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Optimization of the district heating zones

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Abstract. A method for determining the optimal action zones of the centralized sources of thermal energy is developed using the calculation of the effective heat supply radius of consumers. The methodology allows to take into account the features of heat supply systems' functioning, their technical and economic indicators, the uneven distribution of heat loads throughout the city, and limitations on the reliability of the system. Practical implementation of the proposed methodology on the scheme of operating a heat supply system is presented, the results of calculating the effective heat supply radius with their subsequent correction for reliability requirements are obtained. The application of this technique in the development of heat supply schemes for cities will allow to determine the boundaries of effective heat supply radii in all directions of the mains of heat networks, taking into account the optimal flow distribution of the coolant in them and the sections' technical characteristics.

1 Introduction

Heat supply is a socially significant branch of the Russian economy. The efficiency of its development and modernization is largely ensured by the optimal planning of heat supply systems (HSS), their scales, the coolant's transport range, the quality and reliability of supply of thermal energy. The validity of the decisions taken to optimize the HSS construction of is largely determined by the heat supply radius or the length of the heat network from the source to the consumer. In this connection, the problem of finding the effective heat supply radius (HSR) is an important task of forming a HSS. This task is considered at various stages of designing of a HSS, the development procedure for which is approved by special regulatory and legal acts, determining the order, sequence, composition, content, timing and other conditions [1-8].

At the same time, there is currently no regulatory document that would contain the methodology for calculating the HSR. So, in the recommendations for developing the heat supply schemes (approved by the Order of the Ministry of Energy and the Ministry of Regional Development of Russia [7]), the HSR is defined in a generalized form, and the methodology for its calculation is not available. In another normative document, SNiPe 41-02-2003 "Heat Networks," this issue is also not addressed.

Thus, the task of determining the optimal scales of the HSS, which has one of the key positions in the justification of the efficiency of the heat supply scheme, requires the

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development of a new methodical support that will make it possible to decide on the connection of new consumers to the system on the basis of the calculation of HSR. According to [5], two criteria are adopted, according to which new consumers are not connected to the system:

1) the consumer is outside the HSR area;

2) there are technical limitations: lack of bandwidth, lack of free capacity for sources of heat energy (SH), etc.

The analysis of scientific and technical literature showed that the issue of calculating the HSR received quite a lot of attention. Thus, in [9], the problem of determining the limiting radius of heating was first formulated, and the concepts of "economic" and "limiting: radii of heating were first considered in the publication [10]. The initial data for calculating the "economic" radius of the heating system were the HSS configuration and the heat density of the district.

Most studies [11-14] on the effective radius of heat supply or the determination of the optimal zones of SH were made in the 60-80s of the last century, since it is during this period that the most intense growth of both the number and the scale of HSS was observed. The research showed that the optimum radii of a heat supply and zones of SH performance essentially depended on concrete features of systems and an arrangement of SH.

Recently, studies have been resumed to identify effective zones of centralized heat supply [15-19]. The authors' methods [15-18] are widely used by developers of heat supply schemes for large cities of the country. The uniform value of the radius for the entire system is determined in [15, 16], assuming that the thermal loads are distributed uniformly around the SH. However, this assumption is close to reality in extremely rare cases and cannot be extended to the majority of active HSSs. At the same time, analytical expressions for calculating the HSR in the proposed methods [15, 16] are similar to each other; the main difference lies in the numerical values of a number of coefficients reflecting the change in the technical and economic conditions of the HSS operation. The authors of [18] propose to evaluate the HSR for each new connection, which can cause difficulties with a large number of applications for technical connection. In addition, these techniques do not take into account reliability requirements in the calculation of HSR, which can lead to more severe consequences of accidents in the system.

2 Method for determining the HSR

Based on the features of the construction and operation of the HSS, along with the definition of HSR for SH, it is necessary to calculate the radius for all directions of the main pipelines and, in addition, to estimate the reliability of heat supply.

The following provisions and assumptions are adopted in the methodology for determining the HSR:

1) Areas of prospective and existing buildings are determined in accordance with the city's master plan and applications for the technical connection of the heat load;

2) The criterion limiting the HSR for SH, beyond which the connection of new consumers leads to an increase in unit costs for the HSS under consideration, is the cost price of production and heat transport;

3) The HSR boundary is defined for the each heat main from SH, and technical and economic parameters of SH and heat pipelines, climatic conditions, etc. are taken into account in the calculations;

4) The HSR is limited to the nodes of the heat network (HN), in which the prime cost (the core cost price) of heat exceeds the average prime cost by HSS;

5) The optimal distance of transporting the coolant along each HN main from SH to the most remote consumer node is determined in accordance with the calculated value of HSR.

