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OPERATION OF HEAT NETWORKS UNDER CONDITIONS OF «REDUCED» HEATING TEMPERATURE SCHEDULE

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РОБОТА ТЕПЛОВИХ МЕРЕЖ В УМОВАХ «ЗНИЖЕНОГО» ОПАЛЮВАЛЬНОГО ТЕМПЕРАТУРНОГО ГРАФІКА

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Abstract. *The article examines the operation of distribution heat networks at different temperatures of the coolant in the heat supply system according to the heating temperature schedule of quality regulation. Comparisons are made of heat and hydraulic losses when changing the temperatures of the heating temperature schedule, with the existing constant diameter of the heating network. The consequences of using this schedule in existing heating systems of the twentieth century are also considered.*

Keywords: *Temperature chart, coolant flow, heat losses, hydraulic losses, thermal energy, consumer, heat networks.*

Анотація. *У статті розглянуто роботу розподільних теплових мереж з різними температурами теплоносіями в системі теплопостачання за опалювальним температурним графіком якісного регулювання. Порівняно теплові та гідравлічні втрати зі зміною температур опалювального температурного графіка з постійним наявним діаметром теплової мережі. Збільшення температури теплоносія призводить до зменшення його витрат, а отже, зменшення гідравлічних втрат у сучасних теплових мережах. Крім того, ремонтуючи або реконструюючи теплову мережу, можна зменшувати її діаметри. Однак збільшення температур теплоносія в деяких випадках може призвести до додаткових витрат, пов'язаних із необхідністю влаштування індивідуальних теплових пунктів із вузлами змішування або встановлення теплообмінних апаратів за незалежної схеми підключення систем опалення до теплових мереж, для необхідного зниження температурного потенціалу.*

Також використання «зниженого» температурного графіка в сучасних системах опалення забудови XX століття призводить до зменшення тепловіддачі наявних нагрівальних приладів, які були запроєктовані та встановлені в умовах роботи за температурними графіками, застосовуваними раніше. Наведено заходи, необхідні для використання «зниженого» температурного графіка в сучасних системах опалення. До них можна віднести реконструкцію системи опалення, пов'язану зі збільшенням площі нагріву нагрівальних приладів; модернізацію будівлі, пов'язану з підвищенням її енергоефективності, шляхом влаштування теплової ізоляції огороджувальних конструкцій, встановлення сучасних склопакетів тощо, що знизить необхідне теплове навантаження системи опалення.

Ключові слова: *температурний графік, витрати теплоносія, теплові втрати, гідравлічні втрати, теплова енергія, споживач, теплові мережі.*

Introduction. Currently, many heat supply organizations have switched to the operation of heat supply sources with a «reduced» temperature schedule of quality regulation. This also applies to the city of Kharkiv. For example, the heat supply source that provides thermal energy to a significant part of the city, TPP-5, previously worked according to a temperature schedule of 150-70 ℃, and from the beginning of the 21st century to the present, it has been working according to a «reduced» temperature schedule of 124-61 ℃. Other heat supply sources have also reduced the coolant temperatures, TPP-3 and many large regional boiler houses, which previously worked according to a temperature schedule of 135-70 ℃, now work according to a temperature schedule of 118-59 ℃.

In the city of Kharkiv, regulation of heat energy supply is qualitative – changing the temperature of the coolant depending on the outside air temperature, while the coolant flow rate is a constant value (true for the heating temperature schedule). Existing types of regulation of heat energy supply and requirements for heating network pipelines are described in [1]. Issues related to the rational use of one or another type of regulation of heat energy supply are considered in articles [11, 12].

Analysis of recent research and publications. The centralized heat supply system consists of a heat supply source, heat networks and a consumer. Heat losses in heat network pipelines depend on the temperature of the coolant, the type of thermal insulation, the type of installation, the outside air temperature, the presence of solar radiation, etc. The requirements for heat network pipelines and the type of installation are determined by [1]. Hydraulic losses depend on the coolant flow rate, the pipeline diameter, the material of the heat network pipes, and the service life (especially for steel pipes, taking into account their overgrowth and, accordingly, an increase in the wall roughness coefficient).

The main part of the development of the city of Kharkiv dates back to the second half of the 20th century. The heating systems in these buildings are mainly single-pipe (with upper or lower wiring, as well as U-shaped). These heating systems are unregulated. The efficiency of reconstruction of these heating systems comes down to the transition from single-pipe unregulated heating systems to two-pipe systems, with the possibility of regulation by installing thermostatic elements (i.e. the possibility of instrumental regulation). In this case, the consumer can independently choose the temperature inside the premises, which is comfortable for him. This is especially economically feasible with horizontal (apartment) wiring of the heating system and the installation of a distribution unit for metering the thermal energy of the heating system in a given apartment. The possibility and efficiency of such reconstruction are discussed in articles [13-17].

Calculations of heat losses in heating networks, as well as their methods, are considered in works [18-21, 23], and the calculation of hydraulic losses in [22-24].

The existing works do not reflect how, from an economic point of view, it is more efficient to transfer thermal energy to the consumer with an increased temperature or with an increased flow rate of the coolant. In addition, there is no analysis of the effect of a decrease in the temperature of the coolant, and, consequently, the temperature pressure, in existing heating systems of the 20th century buildings.

