

Designing of hydraulic systems on computer models

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Abstract. Project of a heat network combining two sources of centralized heat supply has been completed with the help of the developed mathematical and computer model. The model is based on the electrohydraulic analogy of electrical potentials distribution in conductors and liquid pressure in piping systems is described by the same differential equations. To build a model of a hydraulic system, the Kirchhoff's laws were applied for the calculation of electrical networks. The research carried out using the model made it possible to determine the optimal parameters of the equipment, its position in the heat network scheme, the lengths and diameters of the pipelines, etc. due to the criteria of the specifications for design and constructions.

1. Introduction

When designing preliminary projects of new branched heat networks, the use of computer models has been an effective method providing almost complete reproduction of the hydraulic processes in heating systems as hydraulically connected systems. In particular, they make it possible to determine pressures, flow rates, velocities of the medium, head losses, energy consumption for displacement, etc. No solution of such problems by any other means for complex multi-ring networks is currently possible [1 – 15].

2. Fundamental provisions of the proposed research method

As a specific example of designing a mathematical and computer model, we find the distribution of flow rates in a network including a ring (Fig. 1) with three branches. Let us denote the flow rates for the sections of the ring a, b, c, d by Q_a, Q_b, Q_c, Q_d , and branches by Q_1, Q_2, Q_3 . It is required to find the flow rates in the ring sections at a given flow rate at its inlet. The flow rates of the medium in branches from the ring Q_1, Q_2, Q_3 are known, and their sum is equal to the flow rate at the ring inlet: $Q = Q_1 + Q_2 + Q_3$.

The first Kirchhoff's law applied to hydraulic systems equates the inflow and outflow of medium in each unit:

$$\sum_{i=1}^n Q_i = 0, \quad (1)$$

where n – number of pipelines in the unit; Q_i ($i = \overline{1, n}$) – flow rates for pipelines.

According to the second Kirchhoff's law, the sum of heads is equal to zero for any closed-ring system:



$$\sum_{i=1}^n H_i = \sum_{i=1}^n S_i Q_i^2 = 0, \quad (2)$$

where S_i ($i = \overline{1, n}$) – hydraulic resistance of i – section.

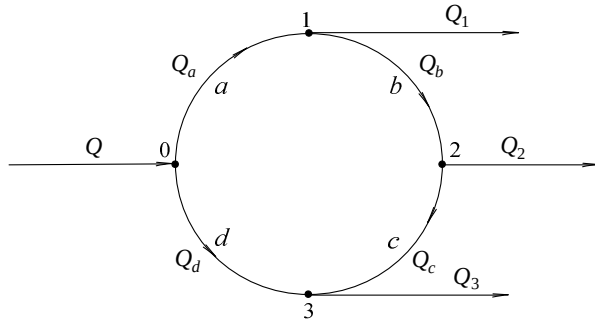


Figure 1. Scheme of a single-ring pipeline network with three branches

Relations (1), (2) by iterative calculation make it possible to find the flow rates in network sections at a certain flow rate Q , given at the ring inlet. At the first step of the iteration, generalized distributions of flow rates Q_a , Q_b , Q_c , Q_d are given. Then for units 0, 1, 2 according to the first Kirchhoff's law, we have $Q_d = Q - Q_a$; $Q_a = Q_1 + Q_b$; $Q_b = Q_2 + Q_c$.

