Generalization of multi-level modeling methods for development and analysis of operating conditions of large heat supply systems*

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Abstract. The paper presents a methodology of multi-level modeling of thermal-hydraulic conditions of large heat supply systems on the basis of the scientific area of research – the theory of hydraulic circuits – that has been developed at MESI SB RAS. The essentials of the applied methods and also the mechanism of their integration with the up-to-date information technologies are described. In combination they make it possible to calculate operating conditions of heat supply systems (HSS) of arbitrary size and structure. The applied approach is based on the multi-level arrangement of data and single-and multi-level calculations. The latter, in turn, are based on application of the methods of equvalenting and decomposition of both the calculation schemes and problems. The methods for multi-level adjustment thermal-hydraulic calculations take into consideration all requirements for feasibility of conditions and are realized as the information-computing system (ICS) "ANGARA-TS". The problems to be solved using the ICS and the technology for development of operating conditions are presented. The ICS is applied to sets of real HSS of big towns to develop conditions and adjustment measures. The composition of the solved tasks implemented in the ICS, the technology of development of operating conditions and an example of a multilevel modeling of the thermal-hydraulic conditions of the HSS in Petropavlovsk-Kamchatsky are presented.

1. Introduction

The Russian heat supply systems are engineering and technical facilities that are unique in their scales and complexity and an essential part of the energy sector, industry, municipal sphere and other sectors of the national economy. The systems are complex spatial large objects which combine a set of heterogeneous components, develop in time and are distributed over the substantial territory. Availability of diverse heat sources (cogeneration plants, district and peak boiler plants), pumping stations, heat points – central and individual, other control units, numerous diverse consumers with different schemes of load connection, extended and looped heat networks with ever-changing operation conditions of HSS makes the problems of development of conditions and their control complex.

The main causes of change in operation conditions of HSS are: inconstancy of their structure in the processes of development, reconstruction and connection (disconnection) of consumers, scheduled maintenances and emergency situations; variability of parameters due to natural aging and wear of equipment, operation of automatic devices; external random effects such as ambient temperature variations, interruptions in operation of adjacent systems (electric power, fuel supply, water pipeline), variability of uncontrolled load of hot water supply (HWS), etc.

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The governing factor in maintaining the quality of heat supply to consumers with reduction of operating costs is a smart planning of operation conditions of HSS, which is possible only on the basis of preliminary calculations to be made. Traditionally the problems of planning normal and post-emergency conditions of HSS are solved by the multi-variant calculations of flow distribution in advance, before the heating season. Moreover, change in operation conditions within the heating period can lead to the fact, when the operating parameters exceed technologically acceptable limits and as a consequence, to equipment damage or its faster wear, violation of heat supply to consumers, etc. This necessitates correction of conditions with change in operational environment.

In addition to large dimensionality and compound structure of large HSS, complexity of their modeling is conditioned by heterogeneity of elements, which require a different degree of detail for solving the operation problems. The multi-level modeling [1–6] developed at MESI SB RAS is a way to overcome contradiction between high dimensionality and requirements of integrity and visualization of the studied object. The approach is based on integration of models and methods for calculation of conditions with information technologies. In combination, they make it possible to link up scattered and inconsistent initial data with the models, solving thereby laborious problems of the quantitative validation of solutions obtained.

Irrespective of the methods of modeling, large HSS have a hierarchical structure to provide multi-stage control: at heat sources; at intermediate stages – central or individual heat points; and directly in heating systems, ventilation systems and hot water supply systems. As a rule, heat networks in such systems have different levels – main and distributionи networks with the central heat points serving as an interface. This fact creates natural opportunities for using multi-level modeling to calculate conditions of large HSS. Here the conditions of main and distribution networks can differ in the temperature charts of heat supply and the method of control – quantitative and qualitative.