The proposed methodology for determining the HSR, taking into account the reliability requirements, consists of the following main steps.

1. Formation of an information base for district heating, including spatial planning, consumer loads, locations, technical, and economic indicators of SH, the extent and parameters of existing and new sections of the HN.

2. Calculation of the connected heat load for the considered SH:

$$Q_i = \sum_{j=1}^{J} Q_j + Q_{HL}, i \in I, j \in J, \quad (1)$$

where *Qi* is the connected heat load of the *i*-th SH, Gcal/h; *Qi* is the thermal load of the *j*-th consumer being connected to the SH under consideration, Gcal/h; Q_{HL} stands for losses in heat networks, Gcal/h.

3. Calculation of the length of HN main for the SH under consideration.

4. Calculation of hydraulic modes in the vehicle is performed using the methods of the theory of hydraulic circuits [14], according to which the flow distribution of the coolant in the network is described by the following system of equations (in matrix form):

$$\mathbf{Ax} = \mathbf{G}, \quad (2)$$

$$\overline{\mathbf{A}}^{\mathrm{T}}\mathbf{P} = \mathbf{h} - \mathbf{H}, \quad (3)$$

$$\mathbf{h} = \mathbf{SX}|\mathbf{x}|, \quad (4)$$

where **A** - (*m*-1) x *n*-matrix of connections of linearly independent m nodes and n sections (branches) of the network; x - vector of coolant flow in the network sections, t/h; ***G*** is the vector of mass expenditures in knots, t / h; $\overline{\mathbf{A}}^{\mathrm{T}}$ is the transposed matrix of connections of nodes and branches of the circuit; ***P*** is the vector of pressures at the nodes, mmwg; **h**, **H** are the vectors of losses and active heads, mmwg; ***S*** is the diagonal matrix of coefficients of hydraulic resistance, m·h2/t2; ***X*** is the vector of expenditure on the network sections, t/h; $|\mathbf{x}|$ is a vector of modules of expenses on the network sections, t / h.

5. Checking restrictions on the availability of free capacity of the existing centralized SH:

$$0 \le Q_i \le Q_i^{\max}, i \in I, \quad (5)$$

where $Q_i^{\max}$ is the maximum thermal load of the *i*-th IT, Gcal / h.

Based on the results of this check, the following conclusions are made:

a) If there is a free capacity in the coverage area of the IT under consideration, additional capital investments are not required to join prospective customers;

b) in the absence of free capacity in the IT coverage area, it is necessary to expand and evaluate the corresponding investments.

6. Calculation of the unit annual costs for the production and transportation of thermal energy (prime cost) in the HSS from the SH under consideration is made according to the following relationship:

$$Z = \frac{(f+\alpha)\cdot\sum_{n=1}^{N}(k_n(d_n)\cdot L_n)}{Q} + \frac{c_e\cdot\tau\cdot\sum_{n=1}^{N}(x_n\cdot\psi_n\cdot L_n)}{367{,}2\cdot\eta\cdot Q} + s_h + \alpha\cdot k_i,\ n\in N\ , \quad (6)$$

where α is the discount factor; f is share of deductions from capital costs for depreciation, repair, and maintenance of HN; k_n stands for specific investment in the construction of the HN site, rub/m; d_n is the diameter of the HN section, m; L_n is the length of the HN section, m; τ is the number of hours of the pumping unit operation with a design load, h; ψ_n is a specific pressure drop in the network, mmwg/m; c_e is the cost of electricity, rub kWh; η stands for the pumping unit efficiency; Q is the connected load of the centralized SH, Gcal/h; s_h is the prime cost of heat energy production, rub/Gcal; k_i focuses on specific investments in the expansion of the SH capacity, rub/(Gcal/h), n is a HN segment.

8. Calculation of the unit annual costs for the production and transportation of thermal energy (cost price) from the SH, along with the considered heat main relative to each of its nodes – $m\,(m\in M)$.

9. The determination of the HSR boundaries at nodes $m-1$ in each heat main, where m is the first node in the considered highway, located outside the HSR zone, and for which the cost price for the production of thermal energy exceeds its average level by the system. The affiliation of the node to the HSR zone is formalized by the following condition:

$$Z_m > Z, \quad m\notin M_{\text{РЭТ}}, \quad (7)$$

$$Z_{m-1} \le Z, \quad (m-1)\in M_{\text{РЭТ}}, \quad (8)$$

where M_{HSR} is a subset of network nodes located in the HSR zone.

