Analysis of heat losses during heat supply of an urban-type settlement using a heat pump

A A Nikitin, O E Konicheva, S S Muraveinikov, E V Nezhurin, N O Rachkovsky

St. Petersburg National Research University of Information Technologies, Mechanics and Optics, Kronverkskiy pr., D. 49, St. Petersburg, Russian Federation, 197101.

E-mail: konicheva-olya@mail.ru

Abstract. Centralized heat supply systems include a network of pipelines connecting buildings and structures in such a way that entire districts and quarters are supplied with a heat carrier from a single boiler plant. District heating is a well-studied part of the energy system. Despite this, low temperature district heating is still underdeveloped, although it is one of the key technologies for energy efficient urban heating. Low-temperature heat supply systems are the basis of 4th generation district heating systems, since they can significantly reduce heat losses during transportation of the heat carrier to the heat energy consumer and allow the use of heat from renewable sources, for example, heat pumps. The study focuses on analyzing the heat loss of a district heating system by comparing simulation results at a standard flow temperature and at a temperature typical of the 4th generation heat supply schedule. On the basis of the created model, the calculation of heat and hydraulic losses of the low-temperature district heating system was carried out, as well as a comparative analysis in comparison with the standard heat supply system.

1. Introduction

Heating and hot water supply accounts for the majority of energy consumption. In many cases, the supply of the heat fund of the system and structure uses centralized heat supply systems. In many ways, this is an economical and promising way; however, heating networks operate at high-temperature modes, increase heat losses during the transportation of the coolant from the boiler plant to consumers. In addition, high-temperature heat supply systems impose restrictions on the use of low-grade heat sources, do not allow the use of waste heat from industrial enterprises or recovered heat from exhaust ventilation systems. The solution to this problem can be the use of 4th generation district heating systems (4GDH). It is sometimes referred to as a low-temperature district heating (LTDH) system, as it involves the use of low-temperature heat transfer fluids in the range of 30-70 ° C. [1]

Such heat supply systems provide stability together with energy systems due to the combined generation of heat and electricity at CHP plants using waste heat of enterprises, as well as the inclusion of alternative energy sources, such as solar and geothermal, into the centralized system.

The transition from high-temperature heat supply systems to low-temperature ones provide a wider use of alternative energy sources in heat supply systems.

This article examines on the topic of using the waste heat of the enterprise in the centralized heat supply system of the Oktyabrsky village located in the Ryazan region using a heat pump. A heat pump
is a device for transferring energy from a source to a consumer, which is expediently used for individual heat supply. [2] However, as part of the development of the idea of 4th generation heat supply systems, modeling and analysis of a district heating system using a heat pump station. In this application, it solves two problems.

The study is focused on checking the heat loss of the district heating system Comparison of calculations at a standard supply temperature of the heating medium and at a temperature typical for the operation schedule of 4th generation heat supply systems.

2. Description of the case study
As an example, a centralized heating system was modeled in the Oktyabrsky village of the Ryazan region.[3] The topology of the system is shown in Figure 1. Heat generation will take place at a heat pump station located on the territory of Serebryanovsky Cement Plant LLC due to the low-grade heat of the plant's circulating water.[4] From it, through pipelines, the coolant will be supplied to the substations of consumers located in each microdistrict, from where it will be further distributed to subscribers.

![District heating system](image)

**Figure 1.** District heating system.

Heat pumps are appropriate for use where there are year-round heat discharges to cooling towers. In this case, the heat pump is installed at the Serebryanovsky Cement Plant, where heat is discharged daily into two cooling towers located on the plant's territory. They do not always cope with their load, so the use of pumps solves two whole problems.

The primary problem was insufficient cooling of the water in the cooling towers. However, on the basis of its solution, it turned out to be possible to solve another important problem - the possibility of heating the village with the help of a secondary energy resource. All this can be turned into life with a heat pump.

3. Methods
The method of using a heat pump makes it possible to use the waste heat of cooling towers for heating the village. At the moment, there is no centralized heating system in the village, so one of its possible models was modeled above. Since the main source of energy will be the low-grade heat of the enterprise, the district heating system must operate with a reduced temperature schedule, for heat pumps the 70/35 schedule is acceptable [5], so the main calculations will be carried out on its basis. As a comparison, calculations are given with the most common 150/70 schedule. The heat load is controlled in a qualitative way, that is, it is characterized by a variable temperature of the coolant with a constant mass flow.

**Head loss**

The main task is to analyze heat losses, however, it makes no sense to consider losses in such a distributed and extended system without taking into account hydraulic losses, therefore, the article also considers hydraulic losses. In the hydraulic calculation, the diameters of the pipelines, the pressure drop are determined, the pressure values are set at various points of the network in order to ensure the
permissible pressures and required heads in the network.