2. Basic principles of multi-level modeling

The multi-level modeling technology enables to: 1) decrease dimension of the problems solved; 2) visualize calculation results; 3) coordinate solution results of the problems requiring different detail of the models; 4) overcome disconnection of information and mathematical models for solving the HSS control problems at different departmental, territorial, organizational and time levels; 5) apply technologies of parallel calculations, which in turn enables to calculate high-dimensional HSS for a shorter time.

The multi-level modeling can be realized by applying multi-level arrangement of data and arrangement of single- and multi-level calculations. The multi-level calculations are based on application of the methods of equivalenting and decomposition of both calculation schemes and problems [1, 4, 5]. This makes the applied calculation methods independent of the level of scheme aggregation and detail.

The decomposition principles of calculation schemes are described in [1, 4]. According to these principles main networks include networks from heat sources to central heat points (if they are absent – to the points of connection to the residential districts). Besides, the main networks comprise pumping stations and sections of the distribution networks, if they form loops with the main networks. The dead ends of central heat points to consumers also refer to distribution networks. The distribution network of one district can consist of several independent fragments, whose number is equal to the number of the points of connection to the residential district. The central heat point with installed heat exchangers in the closed heat supply systems is the common element that transmits parameters to coordinate conditions of different levels. In the open systems the common element is a generalized consumer at the main network level with the total load of the residential district, which is a generalized source at the distribution network level. The calculation schemes must be decomposed in terms of possible calculation of the whole heat supply system with mutual coordination of networks of different levels. Correct generation of the calculation scheme determines effectiveness of modeling. The main criteria of scheme decompositions are the degree of the impact of HSS elements on operation conditions of the whole system; possibility of calculation and analysis of the condition after control actions; possibility of operational control of change in the scheme configuration. Accordingly, the following structure of the calculation scheme decomposition is developed (Fig. 1).

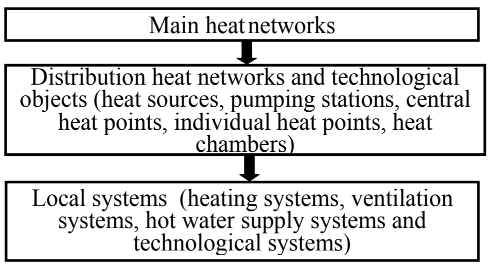

Fig. 1. Hierarchy of calculation schemes of HSS.

Such principles of scheme decomposition of large HSS with many thousands of elements make it possible to consider different departmental networks of different levels, visualize the studied object and perform modeling for various purposes. The mechanisms for supporting the hierarchy of calculation schemes are presented in [3].

The principles of problem decomposition are described in [1, 4]. The assumptions made allow the calculation of hydraulic condition irrespective of thermal condition and decomposition of the problem on thermal-hydraulic calculation of HSS into two subproblems: the hydraulic-thermal condition of the network and the hydraulic-thermal condition of the heat point. Each subproblem is also reduced to solution of the problem of hydraulic condition calculation and the thermal condition calculation of its base. The issues of modeling the hydraulic and thermal conditions of heat networks were analyzed in the works [7-13]. The mathematical model of thermal-hydraulic conditions of heat points is described in [14-15].

The calculation scheme of any HSS object can be represented by one element in the scheme of a higher level. The equivalenting procedure is performed for this element in advance, i.e. the parameters of aggregated characteristics, which are assigned to this element and used to calculate the scheme of an upper level, are calculated. Then the procedure of disaggregation, which consists in specification of the results of calculating an upper level element, is performed for all elements of its own scheme of a lower level. Interaction of the models for calculation schemes of different levels is demonstrated in Fig. 2.