Goal and task setting. The main objective of this work is to determine the economic feasibility of using a «reduced» temperature schedule. The amount of thermal energy is determined as the product of the coolant flow rate and the temperature difference between the supply and return pipelines of the heating networks, and, therefore, when the temperature difference decreases, we increase the coolant flow rate, which leads to an increase in hydraulic losses.

The second aspect of this work is to determine how much the amount of heat supplied to the consumer will decrease for existing heating systems of the 20th century buildings, with a decrease in temperature pressure. With previously existing temperature schedules of 150-70 °C and 135-70 °C, the maximum calculated temperature of the coolant supplied to the heating systems after the mixing unit was 95-70 °C, and in some cases, with a single-pipe heating system in sixteen-story residential buildings, a temperature schedule for heating systems of 105-70 °C was used.

Today, according to [2], the maximum permissible temperature of the coolant supplied to the heating system of residential and administrative buildings for two-pipe heating systems is 95 °C, and for one-pipe heating systems of these buildings it can reach up to 105 °C.

The main part of the study. For the study, we considered a dead-end distribution (intra-block) section of the heating network with a heat load of the heating system of the connected consumer of 0.37 Gcal/h or 0.43 MW. The heat supply system is closed, four-pipe; coolant is water; regulation is high-quality, according to the heating temperature schedule; hot water supply is provided by separate pipelines from the central heating station (CHS), where the heat exchanger of the hot water supply system is installed. The heat source operates according to the temperature schedule of 118-59 °C. The mixing unit is provided at the individual heating station (IHS), which reduces the coolant temperature from 118 °C to 78 °C. Before the beginning of the 21st century, the heat supply source operated according to the temperature schedule of 135-70 °C, and after the IHS, the temperature schedule was 95-70 °C. The section of the heating network in question is laid above ground, the existing pipelines of the heating network are made in accordance with the requirements of [1], these are pre-insulated factory-made pipes in polyurethane foam thermal insulation with a protective shell made of galvanized metal sheet («Spiro» pipes). The diameters of the pipelines of the existing section of the heating network are 76/140*3.5 [8];

where 76 – outer diameter of steel pipe according to [7], mm;

140 – total diameter of pipe, taking into account thickness of thermal insulation, mm;

3.5 – wall thickness of steel pipe, mm.

The length of the existing section of the heating network is 82 m.

In a residential building, cast iron radiators of the M-140 brand are installed in the heating system, which have a maximum heat output of 160 W, with a temperature pressure of 70 °C.

In the first part of the study, we will consider two options for the operation mode of heating networks, with different temperature characteristics: with a temperature schedule of 118-59 °C and with a temperature schedule of 135-70 °C. We will determine the hydraulic and thermal losses of the section under consideration.

Option 1. We determine the hydraulic and thermal losses of a section of the heating main with a temperature schedule of 118-59 °C.

To determine the hydraulic losses, it is necessary to determine the flow rate of the coolant. The flow rate of the coolant, t/hour, for the needs of the heating system is determined according to [1]

$$G_{o.max} = \frac{3{,}6 \cdot Q_{o.max}}{c \cdot (\tau_1 - \tau_2)} \cdot 10^{-3}, \quad (1)$$

where $Q_{(o.max)}$ – maximum heat load of the heating system, W;

c – specific heat capacity of water, 4.187 kJ/(kg·°C) is assumed in calculations;

τ_1 – coolant temperature in the supply pipeline, °C;

τ_2 – coolant temperature in the return pipeline, °C.

Having determined the coolant flow rate and knowing the pipeline diameter, using tables

[24] we determine the specific pressure losses, Pa/m. The hydraulic calculation table is made for a coolant density of 958 kg/m^3 and $k_e = 0.5$. For the actual coolant temperature, it is necessary to recalculate using the formula

$$R_f = R_v \rho_v /(\rho_f), \qquad (2)$$

where ρ_f – coolant density, which depends on its temperature, kg/m^3.

Formula (2) is valid for new pipes with $k_e = 0.5$.

We find the speed of the coolant, m/s, using the formula

$$w = \frac{4 \cdot G_{o.max} \cdot 10^6}{3{,}14 \cdot d^2 \cdot 3{,}6 \cdot \rho_f}, \qquad (3)$$

where d – internal diameter of the pipeline, mm.

We determine the value of the reduced length of the heating main, m, using the formula

$$l_{pr} = l \cdot (1 + \alpha), \qquad (4)$$

where l – length of the heating main section, according to the plan, m;

α – the coefficient that takes into account pressure losses in local resistances is determined from tables [24].

Pressure losses in a network section, Pa, are determined by the formula

$$\Delta P = R \cdot l_{pr}, \qquad (5)$$

where R – specific pressure losses, which are determined based on the known diameter and the found flow rate, according to hydraulic calculation tables [24], Pa/m.

Based on the pressure losses found, we determine the head loss, m.water column, using the formula

$$\Delta H = \Delta P/(\rho_f \cdot g), \qquad (6)$$

where g – acceleration of gravity, which we take to be 9.807 m^2/s.

Using formula (1), with a temperature graph of 118-59 ℃, we find the value of the coolant flow rate, which is 6.3 t/h; 1.74 kg/s or 6.7 m^3/h.

