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Mathematical Models and Methods of the Analysis and Optimal Synthesis of the Developing Pipeline and Hydraulic Systems 2022

The current state of district heating processes in China and directions for the development of the methodological and instrumental base to support them

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Abstract. The article assesses the current state of district heating systems covering more than 100 cities in northern China. The main features of such systems, as well as the problems that arise during their design and operation, are disclosed. The relevance of the development and application of independent methods of mathematical and computer modeling to solve these problems is disclosed. As a methodological basis, it is proposed to use the modern achievements of the theory of hydraulic circuits developed at the Energy System Institute of the Siberian Branch of the Russian Academy of Sciences. The characteristics of the possibilities of the software tools available here are given. The main directions and prospects for the development of these scientific, methodological and software developments are disclosed.

1. Current status, features and development trends of district heating systems in China

Increasing the efficiency of energy use, meeting the tightening environmental requirements, providing heat to the population and industry is possible only on the basis of heating large territories and cities in northern China using district heating systems (DHS). Creation of DHS is the main way of development of large cities. With the advancement of the urbanization process in China, DHS area has expanded every year. So in China, urban district heating area in 2022 was about 11.367 billion m^2, an increase of 7.53% year on year, and the average annual compound growth rate over the past 7 years is 7.73%.

Most of China's DHS use coal-fired heat sources (HS), supplying over 6 billion m^2. In response to the government's call, some small towns are using cleaner energy technologies such as natural gas heating 2.8 billion m^2, electricity 1 billion m^2, geothermal heating 1.6 billion m^2, biomass heating 250 million m^2, solar heating 50 million m^2, nuclear - 400 million m^2, waste heat recovery from industrial and energy enterprises - 200 million m^2.

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Low cost is the main advantage of coal-fired cogeneration. However, its shortcomings are also obvious - district heating networks are difficult to extend too much of the countryside. China's urban area is also large, with a large population and a huge heating area. So in the north of China there are more than 20 cities with a population of over 5 million people. Some cities already have DHS, some are under construction or planned for implementation. Today, there are more than 100 cities with DHS in northern China. Most DHS companies operate with low efficiency. In recent years, both the government and heat supply companies have begun to pay attention to improving the DHS efficiency.

In the future, the main HS will be nuclear and coal-fired power plants, which will supply heat to residents of large cities through main pipelines. Small and medium cities will use biomass, solar energy, heat pumps and other heating technologies. Natural gas has a limited distribution due to its high cost.

In order to reduce the impact of HS on the environment in large cities, coal-fired boilers were excluded, and waste heat from power plants located far from the city began to be used more. Therefore, to transport hot water from HS to the city, main, long distance pipelines with a diameter of 1200-1600 mm and a length of about 30-70 kilometers are required, and the height difference is sometimes 100-300 meters. The main (transmission) heating network of the city is connected to these pipelines through heat exchangers. Distribution networks that directly supplying consumers are connected with transmission networks through central heating points (CHP). A typical DHS scheme in China is shown in Fig. 1.

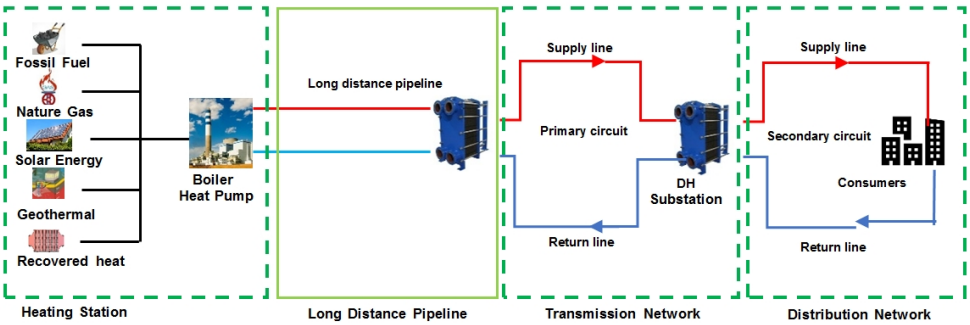

Fig. 1. Scheme of a typical DH system in China.

Problems faced by the technology of district heating with remote HS: 1) large heat losses associated with the remoteness of HS from consumers; 2) the need to reduce the temperature of the return water and utilize the waste heat of the power plant; reduction in the cost of heat; 3) ensuring uninterrupted and safe operation of the DHS, including by preventing water hammer; 4) ensuring full-scale control over the DHS and increasing the level of self-control of the staff; 5) ensuring the efficiency of heat transfer by controlling the temperature drop in pipeline sections.

All DHSs in large cities have two to four HSs, an tree or ring network structure, and the DHS load can be 500-2000 MW. Pumping stations are located at sources, in the network of heating mains to the city, main heating networks and in CHP. The development of the DHS operation mode is come down to the creation of a piezometric map from the HS to the most unfavorable consumer to assess the supply of heat to consumers at given pressures at the source and pumping stations.