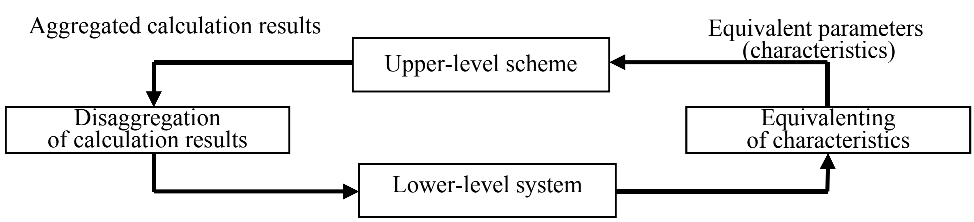

Fig.2. Interaction of models for calculation schemes of different levels.

3. Arrangement of information models

The multi-level modeling can be realized by applying the multi-level arrangement of data according to the following principles [5]: the modeled HSS can consist of sets of calculation schemes of different types; the scheme of a certain type is generated from its mix of elements; each element type can be preset in one of two formats: node, link; a real element of HSS can be represented by the aggregated element at the upper level, and by the own calculation scheme at the lower level; each element can be in one of several states (connected, disconnected, etc.); all elements of a certain type have the same set of parameters; the information model contains both the data on heat supply system elements, and the information on interrelations between: graphical representations of each element and its data, scheme elements, different schemes, each scheme and its layout, each scheme and its type of the problem solved, each problem and its calculation scheme. Each element has: number of the scheme it belongs to; number of the lower-level scheme, which is represented by it at its level; number of the upper-level scheme, with which the scheme including this element is associated. Application of such interrelations between the elements allows the modeling of diverse relations in the hierarchy of calculation schemes, i.e. both the tree-like and multi-loop structure of relations between the levels.

4. Technology of development of HSS operation conditions

The purpose of operational conditions development is to find such parameters of control elements (heat sources, pumping stations, central heat points), the composition and parameters of the control devices on the network and the consumers. These parameters should ensure the supply of all consumers with the required amount of heat of a given quality, taking into account all technical and technological requirements. The technology of operating condition development is treated in detail in [16] and consists of four main stages.

1. Development of the computer model of HSS in accordance with the accepted structure of calculation scheme decomposition (see Fig.1), which consists in creation of the graphic database for HSS and includes graphical presentation of the calculation scheme on the urban development plan and input of information on all system elements into the database. An example of the multi-level model of HSS is given in Fig. 3.

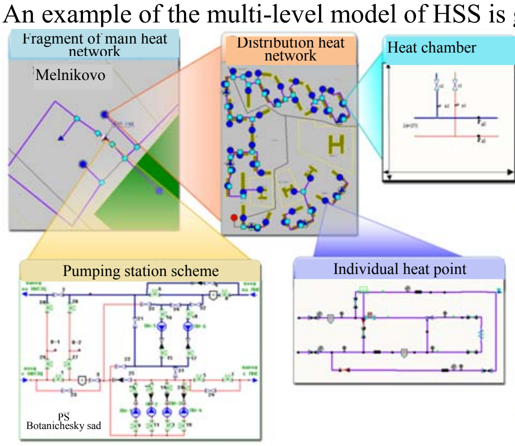

Fig. 3. Example of multi-level HSS model.

2. Analysis of the HSS conditions under the formed situation of operation to reveal bottlenecks, violations of the HSS condition and the quantitative estimation of the available level of heat supply to consumers. For this purpose the calculations of the thermal-hydraulic condition of HSS for the existing scheme of their operation and parameters at heat sources and central heat points which were maintained in the previous heating season. The calculation results are checked for condition feasibility in accordance with the requirements in [16].

3. Development of the feasible operation condition of HSS which will supply a required amount of heat of the specified quality for all consumers provided the requirements for operating parameters of all elements and minimum possible values of pressure in the network and heads in the pumping stations are observed. This stage includes a series of calculations of thermal-hydraulic conditions of HSS. In the case of rugged topography, which considerably narrows a feasible condition region, a multi-stage throttling is applied in the network and at consumers. The task to choose a place for throttler installation on the network is considered in [17, 18]. To develop the operating condition the parameters of control elements are chosen using the master nodes and consumers [16].