On the basis of given flow rates in the sections of the ring there is a head discrepancy:

$$\delta H = \sum_{i=1}^4 S_i Q_i^2 = S_a Q_a^2 + S_b Q_b^2 + S_c Q_c^2 - S_d Q_d^2. \quad (3)$$

To approach δH to zero, the correctional (balancing) flow rate δQ is introduced, which should be subtracted from the flow rate on the overloaded sections and be added to the underloaded ones. The value of the balancing flow rate can be found from relation (3), if $\delta H = 0$.

$$S_a (Q_a - \delta Q)^2 + S_b (Q_b - \delta Q)^2 + S_c (Q_c - \delta Q)^2 - S_d (Q_d + \delta Q)^2 = 0. \quad (4)$$

Neglecting terms containing $(\delta Q)^2$ as relatively small, the relation (4) with respect to the correctional flow rate δQ is reduced to an algebraic linear equation. Its solution is:

$$\delta Q = \delta H / \left(2 \sum_{i=1}^n S_i Q_i \right), \quad (5)$$

$$\text{where } \sum_{i=1}^n S_i Q_i = S_a Q_a + S_b Q_b + S_c Q_c + S_d Q_d.$$

Having calculated δQ , the flow rates in ring sections are to be refined. Calculations are continued until the flow rates of the last two iterations differ by a specified value.

In case of multi-ring branched hydraulic networks, the implementation of the above calculation algorithm is possible only with the use of the computer technology.

So, it is necessary to design a computer model of the flow rate distribution process in the hydraulic network. Kirchhoff's laws (1), (2), as well as the theory of graphs [7 – 11] form the basis of its design, resulting in a «tree» of the heat network (Fig. 2).

Let us call the vertices (units) of the graph by the numbers 1, 2, 3, ..., 9, and the arcs – by letters a , b , c , ... (Fig. 2). The vertices of the graph are the connection points of the pipelines, and the arcs are their sections. The «tree» is constructed so that any other vertex can be reached from vertex 1. Thus, it is possible to perform Pascal's law and the equation of continuity of the flow.

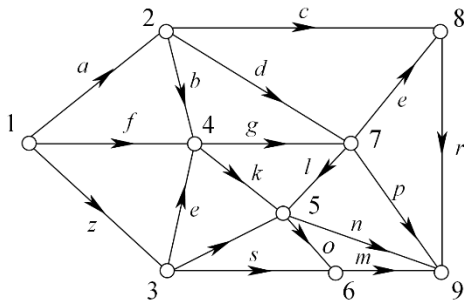


Figure 2. Scheme of the heat network

With the help of relations (3), (5), we can build a closed equation system for relatively unknown flow rates in the sections of the network and pressures at its units. By the iterative method of calculation applied to complex multi-ring networks, the problem of iterations convergence occurs. In computational practice, the most common method is the full-system pressure drop balancing. According to this method, a certain initial approximation for flow rates in all sections is given; pressure losses and total discrepancies are found. These discrepancies determine the values of so-called «balancing flow rates»; a minimum of discrepancies within the specified values is found. Let us note that the method of full-system pressure drop balancing is characterized by rapid iteration convergence [1 – 3, 5, 8].

Thus, the «tree» of the heat network includes units and sections. The units may be with a given flow rates (the heating agent is taken from the unit) and with a given inflow (the heating agent enters the unit). The sections are divided into: sections-pipes; sections-pumps; sections-valves and sections-heat exchangers. When designing a network model it is necessary to find hydraulic characteristics (functions of losses from the flow rate) in all sections. For example, head losses in a pipeline include linear losses and losses in local resistances:

$$\Delta h = \lambda \frac{l}{d} \frac{v^2}{2g} + \sum \xi \frac{v^2}{2g}, \quad (6)$$

where Δh – head loss, m; λ – friction factor; l – length of the pipeline, m; d – inner diameter, m; v – average speed, m/s; $\sum \xi$ – sum of local resistance factors in the section; g – acceleration of gravity, m/s².

Head losses in local resistances are reduced to linear ones with the calculation of the equivalent length by the formula $l_e = d \sum \xi / \lambda$. From here, the formula (6) will be:

$$\Delta h = \frac{v^2}{2g} \left(\lambda \frac{l}{d} + \lambda \frac{l_e}{d} \right) = \frac{\lambda v^2}{2g} (l + l_e). \quad (7)$$

Considering that $v = 4Q/(\pi d^2)$, we find $\Delta h = 8\lambda Q^2 (l + l_e) / (\pi^2 g d^5)$. Hydraulic characteristics of the section-pipe will be $\Delta h = sQ^2$, where $s = 8\lambda (l + l_e) / (\pi^2 g d^5)$ – hydraulic resistance of the section, s²/m².

