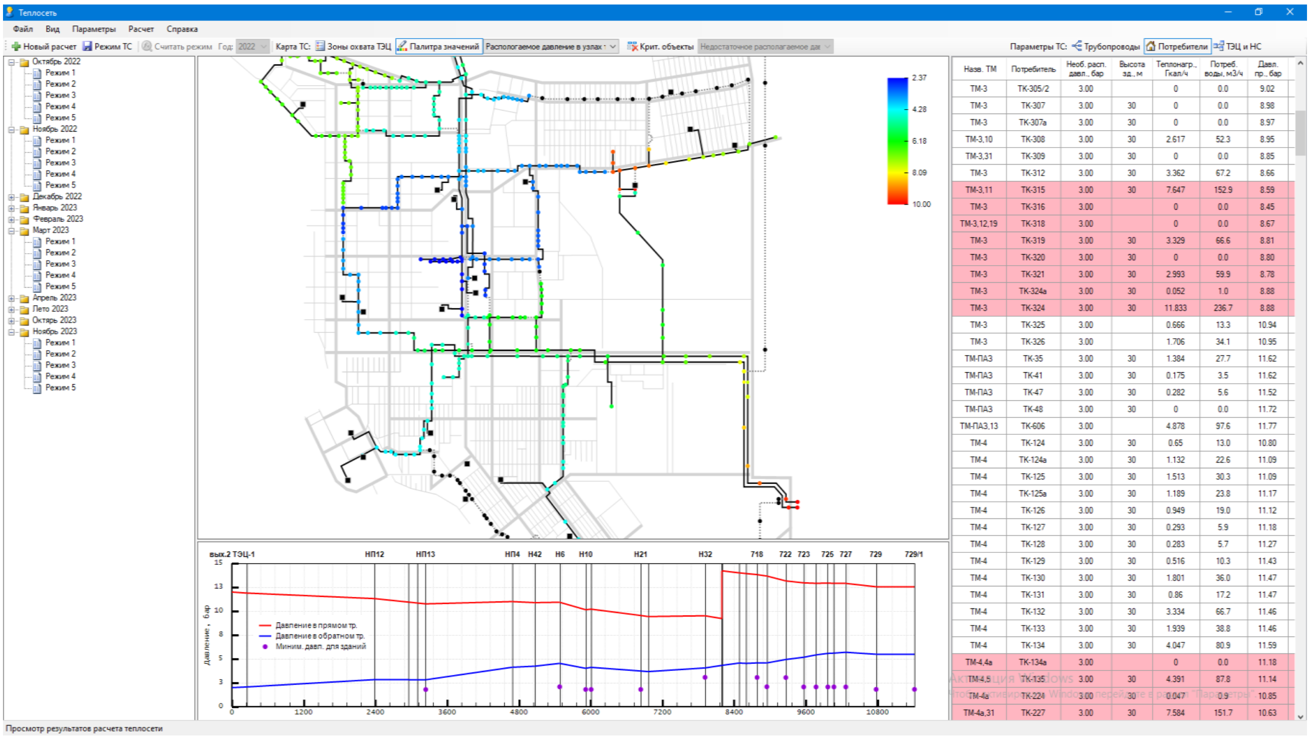
Algorithms have been developed for the following types of calculations:

- Thermal-hydraulic network calculations;
- Selection of the required temperature mode for HPP;
- Selection of the required operating mode for pumps at pumping stations and HPP;
- Optimization calculations to ensure the required thermal mode with minimal costs for the operation of HPP and PS.

For a more visual representation, the calculation results are displayed (Fig. 4) in the form of tables, graphs, diagrams, or on a color-coded map of the entire heating network. Various filters and slices can be made over the output data, as well as the coloring of heat network elements. The following parameters of the heating network can be obtained from thermal-hydraulic calculations:

- Pressure distribution in the network, which allows for assessing the dynamics and pressure variations in the heating network at different sections. This provides information about the load level and potential bottlenecks in the system.
- Temperature distribution in the network to represent the thermal regime.
- Flow rate of the heat transfer medium in the network, which allows evaluating the efficient use of resources and identifying opportunities for energy savings.
- Pressure at the inlet/outlet of the pumping station and HPP. Monitoring pressure at pumping stations and HPP is a critical factor for ensuring the reliable operation of the system.
- Temperature of the heat transfer medium at the outlet/inlet of HPP.
- The amount of electricity consumed by pumps at the PS and HPP, which allows for assessing the efficiency of pumping stations' operation and optimizing their energy consumption.
- The amount of fuel burned at HPP for balancing energy costs and resource savings.

These calculation results provide operators and engineers with valuable information for more effective management and optimization of the city's heating network, contributing to the stable and efficient heat supply of Pavlodar.