Unlike transmission networks, the distribution heat network is usually equipped with frequency-controlled pumping stations located in the CHP or at the consumers. The ideal scheme for variable speed heating is to install a low head variable frequency pump at the heat source, which reduces electricity consumption, and a variable frequency booster pump on the return pipe of each consumer to ensure the required heating temperature.

Energy saving based on the intellectualization of DHS has become a key trend in the industry today. With the introduction of regulatory documents such as the «Notice of the state council on the comprehensive work plan for energy saving and emission reduction in the 13th five-year plan», the state has stepped up efforts in the field of energy saving and emission reduction. The energy-saving transformation of DHS is supported by the Internet of Things, consisting of sensors, data acquisition and transmission equipment, which provides intelligent decision support for operational management and effectively reduces current energy consumption. Compared with traditional DHS, smart district heating has four characteristics: smart operation, smart control, smart transmission and distribution, and smart maintenance.

2. Existing methodological base and software for large DHS modeling

A review of the current state of DHS in the world [14] showed that today the intellectualization of DHS is a relevant and practically uncontested direction of their innovative transformation. International experience in the development of district heating technologies shows that there are all the necessary prerequisites for the intellectualization of the processes of technological management of DHS. Such studies can be based on the one formulated and developed at the Energy Systems Institute named after Melentyev (ESI) of the Siberian Branch of the Russian Academy of Sciences - Theory of Hydraulic Circuits (THC) [1,2]. Within the framework of this scientific direction, a unique experience has been gained in the development of methodological and software for solving problems of modeling, calculating and optimizing the operating modes of pipeline systems of various types and purposes, which is used in dozens of research, design and operational enterprises in Russia and neighboring countries.

To date, many software systems have been developed in the world for DHS operation modes modeling: «ANGARA-HN» (Russia), Potok (Russia), Termis (EU), NEPLAN (Switzerland), NetSim (Sweden), STANET (Germany), PSS Singal (Germany), Wanda (Netherlands) and other software systems [5]. The basic methods for calculating hydraulic modes are the general methods for calculating the flow distribution: the pressure method [6], loop method [1], the global gradient method [7], and other optimization methods [8,], which have been generalized and most developed based on the THC.

The results of these studies are implemented in the information-computing complex (ICC) "ANGARA-HN" (Fig. 2.) and provide [3] the solution of the following main tasks: single- and multi-level adjustment and checking calculations of the hydraulic mode, temperature field and thermal-hydraulic mode of DHS operating [1, 4]; calculation and plotting of piezometric graphs, temperature graphs of heat supply at sources; calculation of the parameters of throttling devices at consumers and in the heating network; calculation of hydraulic and thermophysical parameters of pipelines.

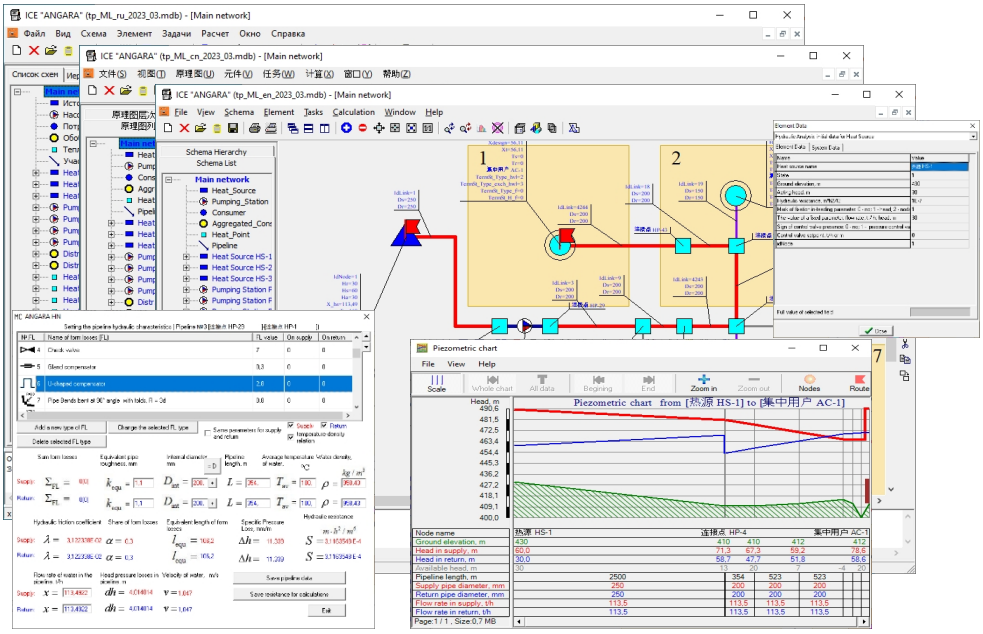

Fig. 2. «ANGARA-HN» interface.