The data for constructing the heating temperature graph, with coolant parameters of 118-59 ℃, were obtained at an air temperature inside residential premises of +20 ℃ [2] and are presented in Table 1.

Table 1

Data for constructing a heating temperature graph at a calculated coolant temperature of 118-59 ℃

t, ℃	-23	-20	-15	-10	-5	-1	0	+5	+8
τ_1, ℃	118	114,0	111,9	101,7	91,3	72,1	69,9	58,8	52,0
τ_2, ℃	59	57,7	57,0	53,7	50,1	43,3	42,5	38,3	35,5
τ_{11}, ℃	118	114,0	111,9	101,7	91,3	52,6	51,3	44,9	40,8

where t – outside temperature, ℃;

τ_{11} – coolant temperature in the supply pipeline, which is supplied to the heating system, ℃.

The data on the calculated heating temperature of the outside air are taken according to parameters B, for the city of Kharkiv. The calculated heating temperature and the average outside air temperature for the heating period are taken according to the data of [3]. The heating temperature graph, coolant flow rate graph, «operating point» and hydraulic characteristic curves of the section under consideration and the consumed power of the electric motor are presented in Fig. 1-4.

The average temperature of the coolant in the supply pipeline during the heating period is 72.1 °C, and in the return pipeline 43.3 °C.

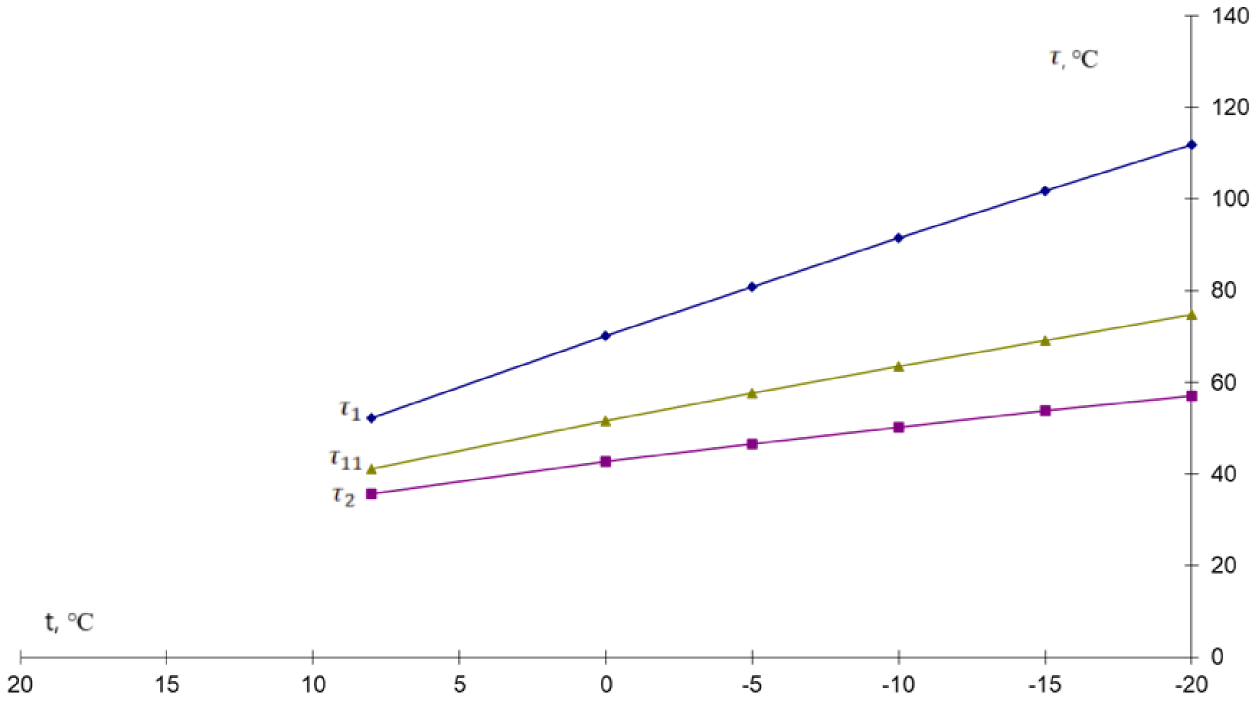

Fig. 1. Heating temperature graph at calculated coolant temperatures of 118-59 °C

Using the data from the tables for hydraulic calculation [24] and formulas (2-6), perform a hydraulic calculation of the section of the heating network under consideration. The calculation is summarized in Table 2.

As can be seen from Fig. 4, to overcome the hydraulic resistance of the considered section of the network, the pump electric motor power of 0.058 kW is required. Fig. 3-4 show the characteristics of the energy-efficient pump with a frequency converter Magna3 32-40 [25].