For each section-pipe we introduce such parameters as diameter mm; length, m and coefficients of local resistances. For the valve section, the hydraulic characteristic will be $\Delta h = sQ^2$, where s – valve resistance coefficient.

Sections-pumps in the model are presented by the dependencies between the head of the pump and its feed. The characteristic of the pump is determined by the formula $H = H_\phi - Q_\phi^2 S_\phi$, where H_ϕ – shut-off head at outlet $Q_\phi = 0$; Q_ϕ – pump feed; S_ϕ – hydraulic pump resistance.

The real pump state may differ from its passport specifications. In the calculation program, it is possible to adjust the characteristics of any pump. For this purpose, two coefficients are introduced

that correct both H_ϕ and S_ϕ which can only be determined on the basis of experimental measurements.

The model designed so allows carrying out practically any number of numerical experiments in relation to the given heat network such as determination the current state according to the distribution of pressures, velocities, flow rates, energy costs for moving the heating agent, etc.

When building a model of a newly designed heating network, its approximate configuration, the length of pipelines, elevation marks and so on are set, as well as those parameters of the heating agent (flow rates, pressures, etc.) which must be maintained during operation. Such characteristics of the heat network as diameters of pipelines, installation sites, the number of locking devices, the need to install pressure (or flow) regulators and boosting or lowering pumps are determined as a result of multivariate calculations on the model. Moreover, all these required values must be found in such a way that the parameters determined by design specification have to be met at different points of the network according to the specifications for design and constructions.

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3. Discussion of the results

Let us consider a specific example of preliminary design of a new heat-removal pipe from CHP-1 for the purpose of heating a residential area powered from CHP-2. The principle scheme for connecting a new heat-removal pipe at CHP-1 to heat networks at CHP-2 is shown in Fig. 3. Currently, the 1st, 2nd and 3rd heat-removal pipes at CHP-2 power the consumers C1, C2 and C3 of the residential area. Due to the different heat supply schemes (open scheme at CHP-2 and closed scheme at CHP-1), the heating agent losses must be compensated for the hot water supply by CHP-2. Therefore, the water will only be heated at CHP-1. It is necessary to power all consumers C3 (4600 t/h - current load and 5800 t/h - prospective load) of the third heat-removal pipe by the new heat-removal pipe at CHP-1.

