IOP Conference Series:
Earth and
Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: A G Kolienko *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1415** 012117

IOP Conf. Series: Earth and Environmental Science **1415** (2024) 012117 doi:10.1088/1755-1315/1415/1/012117

Determination of operating parameters of accumulative electric heating systems

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Abstract. The article presents the results of research aimed at determining the parameters and characteristics of storage heating systems, justifying the possibility of using heat accumulators to increase the efficient use of energy that is generated, including from renewable sources. The virtuality, frequency and significant dependence on natural conditions and climate of renewable energy sources, as well as the need to optimize their installed capacity, leads to the need to use energy storage installations. The presence of efficient energy batteries is a prerequisite for modern efficient energy and heat supply systems. The methodology of the work is based on our own theoretical and experimental studies, which provide practical recommendations for the arrangement of energy accumulators obtained using renewable heat sources. This is especially relevant for Ukraine during the period of active military operations on its territory, the destruction of traditional energy sources and a shortage of generating capacity. Recommendations have been developed for the design of heat accumulators for heating systems of residential and public buildings. Their effectiveness has been assessed under conditions of limited use of fossil fuels and the use of hybrid energy sources. Scientific and practical results of the work make it possible to carry out low-cost reconstruction of heating systems for the introduction of storage systems using electrical energy, the source of which is wind and solar energy. Such developments are becoming particularly relevant in Ukraine, taking into account the requirements for ensuring the stability and efficiency of infrastructure facilities in war conditions.

1. Introduction

Thermal batteries are one of the important elements when addressing the issue of replacing fossil fuels, such as natural gas, with renewable energy sources, as well as when using low-potential energy sources. The use of energy batteries when installing hybrid systems is also mandatory [1]. Accumulation makes it possible to solve important tasks set in the updated energy efficiency directive [2].

The use of thermal accumulators in thermal power systems with renewable sources, including the generation of electrical energy from biogas, helps reduce CO_2 emissions into the atmosphere and reduce the greenhouse effect [3].

Renewable energy sources generate energy that is variable in both time and quantity. For example, the use of solar or wind energy for heating purposes is practically impossible without the use of heat storage. In addition, heat accumulation can be considered as a means of leveling the energy consumption schedule. When using two and three-rate tariffs, heat accumulators make it possible to obtain a significant economic effect associated with the possibility of obtaining energy during periods of the lowest tariffs.

An additional challenge is charging for the installed power of the power generator. The use of heat accumulators makes it possible to reduce the installed capacity of consumer heat and power systems by leveling the load and covering peak loads using accumulated heat. In addition, heat accumulation allows for more efficient use of renewable energy sources with variable generation capacity.

There are two types of such batteries. The first type includes those whose temperature increases as a result of the supply of heat, the second – those in which the supplied heat is spent on some kind of phase transition – most often melting. In the first case, the specific energy of the battery is determined by the heat capacity of the storage substance and the permissible change in its temperature, and in the second – by the latent heat of phase transition.

The article discusses the issues of determining the operating parameters of water batteries without a phase transition.

The developed methodology for determining the characteristics of thermal accumulators can be applied not only when using electrical energy, but also for any other energy sources in heating systems. It is also possible to use the technique when using hybrid energy sources.

Algorithm for researching the given problem:

- work with literary sources on the topic of using electrical energy in heating systems [4–6];
- analysis of the issue of using heat accumulators in electric heating systems [7–9];
- full-scale studies of operating modes of heating systems in residential and public buildings;
- construction of a mathematical model to determine the operating parameters of heat accumulators;
- determination of the main parameters of the heat accumulation system;
- experimental verification of the obtained dependencies to determine the operating parameters of the accumulation system.

2. Methodology

The design and installation of storage heat supply is facilitated by the continuous increase in the price of natural gas and other types of fossil fuels. This, in turn, leads to an increase in tariffs for thermal energy received in centralized and other heat supply systems.

Thus, renewable energy can be considered as a useful alternative to energy obtained by burning fossil fuels (such as natural gas).

However, the use of electrical energy for heating needs helps solve the problems of power engineers themselves. Namely, the problem of a shortage of shunting capacity to regulate the daily load schedule of the energy system against the backdrop of a surplus of electrical energy generation. The use of electrical energy for heating buildings at night can be a good way to level out the unevenness of electrical energy consumption in the power supply system. Especially when using electrical energy generators using renewable and alternative energy sources. And also in conditions of military threats to infrastructure facilities.