Table 2

Hydraulic calculation of the considered section of the heating network at the calculated coolant temperature of 118-59 °C

G, kg/s	l, m	a	L_{pr}, m	d, mm	w, m/s	R, Pa/m	R_f, Pa/m	ΔP, Pa	H, m.water column	ΣH, m.water column
1.74	82	0.3	106.6	76	0.47	51.8	52.5	5596.5	0.6	1.2

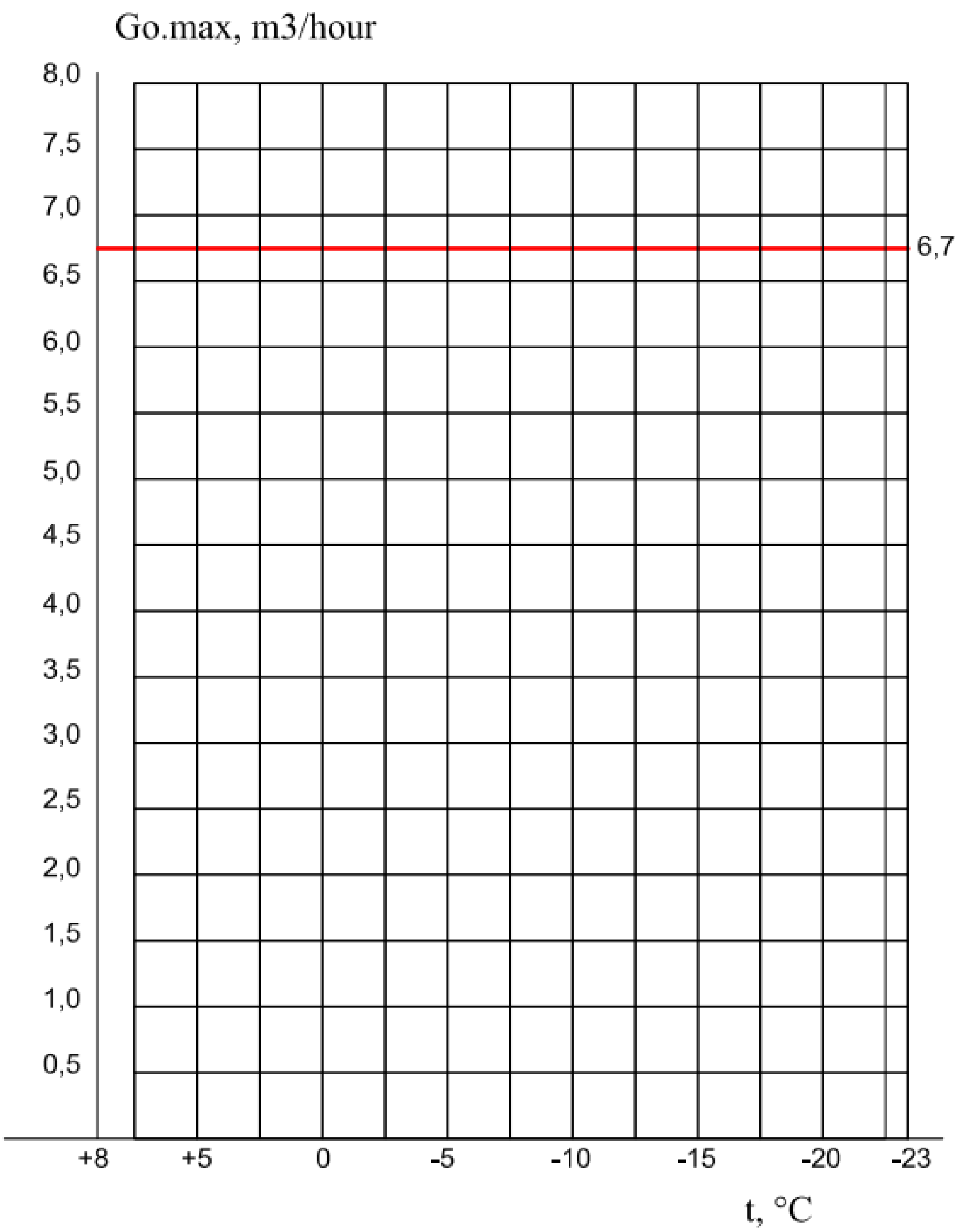

Fig. 2. Heat carrier flow rate graph, at calculated heat carrier temperatures of 118-59 °C, high-quality regulation

Next, we determine the heat losses of the heating network pipelines, which have a diameter of 76/140*3.5. The laying is above ground, the pipes are steel, pre-insulated, factory-made. The average temperatures of the coolant during the heating period are: supply pipeline 72.1 °C, return pipeline 43.3 °C.

The calculation is performed according to the method given in [4].

We find the ratio of the total diameter of the pipe, taking into account thermal insulation, to the outer diameter of the pipe.

$$\mathrm{B} = \frac{d_i}{d}, \quad (7)$$

where d_i – total pipe diameter, taking into account thermal insulation, m;

d – outside diameter of the pipe, m.