To date, many years of experience in the practical application of the ICC «ANGARA-HN» in various fields have been accumulated - to develop recommendations for organizing the operating modes of existing DHS, automating workplaces for specialists in design and operating organizations, teaching students and graduate students, and for scientific research. Methods and algorithms have been widely tested in the calculation of HSS modes of the cities of the CIS countries, Mongolia and China: Irkutsk, Angarsk, Bratsk, Shelekhov, Ust-Kut, Cheremkhovo, Zheleznogorsk Ilimsky, Moscow, St. Petersburg, Yekaterinburg, Kiev, Dnepropetorovsk, Ulan -Bator, Darkhan, Tyumen, Tambov, Petropavlovsk-Kamchatsky, Luoyang, Dalian, Jinan, Xi 'an, Beijing, Wuhan, Daqing, etc. This was made possible thanks to many years of close cooperation with a number of design and operating organizations, research institutes and universities.

The use of the ICC «ANGARA-HN» for real DHS in many cities of the Russian Federation made it possible not only to normalize the level of heat supply for consumers, but also to identify and realize a great energy saving potential due to: a significant reduction in circulation costs; reducing the consumption of make-up water and water discharges by the consumers; decrease of unproductive heat losses; reducing the cost of fuel and electricity, etc.

3. Directions for the development of the methodological base and software

An analysis of the features of China's DHS and the current level of software in the field of DHS modes simulation allows us to formulate the following basic requirements for the development of software to take into account these features.

1. The location of HS at a considerable distance entails a large transport delay of the heat flow, which requires dynamic models to determine the time it takes for the heat front to reach the consumer.

2. A large-scale and complex DHS model requires calibration (identification) - ensuring the adequacy of the model to a real object.

3. Taking into account new equipment, active behavior of the consumer, a large saturation with automatic control devices, the range of which continues to increase steadily, requires software that can add models of new equipment without reprogramming of existing calculation methods.

4. Ensuring high speed of calculations due to the large dimensionality of the DHS and the need to carry out multivariate calculations to find the rational way to organize operation modes.

5. The presence of advanced analytical functions that allow the interpretation of the initial data and calculation results on the network scheme (for example, according to the values of pressures, flow rates, velocities, temperatures and other parameters) or in the form of special graphs (piezometric, temperature); determination of violations in the design mode and their visualization on the schemas.

6. Multilingual user interface, which greatly simplifies the process of entering, checking information and performing calculations.

7. An open data storage format for the possibility of export / import and simple integration with other information systems when creating a common information space of the operating enterprise.

8. Availability of a Web-interface to support the possibilities of online DHS modeling.

In addition to the listed requirements, the software must have long-term developed support with the possibility of consulting users on complex modeling issues, the prospect of implementing new program functions, calculation methods and computational problems.

Currently, active work is underway to meet these requirements as part of the development of the capabilities of the ICC «ANGARA-HN», which already supports several interface languages (Russian, English, Chinese), is used in various organizations in China and has great prospects for wider application. This work, among other things, requires the development of a scientific and methodological basis, which is also being carried out in the following main areas:

1. Simulation of dynamic processes in hydraulic circuits, the need for which arises for DH, mainly with a significant delay in the temperature front of heat release from HS. Actually, the development of such models is aimed at obtaining a rational balance between the adequacy of the model and computational efficiency.

2. Development of a multilevel approach to mode modeling to overcome the problems of DHS high-dimensionality based on parallel computing technologies, which are organically combined with this approach and can potentially provide a multiple increase in the speed of high-dimensionality DHS calculations.

3. Methods for monitoring the technical condition and modes of DHS operation based on measurement data, as well as methods for optimizing the metrological base to obtain the required volume and quality of measurement information.

4. Optimization of the operating modes of the DHS (hydraulic, temperature, thermal-hydraulic, dynamic).

5. Development of the concept, methods and software components of a new generation of computer models of DHS in the form of their digital twin, reflecting the possibility of reproducing real processes of the dynamics of the internal state, stochastics of external influences, goal-oriented control algorithms

4 Conclusion

1. The paper analyzes the features and specifics of China's DHS. The relevance of the widespread use of mathematical modeling methods and computer programs to support decision-making in the design, development and operation of DHS is revealed.

2. The relevance of the use of THC for the adaptation and further development of software tools in relation to China's DHS is disclosed.

3. Requirements for software systems for modeling China's DHS are formulated. It is shown that the ICC «ANGARA-HN» largely meets these requirements and has a great development potential to meet them.

4. The main directions of the development of the methodological base for the creation of a new generation of software and support for the processes of intellectualization of the DHS have been formulated.

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