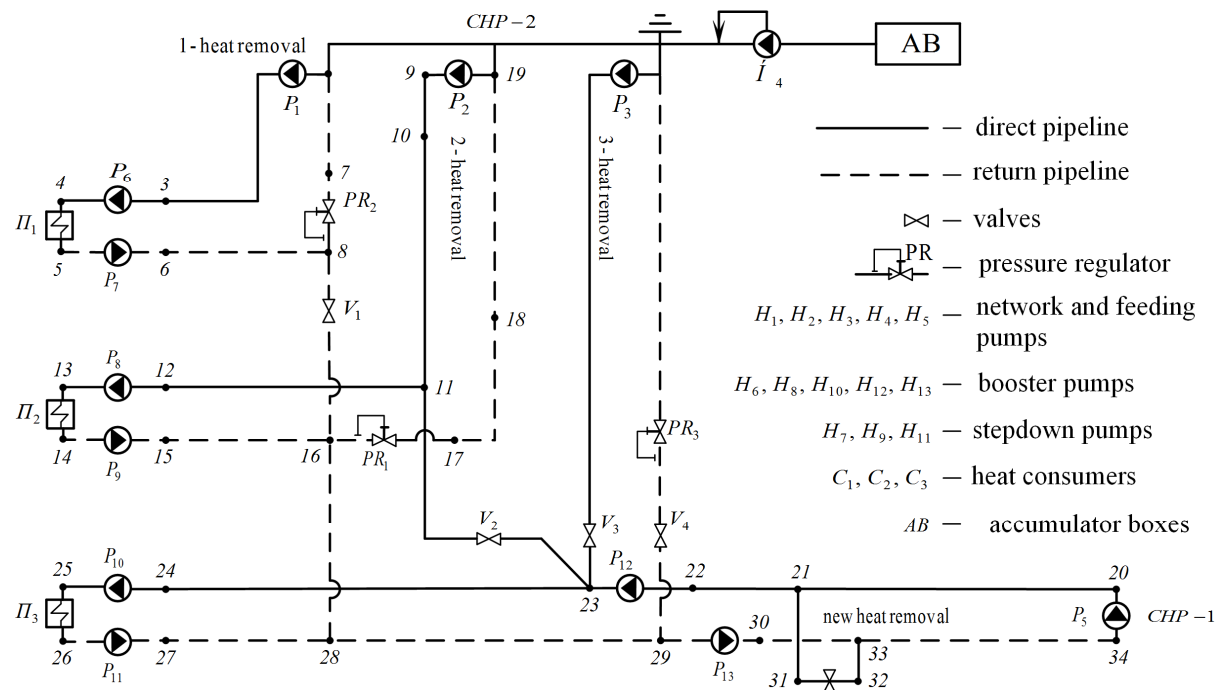


Figure 3. The scheme of connection of the new heat removal pipeline at CHP-1 to the heat networks of CHP-2. 1, 2, 3, ..., 34 – characteristic points of the network

Specifications for design and constructions were as follows: to connect the new heat removal pipe at CHP-1 to the networks at CHP-2 at point 23 of a direct pipeline and at point 29 of the return

pipeline (Fig. 3); to ensure a given pressure drop between the direct and return pipelines for consumers C_3 , the pressure at the connection point (point 23) should not be less than 11 kgf/cm^2 ; to feed consumers C_3 through the existing crossover pipe 16 - 28 with a diameter of 1000 mm; the pressure at point 16 should not exceed 7 kgf/cm^2 ; the pressure in front of the CHP-1 network pumps (point 34) should be in the range of $1.5 - 3 \text{ kgf/cm}^2$, according to the conditions of their cavitation free operation; under the conditions of cavitation free operation of the return pipelines for consumers C_2 and C_3 , the pressure at points 15 and 27 should not be less than 4 kgf/cm^2 ; the maximum flow rate of the heat agent in the direct pipeline of the new heat removal pipe at CHP-1 must be at least 10000 t/h (diameters of the direct and return pipelines 1200 mm); the pressure at the outlet of the network pumps at CHP-1 should not exceed 16 kgf/cm^2 .

To solve this problem, a computer model for the combined heat-network was developed which makes it possible to consider it as a single hydraulic system, taking into account the lengths and diameters of pipelines, elevation marks of the equipment location, etc. Therein, the basis pressure was the pressure from the feeding pumps P_4 at CHP-2 (2.5 kgf/cm^2). The calculations on the model were performed for the following options of heating network operation: the new heat removal pipe at CHP-1 fully provides heating for consumers C_3 of the third heat removal pipe at CHP-2. The modes of operation with the existing, prospective and minimum load are considered.

The initial data for the operating mode of the heating network with the existing load were as follows. The water flow rates in the supply pipeline of the third heat removal pipe at CHP-2 was 4575 tons/hour, in the return pipeline – 3097 tons/hour. Consequently, the water flow rate for hot water supply was 1482 tons/hour. The corresponding data for the second heat removal pipe at CHP-2 were 5064 t/h, 3181 t/h, 1983 t/h. The value of feeding the new heat removal pipe at CHP-1 through the crossover pipe 16 – 28 (Fig. 3) was equal to the flow rates for hot water supply of the third heat removal pipe at CHP-2, i.e. 1482 tons/hour. The pressure in the return pipeline of the 2nd heat removal pipe at CHP-2 (point 19) was equal to 2.2 kgf/cm^2 . The pressure in the supply pipelines after the step-down pump P_8 and P_{10} was 10 kgf/cm^2 . The pressure in the return pipeline before the step-down pump P_9 was equal to 3.0 kgf/cm^2 , and before the pump P_{11} – 4.5 kgf/cm^2 .