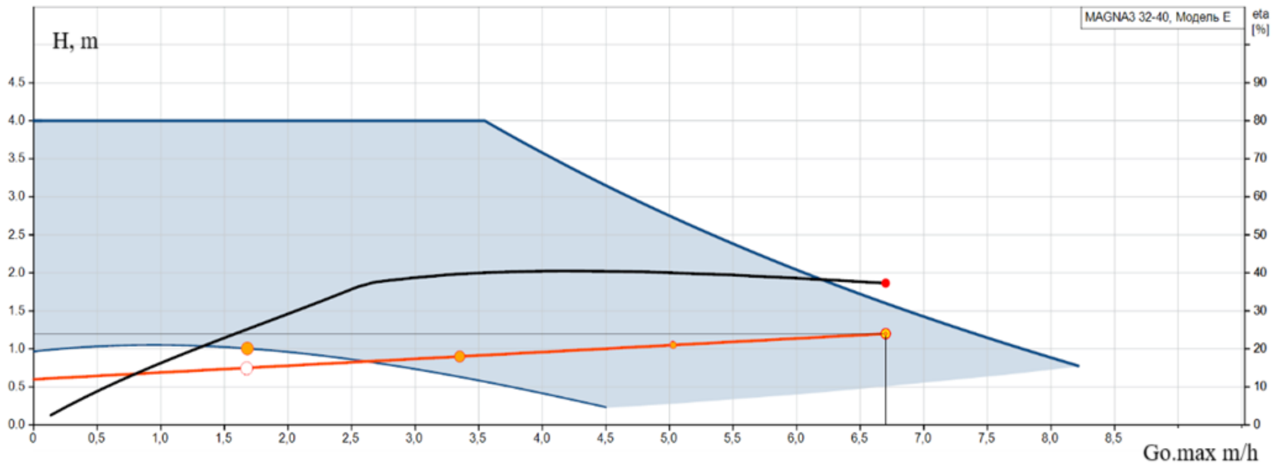

Fig. 3. Operating point and hydraulic performance curves of the pump

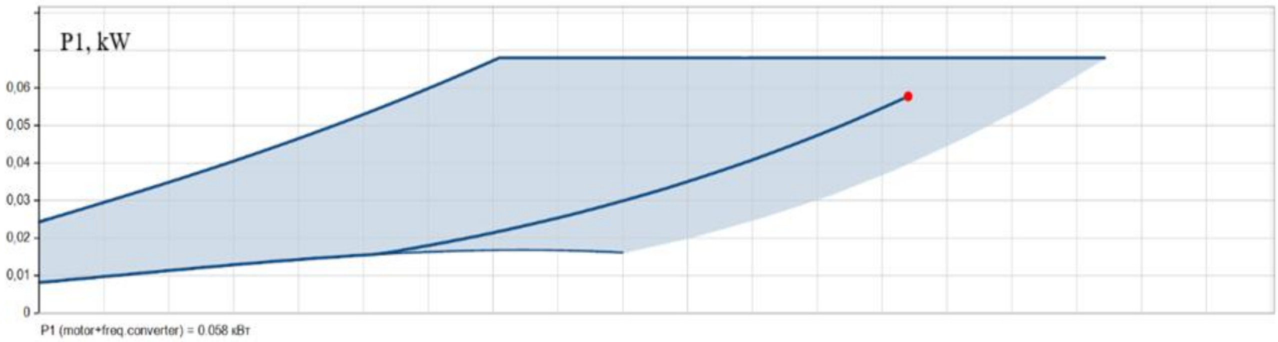

Fig. 4. Power characteristic of the pump electric motor

Defining the natural logarithm B (ln B).

We determine the total thermal resistance of the thermal insulation layer and additional thermal resistances along the heat flow path using the formula

$$r_{tot} = \frac{lnB}{2 \cdot \pi \cdot \lambda_k} + \frac{1}{a_e \cdot \pi \cdot (d+1)}, \quad (8)$$

where λ_k – thermal conductivity of the heat-insulating layer, W/(m^2·°C), we take 0.027 according to the data [26];

a_e – heat transfer coefficient from the outer surface of thermal insulation, taken according to data [4], W/(m^2·°C).

We determine the specific thermal loss, W/m, using the formula

$$q_e = \frac{\tau - t_c}{r_{tot}}, \quad (9)$$

where τ – average temperature of the coolant during the heating period, °C;

t – average outside air temperature during the heating period, taken according to [3], °C.

The calculation of heat losses through heating network pipelines is summarized in Table 3.

Table 3

Average thermal losses by pipelines during the heating period, with a calculated coolant temperature of 118-59 °C

τ, °C	t, °C	d, m	d_i, m	B	ln B	L, m	r_{tot}	Thermal losses		
								q_e, W/m	q, W	q_o, kW
72.1	-1	0.076	0.14	1.842	0.611	82	3.65	20.03	1642.2	7055.1
43.3	-1	0.076	0.14	1.842	0.611	82	3.65	12.14	995.2	4275.5
Total										11330.6

where L – length of the considered section, m;

q_o – average thermal losses by pipelines during the heating period, the heating period for the city of Kharkiv is taken as 179 days, according to data [3].

Option 2. We determine the hydraulic and thermal losses of a section of the heating main at a temperature schedule of 135-70 °C.

According to formula (1), at a temperature schedule of 135-70 °C, we find the value of the coolant flow rate, which is 5.7 t/h; 1.58 kg/s or 6.1 m^3/h.

The data for constructing the heating temperature schedule, at coolant parameters of 118-59 °C, were obtained at an air temperature inside residential premises of +20 °C [2] and are presented in Table 4. The data on the calculated heating temperature of the outside air are taken according to parameters B, for the city of Kharkiv. The calculated heating temperature and the average outside air temperature for the heating period are taken according to the data of [3]. The heating temperature schedule, coolant flow schedule, «operating point» and hydraulic characteristic curves of the section under consideration and the consumed power of the electric motor are presented in Fig. 5-8.