**70/35 mode**

We select the design line, it should have the lowest specific pressure drop. The main highway will be line 1-6.

*Calculation of the main highway.* The total water consumption through the heating network during the heating period is known \( G = 200 \text{ t/h} = 55.6 \text{ kg/s} \)

Let's take the same water flow in each area to simplify the calculation. Then, taking into account the fact that there are 4 regions, the total consumption per region is \( G = 50 \text{ t/h} \). Knowing \( G \) and \( R \) according to the nomogram, we will preliminarily determine the diameter of the pipeline at the site.

In the final calculation, we specify the obtained pipeline diameter to the nearest one in accordance with GOST, while also specifying the specific pressure drop.

Pressure drop in the area:

\[
\Delta P = (1 + \alpha) R \cdot l.
\]

Head loss:

\[
\Delta H = \frac{\Delta P}{g \cdot \rho}.
\]

The results are summarized in the table.

**Table 1.** Head loss on the main highway at 70/35 mode.

| Site | Length, (m) | Mass flow, (t/h) | Specific pressure drop \( R, (\text{Pa} / \text{m}) \) | Inner diameter, (mm) | Pressure loss, \( \Delta P, (\text{Pa}) \) | Head loss, \( \Delta H, (\text{m}) \) |
|------|-------------|-----------------|-------------------------|----------------------|-----------------|-----------------|
| 1    | 630         | 200             | 50                      | 259                  | 35910           | 3.74            |
| 4    | 3150        | 100             | 76                      | 184                  | 272916          | 28.45           |
| 6    | 5740        | 50              | 54                      | 150                  | 353354          | 36.84           |

Total head loss \( \Sigma \Delta H = 69.03 \text{ m} \).

*Calculation of the branches.* Similarly, we calculate the branches.

**Table 2.** Head loss on the branches at 70/35 mode.

| Site | Length, (m) | Mass flow, (t/h) | Specific pressure drop \( R, (\text{Pa} / \text{m}) \) | Inner diameter, (mm) | Pressure loss, \( \Delta P, (\text{Pa}) \) | Head loss, \( \Delta H, (\text{m}) \) |
|------|-------------|-----------------|-------------------------|----------------------|-----------------|-----------------|
| 2    | 980         | 50              | 137                     | 125                  | 153056          | 15.96           |
| 3    | 2590        | 50              | 137                     | 125                  | 404506          | 42.17           |
| 5    | 420         | 50              | 137                     | 125                  | 65595.6         | 6.84            |

Based on the calculation data, a pressure graph is built (piezometric graph). The piezometric graph provides a visual representation of the pressure or head at any point in the network.

**Figure 2.** Piezometric graph for 70/35 mode.

**150/70 mode**
We also choose line 1–6 as the main highway. All calculations are performed in the same way, only the density of the water changes.

**Calculation of the main highway.**

| Site | Length, (m) | Mass flow, (t/h) | Specific pressure drop R, (Pa / m) | Inner diameter, (mm) | Pressure loss, ΔP, (Pa) | Head loss, ΔH, (m) |
|------|-------------|-----------------|----------------------------------|---------------------|------------------------|-------------------|
| 1    | 630         | 200             | 50                               | 259                 | 35910                  | 3.99              |
| 4    | 3150        | 100             | 76                               | 184                 | 272916                 | 30.32             |
| 6    | 5740        | 50              | 54                               | 150                 | 353354                 | 39.26             |

Total head loss ∑H = 73.57 m.

**Calculation of the branches.**

| Site | Length, (m) | Mass flow, (t/h) | Specific pressure drop R, (Pa / m) | Inner diameter, (mm) | Pressure loss, ΔP, (Pa) | Head loss, ΔH, (m) |
|------|-------------|-----------------|----------------------------------|---------------------|------------------------|-------------------|
| 2    | 980         | 50              | 137                              | 125                 | 153056                 | 1.00              |
| 3    | 2590        | 50              | 137                              | 125                 | 404506                 | 44.94             |
| 5    | 420         | 50              | 137                              | 125                 | 655956.6               | 7.29              |

Based on the calculation data, a pressure graph is built (piezometric graph).

**Figure 3.** Piezometric graph for 150/70 mode.

**Heat loss**

Next, we will make a thermal calculation of heat pipelines, which includes the determination of heat losses of a heat pipe. In the village, a channelless gasket will be used, and polyurethane foam is used as an insulating material. Depth of laying is 700 mm.