4. The multi-level adjustment calculation of thermal-hydraulic conditions by the approach in [19–22] with determination of individual corrections of heat carrier flow rates to compensate for heat losses in the networks for each consumer. If the network throughput is

insufficient, the temperature chart is corrected according to [23–24]. Then the parameters of throttlers at consumers with further verification of thermal-hydraulic conditions are calculated and the level of consumer supply is estimated. In the case of limited network throughput the analysis, whether the specific pressure losses are exceeded, is carried out and the pipeline sections to be re-laid for a larger diameter are selected. Sectionalizing valves, if available, can increase network throughput by changing the scheme of HSS sectioning [25].

5. Programs and their application

The methods for multi-level modeling of thermal-hydraulic conditions are realized in the ICS "ANGARA-TS [6, 12]. It is intended for automated development of operating conditions of HSS of an arbitrary structure (with any number and location of heat sources, pumping stations, heat points, consumers), arbitrary configuration (branched, multi-loop) and practically of any dimension. Herein, it is possible to calculate an individual level (for example, main or distribution network), and perform multi-level calculation of HSS with automatic coordination of boundary parameters between the levels. The ICS is applied to solve the following types of tasks.

Calculation tasks (single- and multi-level): adjustment and verification calculations of hydraulic condition; adjustment and verification calculations of thermal conditions; adjustment and verification calculations of thermal-hydraulic conditions; calculation of temperature charts of heat supply from heat sources; calculation of parameters of throttlers on the subscriber systems and in the heat network.

Analytical tasks: construction of the piezometric graphs; construction of temperature charts of heat supply from heat sources; determination of violations for state parameters, taking into account the limitations on admissible values of pressures, flow rates, speeds, temperatures and other parameters.

Let us consider the principle of multi-level modeling by the example of the real heat supply system in the Petropavlovsk-Kamchatsky city. The city is supplied with heat by 2 cogeneration plants and 30 boiler plants. The heat supply scheme is closed, independent with connection of distributed networks to the main networks through heat exchangers at the central heat points. The number of central heat points in the city totals 86. The problems of consumer provision with thermal energy are caused by: highly broken terrain; great heterogeneity of the schemes of consumer connection within a distribution network; misalignment of networks; excessive pump capacity at the central heat points; technical impossibility to drop excessive heads at the points of connection to buildings with low loads and direct connection of heating systems.

Development of conditions and adjustment measures on the basis of the suggested approach enabled to improve heat supply quality of the city and reveal and realize, in parallel, a high potential of energy saving owing to: considerable decrease of circulating water flow rate; decrease of make-up water consumption and water discharges by population; reduction of heat losses; decrease of electricity consumption for heat carrier pumping and chemical water treatment; switching of work of some central heat points with direct connection of heating systems to a lower temperature chart due to decease in flow rates. The economic effect of development of conditions and adjustment measures [26], carried out on the basis of calculations, amounted to 182 thousand rubles for one central heat point during the first year after their implementation. For the total number of central heat points in the city (86) the total expected economic effect will reach 15 million rubles annually.

6. Conclusion

The hierarchical structure of large HSS with intermediate control stages naturally involves the use of multi-level approach to modeling their conditions. Application of multi-level modeling enables to separate networks into fragments (main and distribution networks) even if there are no real central heat points among them, which essentially reduces problem dimension. The mathematical models and methods realized in the ICS “ANGARA-TS” are used to calculate networks within one fragment with a dimension of up to 32000 links. Hence, the existing large HSS practically of any dimension can be modeled with decomposition into levels.

A special methodology was developed for application of the multi-level approach to modeling of operation conditions of large HSS. It comprises the methods of multi-level adjustment thermal-hydraulic calculation of heating systems and hot water supply systems, determination of master consumers, the method of multi-step throttling on the network and by consumers.

Application of the multi-level modeling methods to develop operating conditions of real HSS in cities considerably improved their heat supply quality and revealed a high potential of energy saving.

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