Table 4

Data for constructing a heating temperature graph at a calculated coolant temperature of 135-70 °C

t, °C	-23	-20	-15	-10	-5	-1	0	+5	+8
τ_1, °C	135	130.3	128.0	116.1	104.0	81.7	79.1	66.1	58.1
τ_2, °C	70	68.3	67.5	63.2	58.7	49.9	48.9	43.4	39.9
τ_{11}, °C	95	92.2	90.7	83.5	76.1	62.1	60.5	52.2	46.9

Using the data from the tables for hydraulic calculation [24] and formulas (2-6), we perform a hydraulic calculation of the section of the heating network under consideration. The calculation is summarized in Table 5.

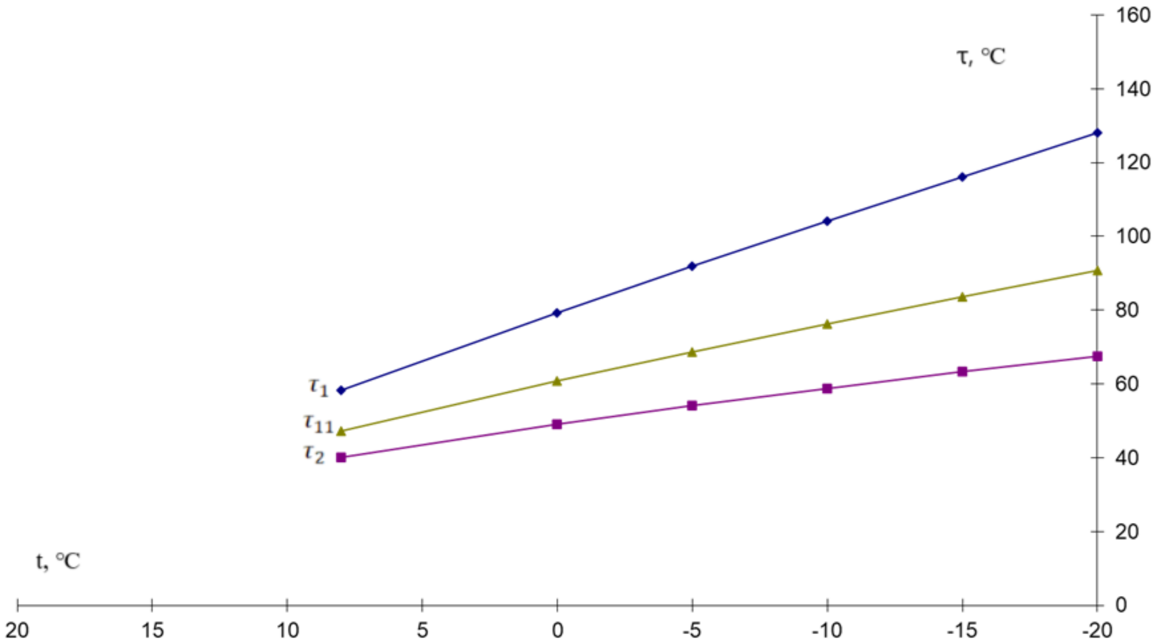

Fig. 5. Heating temperature graph at calculated coolant temperatures of 135-70 °C

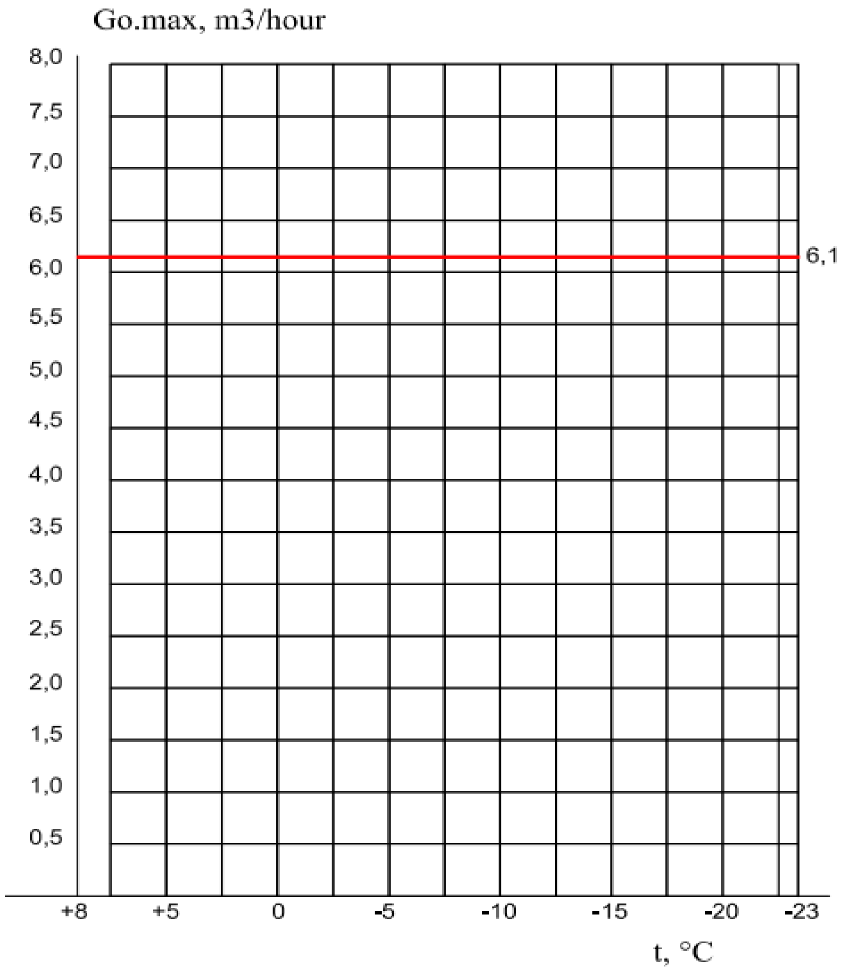

Fig. 6. Heat carrier flow rate graph, at calculated heat carrier temperatures of 135-70 °C, high-quality regulation