The advantage of using electrical energy as an energy carrier is also the ability to maintain the temperature regime of heating water in boilers with high accuracy.

The use of electric heating systems makes the task of assessing the efficiency of storage systems extremely relevant. From a thermodynamic point of view, from 1 m^3 of natural gas of group L or E according to the classification [10,11] with a calorific value of up to 40 MJ/m^3 it is theoretically possible to obtain (provided that the process is 100% efficient) up to 11 $kW{\cdot}hour/m^3$ of electrical energy.

However, the low efficiency of condensing thermal power plants leads to the fact that the amount of generated electrical energy does not exceed 3-4 kW·hour/m^3, which immediately affects electricity tariffs.

Let's perform a thermodynamic analysis of the use of various types of energy.

The advantage of electric heating boilers, without a doubt, is their high thermal efficiency of converting electrical energy into heat, which is close to 99%.

For comparison, when using the best hydrocarbon fuel – natural gas – in non-condensing boilers, the thermal efficiency does not exceed only 91-92%. It cannot be large due to the fear of condensation of water in the composition of fuel combustion products. In condensing heat generators, the efficiency of fuel use can be increased to 95-96% [12].

However, the difference in the efficiency of heating gas and electric boilers for municipal energy is easily compensated by the extremely low efficiency of the steam power cycle for generating electrical energy at condensing power plants.

The situation may change if renewable sources are used to generate electricity. However, the potential of such energy sources in the cold season, as a rule, decreases, and the virtuality of obtaining energy from renewable sources, on the one hand, and the high requirements for the reliability of heating systems, on the other, transform this task into a multi-variant one. This conclusion may also be valid when comparing the cost of energy, unless the cost of electrical energy is subject to any preferences, such as a "night tariff".

A significant reduction in the cost of electrical energy occurs when switching to a two-part (or three-rate) tariff for electrical energy. This method of payment for electrical energy makes it possible to implement such a method of electric heating as electric storage heating.

During the night period of the day, during the period of preferential tariff for electrical energy, the electric storage system takes electrical energy from the network for the purpose of heating water and accumulates hot water in the storage tank. The volume of accumulation must be sufficient for full operation of the heating system during the daytime period, when the selection of electrical energy from the network at an increased tariff is impractical. During this period of the day, coolant will be withdrawn from the storage tank.

A schematic diagram of the arrangement of such a system is shown in figure 1.

It is possible to determine the main parameters of such a system and performance indicators of its operation.

Initial data for calculation:

M_o – the flow rate of water that circulates in the heating system of the building is determined according to the relationship:

$$M_o = \frac{Q_o}{(t_1 - t_2)c_w}, \tag{1}$$

where Q_o is the heat flow for heating the building, depends on the heat-protective characteristics of the building envelope, kW; c_w – heat capacity of water, kJ/(kg·°C);

M_b – the mass of water in the accumulation tank (kg) which can be written as:

$$M_b = V_b \rho_w, \tag{2}$$

where V_b is the volume of the accumulation tank, m^3; ρ_w – density of water in the container, kg/m^3.

Let us introduce other factors that influence the solution of the problem.

N is the power of the electric heater, which should ensure heating of water with a flow rate of M_o to a temperature t_1 sufficient to ensure comfortable conditions for people to stay in the building during periods of both supply and accumulation, and consumption of thermal energy.

τ_n – duration of night supply of electrical energy and accumulation of heat throughout the day, at a reduced tariff, per hour, for example $\tau_n = 7$ hours (from 23:00 to 6:00) – time of supply and accumulation of energy.