Назв. ТМ	Потребитель	Необ. расп. давл., бар	Высота зд., м	Теплонагр., Гкал/ч	Потреб. воды, м3/ч	Давл. пр., бар
ТМ-3	ТК-305/2	3.00		0	0.0	9.02
ТМ-3	ТК-307	3.00	30	0	0.0	8.98
ТМ-3	ТК-307а	3.00	30	0	0.0	8.97
ТМ-3,10	ТК-308	3.00	30	2.617	52.3	8.95
ТМ-3,31	ТК-309	3.00	30	0	0.0	8.85
ТМ-3	ТК-312	3.00	30	3.362	67.2	8.66
ТМ-3,11	ТК-315	3.00	30	7.647	152.9	8.59
ТМ-3	ТК-316	3.00		0	0.0	8.45
ТМ-3,12,19	ТК-318	3.00		0	0.0	8.67
ТМ-3	ТК-319	3.00	30	3.329	66.6	8.81
ТМ-3	ТК-320	3.00	30	0	0.0	8.80
ТМ-3	ТК-321	3.00	30	2.993	59.9	8.78
ТМ-3	ТК-324а	3.00	30	0.052	1.0	8.88
ТМ-3	ТК-324	3.00	30	11.833	236.7	8.88
ТМ-3	ТК-325	3.00		0.666	13.3	10.94
ТМ-3	ТК-326	3.00		1.706	34.1	10.95
ТМ-ПАЗ	ТК-35	3.00	30	1.384	27.7	11.62
ТМ-ПАЗ	ТК-41	3.00	30	0.175	3.5	11.62
ТМ-ПАЗ	ТК-47	3.00	30	0.282	5.6	11.52
ТМ-ПАЗ	ТК-48	3.00	30	0	0.0	11.72
ТМ-ПАЗ,13	ТК-606	3.00		4.878	97.6	11.77
ТМ-4	ТК-124	3.00	30	0.65	13.0	10.80
ТМ-4	ТК-124а	3.00	30	1.132	22.6	11.09
ТМ-4	ТК-125	3.00	30	1.513	30.3	11.09
ТМ-4	ТК-125а	3.00	30	1.189	23.8	11.17
ТМ-4	ТК-126	3.00	30	0.949	19.0	11.12
ТМ-4	ТК-127	3.00	30	0.293	5.9	11.18
ТМ-4	ТК-128	3.00	30	0.283	5.7	11.27
ТМ-4	ТК-129	3.00	30	0.516	10.3	11.43
ТМ-4	ТК-130	3.00	30	1.801	36.0	11.47
ТМ-4	ТК-131	3.00	30	0.86	17.2	11.47
ТМ-4	ТК-132	3.00	30	3.334	66.7	11.46
ТМ-4	ТК-133	3.00	30	1.939	38.8	11.46
ТМ-4	ТК-134	3.00	30	4.047	80.9	11.59
ТМ-4,4а	ТК-134а	3.00		0	0.0	11.18
ТМ-4,5	ТК-135	3.00	30	4.391	87.8	11.14
ТМ-4а	ТК-224	3.00	30	0.047	0.9	10.85
ТМ-4а,31	ТК-227	3.00	30	7.584	151.7	10.63

Fig. 4. Calculation results output

The further development stages of the digital twin program for the heating network may include the following steps to expand its functionality:

1) Integration of the digital twin with control and monitoring systems to obtain real-time network status information, increase responsiveness, and automate responses to changes.
2) Development of a module for optimization calculations to ensure the required thermal regime for heating the population.
3) Modeling and analysis of various scenarios of the heating network's operation to assess efficiency, forecast loads, and optimize heat distribution.
4) Determination of the system's reliability (forecasting emergency situations) in heat supply.
5) Predicting future states of the system and diagnosing potential problems, which will aid in planning repairs and maintenance.

Conclusions

In the contemporary economic climate, characterized by acute oscillations in global market prices of nickel and cobalt, an exigent issue arises regarding the economically viable processing of low-grade oxidized nickel ores indigenous to Kazakhstan. In an endeavor to address this, we proposed a novel and more promising hydrometallurgical methodology as a feasible alternative to the extant ore processing techniques being implemented within the nation.

The novelty of our technology revolves around the comprehensive extraction of nickel and cobalt from oxidized nickel-cobalt-bearing resources. This innovative approach is distinctive in its obviation of the high-temperature process. Conventionally, this process is notorious for the emission of noxious gases and has a proclivity for energy profligacy. Our method, thus, not only minimizes environmental hazards but also underscores energy conservation - features that are instrumental in driving the transition towards sustainable mining practices.

Upon meticulous analysis of the experimental data gleaned from our research, we ascertain that our groundbreaking technology facilitates enhanced extraction efficacy of nickel and cobalt from refractory oxidized ores. We therefore postulate that the deployment of this technology in industrial-scale operations can potentially revolutionize the nickel and cobalt mining landscape by augmenting metal recovery rates, thereby maximizing resource utilization and industrial efficiency.

In summary, our work is not only responsive to the immediate challenges posed by fluctuating commodity prices, but it also sets a benchmark for future endeavors in the field, thus pushing the frontier of sustainable mining practices. Further research will be instrumental in understanding the scalability of this innovative technology and its broader implications for the industry.

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