The main parameter of regulation according to the adopted scheme of operation is the pressure at the input of the network pumps P_5 at CHP-1 (point 34 in Fig. 3). According to the conditions of the cavitation free operation of pumps it should be within the limits of $1.5 - 3 \text{ kgf/cm}^2$. Maintenance of this parameter in the specified pressure range is provided by the corresponding adjustment of the pressure regulator PR1.

The results of piezometric pressure calculations for some heat-removal pipeline paths with respect to the first option of the heating network operation are shown in Fig. 4, 5, 6 (in this operating mode the pressure regulator PR 2 is bypassed, PR 3 is closed, pumps P_{12} , P_{13} are disconnected (bypassed), valves V1, V2, V3, V4 are closed). The various branches of the heat network in Fig. 4, 5, 6 are marked by control points that coincide with the corresponding points in Fig. 3.

Analysis of calculations results makes it possible to conclude that in order to ensure the input network pumps at CHP-1 (point 34) with the pressure of 2.5 kgf/cm^2 , the pressure regulator PR1 must be adjusted to the pressure of 5.5 kgf/cm^2 (pressure at point 16). This value does not exceed the pressure level at point 16, as determined by the specifications for design and constructions. The consumers' pressure (after the booster pump P_{10}) at the required level (10 kgf/cm^2) can be provided by network pumps P_5 at CHP-1, which excludes the need for the operation of the booster pump P_{10} . Therein, the outlet pressure of the network pumps P_5 must be at least 11.5 kgf/cm^2 (piezometric pressure – 202 mH₂O, point 20 in Fig. 4).

Analysis of the pressure diagrams shown in Fig. 5 allows concluding that in the section 19 – 17 (Fig. 3) of the return pipeline of the 2nd heat removal pipe at CHP-2 the excess (manometric) pressure is reduced to values less than 10 m H₂O (1 kgf/cm^2), it may result in liquid boiling in this section. This is due to the flow rate decrease in the section 16 – 17 – 18 – 19 by the value $G=1482 \text{ t/h}$, which is equal to the feed of consumers C_3 of the new heat removal pipe at CHP-1. Therefore, it is recommended to raise the plus pressure produced by feeding pumps P_4 at CHP-2 up to $3 - 3.5 \text{ kgf/cm}^2$.

To calculate the hydraulic control with the prospective increase in load at the new heat removal pipe at CHP-1, the following initial data were given. The water flow rate in the supply pipeline at CHP-1 was 5800 t/h, in the return one – 3792 t/h. The water loss in hot water supply for consumers C_3 of the new heat removal pipe at CHP-1 was equal to 2008 t/h, i.e., it was equal to the feed of the new heat removal pipe at CHP-1. Analysis of calculations results of the operating control with the prospective load showed that for maintaining at the inlet of network pumps P_5 at CHP-1 of the required pressure of 2.5 kgf/cm², PR1 should be adjusted to the pressure of 6.6 kgf/cm². This pressure does not exceed the value of 7 kgf/cm² specified by the specifications for design and constructions (Fig. 6).