Table 5

Hydraulic calculation of the considered section of the heating network at the calculated coolant temperature of 135-70 ℃

G, kg/s	l, m	a	L_{pr}, m	d, mm	w, m/s	R, Pa/m	R_f, Pa/m	ΔP, Pa	H, m.water column	ΣH, m.water column
1.58	82	0.3	106.6	76	0.45	51.8	42.7	4551.8	0.5	1.0

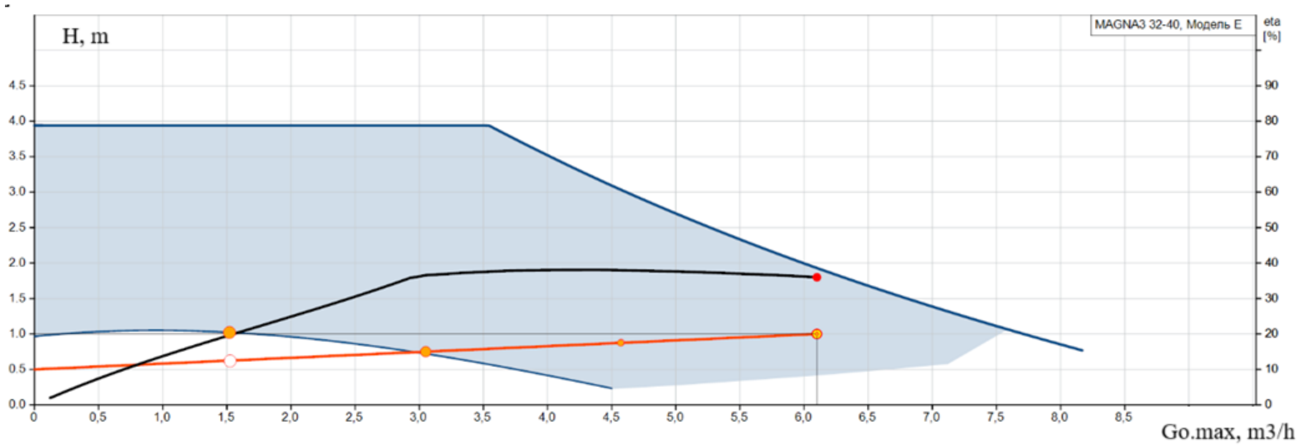

Fig. 7. Operating point and hydraulic performance curves of the pump

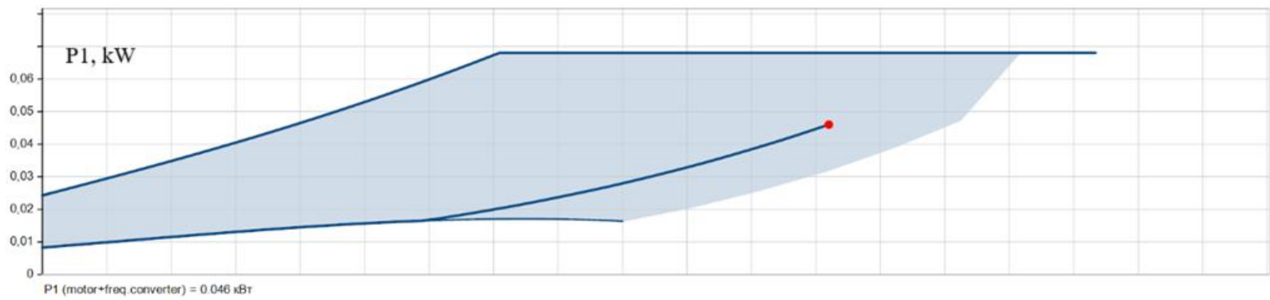

Fig. 8. Power characteristic of the pump electric motor

As can be seen from Fig. 8, to overcome the hydraulic resistance of the considered section of the network, the pump electric motor power of 0.046 kW is required. Figures 7-8 show the characteristics of the energy-efficient pump with a Magna3 32-40 frequency converter [25].

Next, we determine the heat losses of the heating network pipelines, which have a diameter of 76/140*3.5. The laying is above ground, the pipes are steel, pre-insulated, factory-made. The average temperatures of the coolant during the heating period are: supply pipeline 81.7 ℃, return pipeline 49.9 ℃.

The calculation of heat losses by the heating network pipelines is summarized in Table 6.