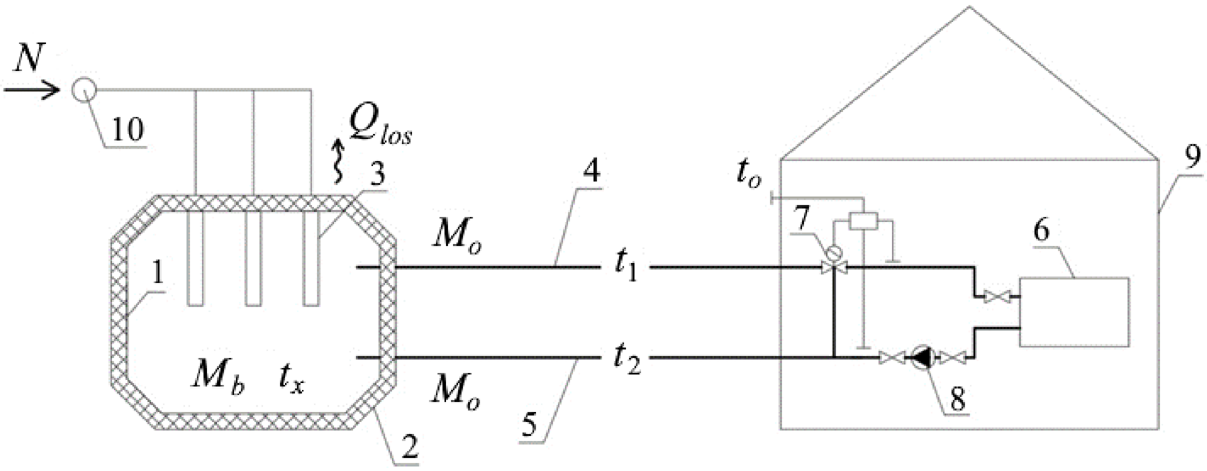

Figure 1. Schematic diagram of the arrangement of an electric storage system with a water storage tank: 1 – water storage tank; 2 – thermal insulation of the tank; 3 – electric heater; 4 – hot water supply pipeline with coolant temperature t_1; 5 – return pipeline with temperature t_2; 6 – heating devices for building heating systems; 7 – three-way control valve; 8 – circulation pump; 9 – heated building; 10 – multi-tariff electric meter; Q_{los} – heat loss from the electric storage tank.

$\tau_u = (24 - \tau_n)$ – daily duration of energy use without external replenishment. During this period of the day, the use of electrical energy to heat the coolant is not economically justified, since the daily tariff for electrical energy exceeds the night tariff.

η_l is a coefficient that takes into account heat loss from the battery tank to the environment. Provided effective thermal insulation of the tank $\eta_l = 0.93 \div 0.95$ (heat loss to the environment is $5 \div 7\%$).

$n' = Q'_o/Q_o$ is a coefficient that takes into account the presence in the system of buildings and structures for which it is possible to partially or completely reduce the amount of heat released for heating during the period of energy supply and accumulation (for example, due to the accumulation of heat in building envelopes or a temporary decrease in temperature in the room).

$n'' = Q''_o/Q_o$ is a coefficient that takes into account the share of buildings in which it is impossible to temporarily reduce the supply of heat for heating during the period of energy accumulation.

Q'_o is a heat flow for heating that part of buildings in which it is possible to reduce the amount of heat supplied for heating during the period of energy supply and accumulation, kW.

Q''_o is the heat flow for heating that part of the buildings in which it is not possible to reduce the amount of heat released for heating during the accumulation period, kW.

Thus, the total amount of heat (kW·hour) supplied for heating needs for a group of buildings and structures can be written as an equation:

$$Q = Q_o \cdot n' \cdot (24 - \tau_n) + Q_o \cdot n'' \cdot 24. \quad (3)$$

If the coefficient $n' = 0$, then this means that there are no buildings in which a temporary reduction in heat supply at night at the subsidized tariff is possible. If during the night period there is a possibility of disconnecting all buildings from the heat source, then $n' = 1$, and the coefficient $n'' = 0$. If it is possible to reduce the heat consumption for heating at night by half, the values of the above coefficients will have the values $n' = 0.5$ and $n'' = 0.5$.

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3. Results and discussion

The main design parameters of electric storage heating systems include the following:

- required electric power of the heater – N;
- capacity of the hot water storage tank – V_b.

Such a tank, under conditions of periodic supply of energy to water, must provide the required temperature of the coolant in the supply line of the heating system throughout the entire period of energy use. This temperature, in addition, depends on the temperature of the external air and is determined in accordance with the temperature schedule for the release of the coolant.