Specific heat losses in the supply line:

\[ q_1 = \frac{\tau_1 - \tau_s}{R_t + R_s} \]

In the return line:

\[ q_2 = \frac{\tau_2 - \tau_s}{R_t + R_s} \]

Data is tabulated.
Table 5. Thermal calculation of the heating network.

| Site | \( d_{in} \) (mm) | \( d_{ex} \) (mm) | \( L \) (m) | 70/35 | 150/70 |
|------|------------------|------------------|------------|-------|-------|
|      | Specific heat losses supply heat pipe, (W/m) | Specific heat losses return heat pipe, (W/m) | Total losses, (W/m) | Specific heat losses supply heat pipe, (W/m) | Specific heat losses return heat pipe, (W/m) | Total losses, (W/m) |
| 1    | 259              | 400              | 630        | 21.98 | 10.32 | 32.30 | 48.61 | 21.98 | 70.59 |
| 2    | 125              | 225              | 980        | 16.35 | 7.68  | 24.03 | 36.18 | 16.35 | 52.53 |
| 3    | 125              | 225              | 2590       | 16.35 | 7.68  | 24.03 | 36.18 | 16.35 | 52.53 |
| 4    | 184              | 315              | 3150       | 17.92 | 8.42  | 26.34 | 39.64 | 17.92 | 57.56 |
| 5    | 125              | 225              | 150        | 16.35 | 7.68  | 24.03 | 36.18 | 16.35 | 52.53 |
| 6    | 150              | 250              | 5740       | 18.67 | 8.77  | 27.44 | 41.30 | 18.67 | 59.97 |

Figure 4. Total heat loss at site No. 1.

An important characteristic of a heat pump is COP (Coefficient of Performance) - the conversion factor, otherwise the heat coefficient. It shows how many times the heat pump produces more energy than it consumes itself, which is, it determines the ratio of heat to electrical power [6].

In theory, COP is defined by the following formula:

\[
\text{COP} = \frac{T_2}{T_2 - T_1}.
\]

Assuming that COP is the ratio of thermal power to electrical power, we rewrite the formula:

\[
\text{COP} = \frac{Q}{N}.
\]

\( Q \) – thermal power, can be expressed:

\[
Q = Gc\Delta t.
\]

This research compares the cost of using a heat pump operating on a low temperature schedule and a heat pump operating on a high temperature (normal) schedule. In fact, the heat pump is not able to heat the coolant to a high temperature; therefore, to heat up the water, it is necessary to use a heat pump in conjunction with an electric boiler. Thus, the electrical power at the high-temperature schedule (150/70) will be made up of three components:

\[
N = N_{hp} + N_p + N_b.
\]
The power of the pumps is determined by the formula:

\[ N_p = G \cdot H \cdot g. \]

Power consumed by the electric boiler:

\[ N_b = \frac{Gc \Delta t}{\eta_b}. \]

As a result, we get the formula for the high-temperature regime:

\[ \frac{T_2 - T_1}{T_2 - T_1} = \frac{Gc \Delta t}{N_{hp} + G \cdot H \cdot g + \frac{Gc \Delta t}{N_b}}. \]

In this case, for the low-temperature regime:

\[ \frac{T_2 - T_1}{T_2 - T_1} = \frac{Gc \Delta t}{N_{hp} + G \cdot H \cdot g}. \]

**Figure 5.** Dependence of total energy costs on the ambient temperature.

4. Conclusion

Thus, it is possible to trace the dependence of the energy consumption for heating the village on the outside air temperature. In the low-temperature mode (70/35), the energy consumption is much lower than that in the high-temperature mode (150/70). In many respects this is the result of the fact that to ensure a high temperature of the coolant, the installation of not only heat pumps, but also electric boilers is required. This is possible, but low temperature district heating is a much more economical option. [7] Outside air temperature can be a problem for the use of such systems, in which case the installation of electric heating units is justified.

References

[1] Li H, Norda N. 2018 Transition to the 4th generation district heating - possibilities, bottlenecks, and challenges.
[2] Babak T., Duić N, Khavin G., Boldyryev S., Krajačić G. 2016 Possibility of Heat Pump use in Hot Water Supply Systems.
[3] Tsvetkov N A, Krivoshein U O, Tolstykha A V, Khutornoi A N, Boldyryev S 2020 The calculation of solar energy used by hot water systems in permafrost region: An experimental case study for Yakutia
[4] Rakhmanov Yu A, Sergiyenko O I, Dmitrieva A P 2020 Heat recovery of waste gases in thermal-oxidative waste disposal systems using gas turbine techniques.
[5] Kauko H, Kvalsvik K, Rohde D, Nord N 2020 Dynamic modeling of local district heating grids with prosumers: A case study for Norway.
[6] Nord N, Rohde D, Andresen T 2016 Interaction between a building complex with an integrated thermal energy system and a district heating system.
[7] Savoskula V A, Sergienko O I, Pavlova A S 2020 Ecological and economical assessment of efficiency of application of alternative energy sources to achieve the goals of the Climate Strategy of St. Petersburg.