Table 6

Average thermal losses by pipelines during the heating period, with a calculated coolant temperature of 135-70 °C

τ, °C	t, °C	d, m	d_i, m	B	ln B	L, m	r_{tot}	Thermal losses		
								q_e, W/m	q, W	q_o, kW
81.7	-1	0.076	0.14	1.842	0.611	82	3.65	22.66	1858.1	7982.4
49.9	-1	0.076	0.14	1.842	0.611	82	3.65	13.95	1143.9	4914.2
Total										12896.6

Next, we conduct an economic comparison of the obtained results of hydraulic and thermal losses obtained for options 1 and 2. We summarize the calculation in Table 7.

Data on the cost of thermal energy are taken from [27]. Data on the cost of electrical energy are taken from [28].

The results in Table 7 show that the use of a «reduced» temperature schedule is currently an economically feasible solution.

Table 7

Summary comparison table

Tempe-rature graph	Thermal losses during the heating period, Gcal	Power consumption of the pump electric motor, during the heating period, kW	Tariff 1 Gcal, UAH	Tariff for 1 kW/h of electric energy, UAH	Price for thermal loss during the heating period, UAH	Price of electric energy, for the heating period, UAH	Total costs, UAH
118-59	9.74	249.2	1539.5	10.05	14994.73	2504.46	17499.19
135-70	11.1	197.6	1539.5	10.05	17088.45	1985.88	19074.33

In addition, when connecting consumer heating systems to heating networks after a mixing unit or using a heat exchanger of the heating system (with an independent scheme), which can be located at the central heating point, it is necessary to take into account that when the coolant temperature increases above the standards specified in [2], it is necessary to provide for the installation of a separate mixing unit or heat exchanger at the central heating point at each consumer. However, combined regulation consisting of: central; local; individual is more economically advantageous than combined regulation consisting of: central; group; individual [11].

The second question of our research is to consider the impact of reducing the coolant temperatures in existing heating systems of the 20th century buildings.

In modern construction, the design and installation of heating systems and heating points are carried out in accordance with existing, modern regulatory documents, taking into account energy-efficient technologies, according to the requirements of [1, 2]. In addition, all modern buildings are constructed, taking into account the requirements for energy efficiency, according to the requirements of [5, 6].

As for five-story, nine-story, twelve-story, fourteen-story, sixteen-story residential buildings of the 20th century, these are mainly panel residential buildings that were built without taking into account energy efficiency requirements.

For example, let's consider a residential building with a heating system heat load of 0.37 Gcal/hour or 430.31 kW. The heating system is two-pipe. Heating devices are cast-iron radiators M-140, 500 mm high. The heat output of one section, at a temperature pressure of 70 °C, is 0.16 kW. Currently, the temperature schedule in the heating system is 78-59 °C. At the time of design and construction, the temperature schedule of the heating system was 95-70 °C. In the calculations, we neglect the heat losses of the heating system pipelines that run through basements, attics, stairwells, etc.

We determine the actual temperature head, °C, using the formula

$$\Delta\tau_f = \frac{\tau_{11}+\tau_2}{2} - t_v , \qquad (10)$$

where t_v – indoor air temperature, °C, is taken according to the requirements [2].

We determine the actual heat output of one section, kW,

$$Q_f = Q_p \cdot \left(\frac{\Delta\tau_f}{70}\right)^{1,3} , \qquad (11)$$

where Q_p – heat output of one section, at a temperature head of 70 °C, kW.

We determine the required number of radiator sections using the formula

$$n = \frac{Q_o}{Q_f} , \qquad (12)$$

where Q_o – maximum heat load of the heating system, W.

We calculate the required number of heating device sections at a temperature schedule of 95-70 °C (the schedule that was used when designing and installing the heating system), and at a temperature schedule of 78-59 °C (which is the current one). We summarize the calculations in Table 8.

Table 8

Summary comparison table

Temperature graph, °C	$\Delta\tau_f$, °C	Q_o, кВт	Q_f, кВт	n, шт.
78-59	48.5	430.31	0.099	4334
95-70	62.5	430.31	0.138	3118
Difference				1216

From the results of the table we see that when using the «reduced» temperature schedule in the heating systems of buildings of the 20th century, which were designed and built for higher temperatures of the coolant, 1216 sections are missing to provide the necessary heat load of the heating system. That is, the actual heat load of the heating system was 308.68 kW instead of the required 430.31 kW, which is 28.27 % of the lost heat energy.

Conclusions. When comparing the operation of heating networks according to the «reduced» temperature schedule with the previously used temperature schedule, in the considered section of the heating network, it can be said that hydraulic losses have not actually changed, and thermal losses have decreased by 1.36 Gcal during the heating period, which is 12.3 %.

However, when using a «reduced» temperature schedule in heating networks, it also leads to a decrease in the temperature of the coolant supplied to the heating system. For modern construction, this is not critical, due to the fact that modern buildings are designed and constructed according to the existing parameters of the heating network, as well as taking into account energy efficiency requirements (installation of modern double-glazed windows, thermal insulation of enclosing structures, etc.). As for the construction of the twentieth century, heating systems were designed for higher temperatures of the coolant and, therefore, the heating area of the heating devices was selected based on these temperatures. When using a «reduced» temperature schedule in these systems, it leads to a shortfall in thermal energy for consumers. The following measures can be used to solve this issue:

- reconstruction of the heating system, associated with increasing the heating area of heating devices;
- modernization of the building, associated with increasing its energy efficiency, by installing thermal insulation of enclosing structures, installing modern double-glazed windows, etc., which will reduce the required thermal load of the heating system.

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