10. Verification of the decisions on the HSR to meet the requirements of heat supply reliability, the level of which is determined by two main indicators [20, 21], namely the availability factor (AF) and the probability of failure-free operation (FFO). These indicators are calculated for each node of the design scheme according to the methodology presented in [21]. The verification of reliability constraints is made relative to the normative values of these indicators:

$$K_m \ge K_m^0,\ m\in M\ , \quad (9)$$

$$R_m \ge R_m^0,\ m\in M\ , \quad (10)$$

where K_m and K_m^0 are the calculated and normative AF values, respectively; R_m and R_m^0 are calculated and normative FFO values, respectively.

If these requirements are violated, the HSR is limited to a node in which the requirements for reliability of heat supply are met and, as a consequence, the HSR zone is reduced. Otherwise, measures are taken to increase reliability: reserving jumpers and heat mains are set, old and emergency sections of the NS are shifted; after this, a return to point 3 of the procedure is done. It is also necessary to take into account additional investments for increasing the reliability, which leads to an increase in the specific annual cost of transporting thermal energy.

When several SH services are used for unified HN, the presented method for determining the HSR is supplemented by several preliminary steps, namely: the optimal flow distribution is calculated in a single HSS with several SH, after which the system is divided into several subsystems for the operation of various HS (each one is with its own source and technical-economic characteristics); further, the above algorithm is applied for calculating the HSR.

3 Assessing the impact of technical and economic indicators of HSS on the HSR value

The amount of HSR affects a variety of economic and technical indicators, the configuration of the system (the number of mains, etc.), as well as external factors (in particular, climate, territorial location). As can be seen from the expression (6), the greatest influence on the HSR boundary is provided by the material characteristic of the network (MCN), which is the product of the heat pipes length by their diameter and its cost. The figure 1 is a graphical representation of the dependence of the specific costs on transport of thermal energy from the specific MCN, referred to 1 km of the pipelines length. The obtained graph of the dependence of the unit costs on the specific MCN has a nonlinear form, which is more gentle for small values of the specific MCN and steeper at their high levels. On the average, within the studied limits of the indicators, the change of the specific MCN by 3 times leads to more than 4-fold increase in the cost of transport of heat energy.

In Fig. 1-b is a graph of the dependence of the unit costs for transportation of heat energy on the cost of electricity for the existing HSS based on the Novo-Irkutsk Cogeneration Plant (NICP) in Irkutsk. The results of the analysis showed that the increase in the cost of electricity by 2 rubles. leads to an increase in the cost of transport of heat energy by 200 rubles per Gcal.

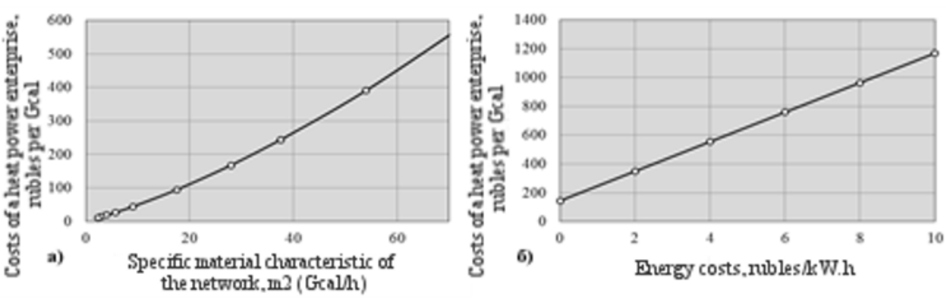

Fig. 1. Change in unit costs for heat transport when: a) the increase in the specific physical characteristics of the network; b) increase in the cost of electricity.

The next factor affecting the HSR boundaries is the value of the connected heat load. The connection of new consumers with significant heat load, remote from SH, increases the boundaries of the HSR more than the connection of the same load in the immediate vicinity of the source.

It should also be noted the effect of the temperature difference between the supply and HSR pipelines on the HSR boundaries. Reducing the temperature drop of the coolant causes a decrease in the efficiency of the HSS functioning due to increasing coolant flow rates to meet heat energy requirements and, as a consequence, an increase in hydraulic losses in the network, which may lead to the need for pumping stations or large diameter pipelines on certain sections of the network. Thus, the reduction of the temperature drop in the network water leads to an increase in the specific costs for transport of the coolant and changes in the HSR.

The reduction in the temperature schedule for the release of thermal energy with preserving the temperature difference favorably affects the decrease in vehicle wear and the prolongation of its life, but it may require significant modernization of the HSS. Together, this can also change the HSR. In European countries, research is actively being conducted on the use of low-temperature HSS in zones with low load densities [22-24]. These studies have shown that the construction of low temperature HSS can be economically feasible and will allow expanding the zone of district heating, especially with the use of renewable resources and secondary energy sources [25]. However, it is necessary to limit the reduction of the coolant temperature in the return pipeline in order to prevent the development of dangerous microorganisms. It should also be understood that the use of low-temperature technologies in Russian systems will require a profound modernization of internal heat consumption systems, and in some cases this cannot be easily implemented.