We determine the required power of the electric heater from the system heat balance equation:

$$\eta_l \cdot N \cdot \tau_n = Q_o \cdot n' \cdot (24 - \tau_n) + Q_o \cdot n'' \cdot 24. \tag{4}$$

After some mathematical transformations we get:

$$\eta_l \cdot N \cdot \tau_n = Q_o \cdot (24 \cdot n' - \tau_n \cdot n' + 24 \cdot n''). \tag{5}$$

Or the required electrical power of the heater should be:

$$N = \frac{Q_o \cdot (n' \cdot (24 - \tau_n) + 24 \cdot n'')}{\eta_l \cdot \tau_n}. \tag{6}$$

The results of calculations of the required thermal power of the electric heater of the system depending on the outdoor temperature, up to which the accumulation mode of operation will be ensured, are shown in figures 2, 3 and 4.

In order to make the calculation results universal and possible for use in the conditions of any building with an arbitrary value of Q_o, the ordinate axis of the graph shows not the absolute, but the relative value of the required power of the electric heater k, which is defined as the ratio of the absolute power N to the calculated value of heat consumption for heating.

$$k = \frac{N}{Q_o}. \tag{7}$$

This coefficient shows how many times the power of the electric heater must exceed the calculated heat flow for heating in order for the heat accumulation system to operate with comfortable microclimate parameters.

For example, in accordance with figure 2, to ensure the functionality of an electric storage heating system for buildings with complete heat extraction ($n' = 0$) during the energy storage period, the required power of the electric heater must exceed the calculated heat requirement for heating by 4 times.

Calculations were made for operating conditions over the entire range of outside air temperatures. For example, provided that the storage system operates at a temperature not lower than -10°C (87% of the time of the total duration of the heating period), an electric heater power at the level $N = (2.5 \div 2.6)Q_o$.

Provided that the duration of the energy supply and accumulation cycle increases from seven to ten hours, the power of the electric heater can be reduced to $N = (1.8 \div 1.9)Q_o$.

However, in this case, the economic attractiveness of the system is significantly reduced. In addition, the question of how to provide consumers with heat for heating during the period when the external air temperature reaches values from -10°C to a standard value of -23°C becomes relevant. And this is about 600 hours of work for the climatic conditions of the city with a standard outdoor temperature about $t_o = -23$°C.

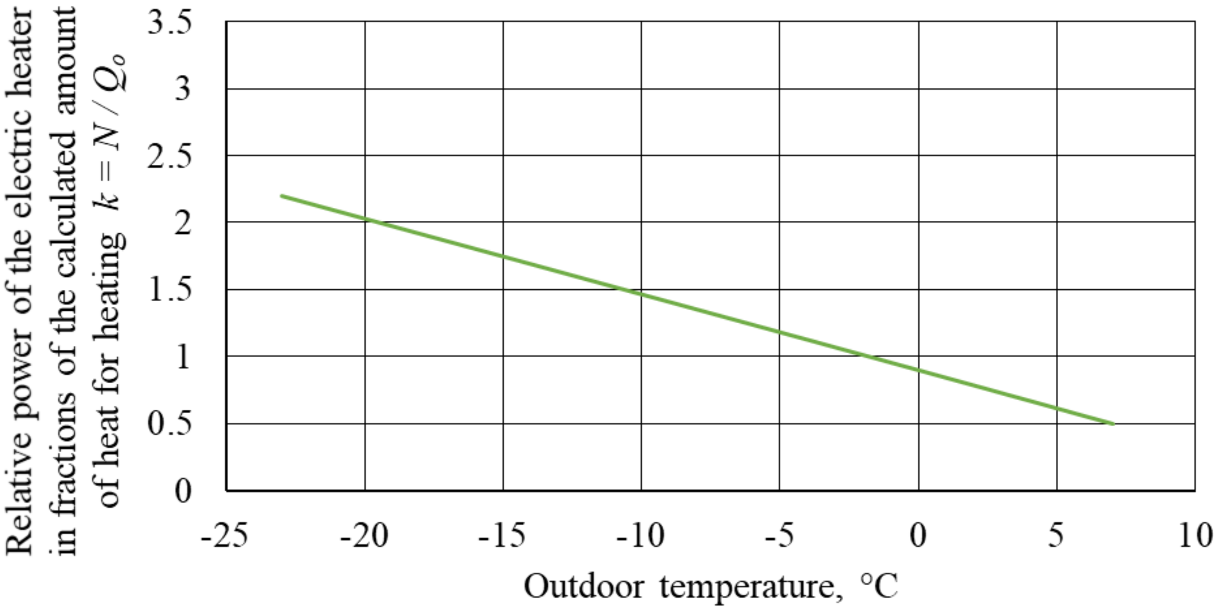

Figure 2. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 1, n'' = 0$ (during the night charging period, all buildings do not consume thermal energy for heating).