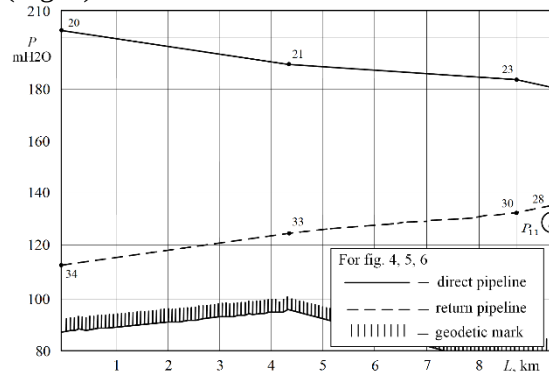


Figure 4. Diagrams of piezometric pressures. L – length of pipelines, km; P – piezometric pressure, mH₂O; P_{11} – lowering pumping

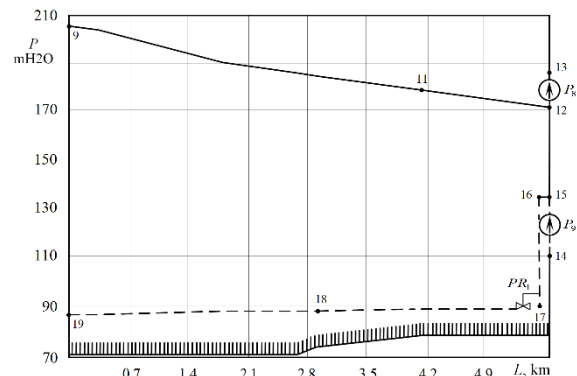


Figure 5. Diagrams of piezometric pressures along lines 9 – 11 – 12 – 13 (direct pipeline), 14 – 15 – 16 – 17 – 18 – 19 (return pipeline)

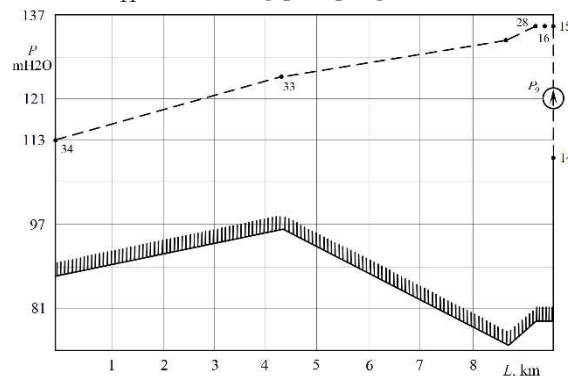


Figure 6. Diagrams of piezometric pressures along the line 14 – 15 – 16 – 28 – 33 – 34 (return pipe)

4. Conclusions

1. A mathematical and computer model for combined heat networks at CHP-2 and CHP-1 was developed. Real lengths and diameters of pipelines, elevation marks, pipe roughness and so on are taken into account in the model. The pumps operate according to their actual parameters. The flow rates in network sections and pressures at individual network points were set by the specifications for design and constructions

2. The easiest option for combining the newly designed heat removal pipeline at CHP-1 with the heat networks powered by CHP-2 is the option with the installation of a crossover pipe 16 – 28 (Fig. 3) between the return pipelines of the heating systems of the 2nd and 3rd heat removal pipelines at CHP-2. Therein, it is necessary to install a pressure regulator PR1 in the section between points 16 – 17. The main regulation parameter (for PR1 adjustment) is the pressure at the inlet of charging pumps P_5 at CHP-1 (point 34).

3. Calculations on the computer model showed that with the current load in the heating networks of the 2nd and 3rd heat removal pipelines at CHP-2, PR11 should be adjusted to a pressure of 5.5 kgf/cm² to maintain the pressure at point 34 within 2.5 kgf/cm². The basis pressure at CHP-2 (point 19) is equal to 2.2 kgf/cm².

4. General analysis of the results obtained allows concluding that while feeding the consumers from two heat sources with different heat supply schemes, we have a number of problems. If we don't solve them, the combined heat network using separate operating modes may be inoperative. Among them, the most important problem is the optimal adjustment of the pressure regulator in order to maintain the parameters specified by the specifications for design and constructions. Such adjustment can be effectively performed on a computer model.

5. Acknowledgments

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6. References

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