4 Brief report on practical research: results of determining the HSR for the Novo-Irkutsk Cogeneration Plant)

According to the presented method, the HSR calculation of the HSR for NICP in Irkutsk was carried out. The installed electric power of NICP is 708 MW, the installed heat capacity is 1729 Gcal/h. Main and distribution vehicles are made in a two-pipe version. The total length of water vehicles from NICP is 474.3 km, of which 112.9 km belongs to the backbone networks. On the heat supply territory from NICP, there are 3 urban districts. All of them are partially or completely supplied with heat energy from NICP on three heat mains (HM), namely HM1, HM2, and HM4, while the HM3 supplies heat energy to consumers of a separate country village.

The obtained HSR values for NICP (without taking into account the reliability requirements) on the leading mains of heating networks and their branches vary considerably: from 2 km (the actual minimum distance of the consumer from the source) to 15.5 km. These solutions are clearly shown in Figure 2. The cost price of thermal energy for consumers located outside the designated areas of the HSR exceeds the average value for the system, and their connection seems inappropriate.

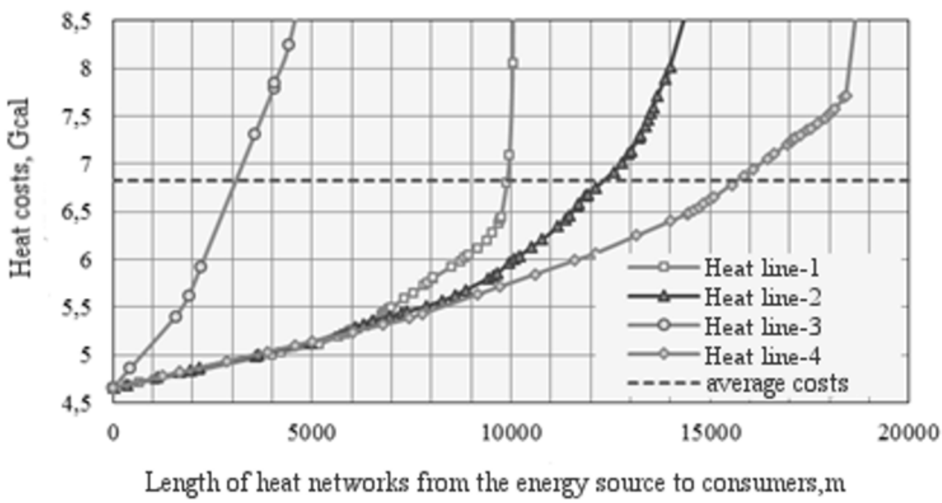

Fig. 2. Dependence of the cost of thermal energy production on the heat mains (HM) of the HSS of Irkutsk (affiliated to NICP): the intersection with the system's average value (dashed line) corresponds to the solution for HSR.

The reliability analysis of the HSS showed that the normative values of the AF and FFO, given in accordance with [21], are not satisfied for some nodes of the system entering the HSR zones. In accordance with the received reliability indicators, the HSR is adjusted in the system under consideration. Thus, the maximum HSR for NICP, taking into account the reliability requirements, will decrease from 15.5 km to 14.6 km. And the total length of the main heat networks in the HSR zone decreased by 4.2 km and amounted to 67.7 km. According to the results obtained, in the HSR area, taking into account the reliability requirements, there are only 284.3 km of HN from 474.3 km, i.e. 40% of the networks are outside the HSR zone. The connection of new consumers within the boundaries of HSR at the available technical capacity does not lead to an increase in the cost of thermal energy.

5 Conclusion

In this paper, a technique for determining the HSR for SH is proposed. The HSR is defined as the set of nodes (heat chambers) on the HN scheme, in which the cost price of production and transport of thermal energy does not exceed its average value for the considered HSS. This method is sufficiently accessible for understanding, has a universal character, takes into account individual features of the territories, and can be successfully applied in the development of heat supply schemes.

The conducted calculations showed that the HSR estimation should be carried out separately for each HSS heat main, taking into account the technical and economic indicators of the HN and SH, as well as the distribution of the heat load by the HN. The HSR is limited to a camera on the HN, after which the core cost price of thermal energy exceeds the average prime cost for the HSS. Based on the calculation results, a set of points is defined on the HN, which are the boundaries of the HSR.

The connection of new consumers within the HSR boundaries, taking into account the reliability requirements, will help to contain the increase in costs for HSS, to reduce the level of heat losses, and to provide the required level of reliability of the HSS operation. To organize the heat supply to consumers outside the HSR area, it is necessary to plan the construction of a new HN.

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