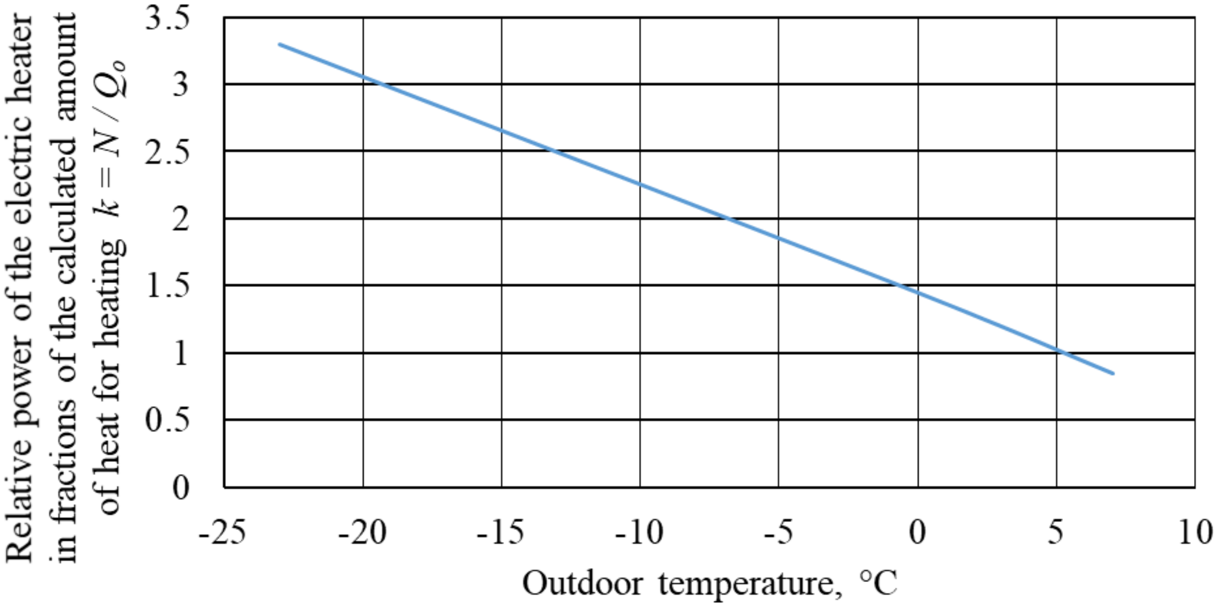

Figure 3. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 0, n'' = 1$ (during the night charging period, all buildings consume thermal energy for heating in full, depending on the outside temperature).

In the absence of a heat source using fossil fuels, the only alternative to supplying heat during this period is the selection of electrical power during the daytime period at an increased tariff, which is economically unprofitable.

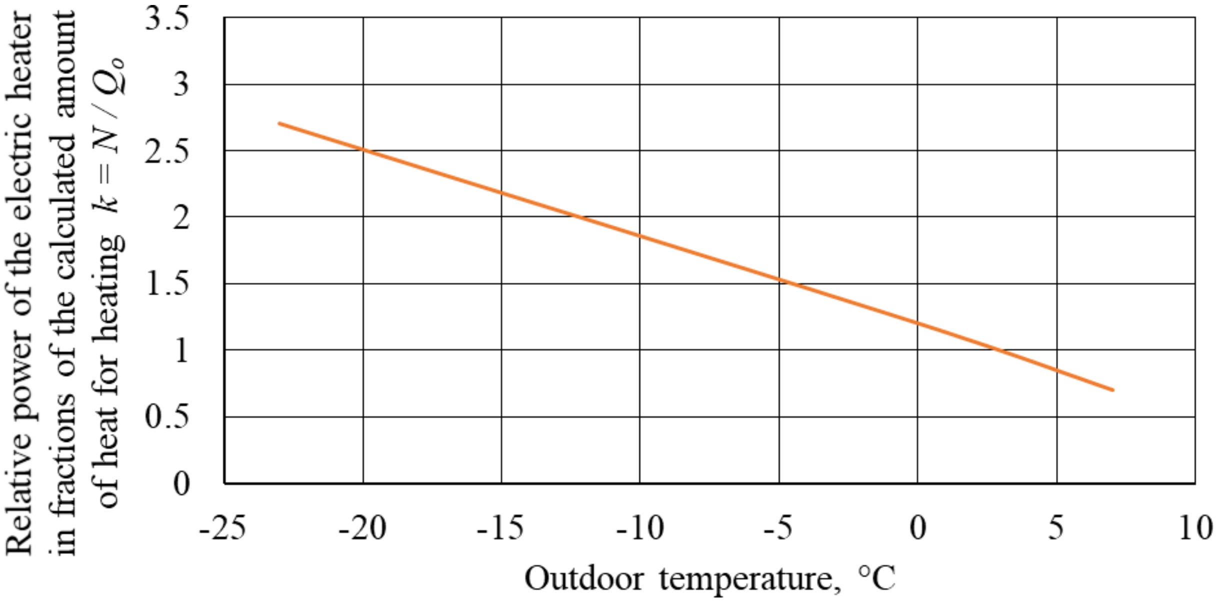

Figure 4. Dependence of the required power of electric heaters of an electric storage heating system on the outside air temperature, up to which the system can operate in storage mode without additional heat supply. $n' = 0.5, n'' = 0.5$ (at night, 50% of buildings do not consume thermal energy for heating, and the remaining 50% consume energy in full, depending on the outside temperature.

Thus, reducing the consumption of primary fuel (for example natural gas), which is usually the main goal of using electric storage heating systems, will lead to an increase in the cost of heating buildings. For hybrid heat supply systems that use several energy sources, including renewable types of energy, the choice of power of the heating source determines the feasibility, cost-effectiveness and possibility of switching from one energy source to another.

A significant problem with the use of electric storage heating systems is the need to modernize external electrical networks, due to the inability of electrical networks to withstand the additional loads that arise during electric heating. Thus, when introducing an accumulative electric heating system in an 80-apartment residential building with an estimated heat requirement for heating of 250 kW, the power of the electric heater, in accordance with the graph in figure 2, should be about 900 kW. Connecting such a heater to the existing electrical networks of the house seems problematic.

Another important design parameter of the system is the volume of the water storage tank.

The capacity of such a tank must ensure the required temperature of the coolant throughout the entire period of its circulation in the system without replenishing energy during the period of increased tariff.

Let us denote by t_x the current values of the coolant temperature in the tank. And through n – the relative capacity of the tank, which we will express through the calculated value of the hourly water consumption in the heating system, M_o':

$$n = \frac{M_b}{M_o'}, \tag{8}$$

where M_o' (t/hour) is the estimated flow rate of network water in the heating system, determined in accordance with the relationship:

$$M'_o = \frac{Q_0}{\Delta t \cdot c_w} \cdot 3.6, \tag{9}$$

where Q_o the heat flow for heating buildings, kW; $\Delta t = t_1 - t_2$ – calculated temperature difference in the heating system (for example $\Delta t = 90 - 70 = 20$°C); $c_w = 4.2$ kJ/(kg·°C) – heat capacity of water.

Let us write the heat balance equation for the period of water withdrawal from the tank in the form:

$$c_w \cdot M_b \cdot t_1 - c_w \cdot M'_o \cdot t_1 + c_w \cdot M'_o \cdot t_2 = c_w \cdot M_b \cdot t_x. \tag{10}$$

From (10) we obtain the value of the current temperature of hot water during its selection from the tank – t_x:

$$t_x = \frac{M_b \cdot t_1 - M'_o \cdot (t_1 - t_2)}{M_b} = \frac{k \cdot M'_o \cdot t_1 - M'_o \cdot (t_1 - t_2)}{k \cdot M'_o} = \frac{t_1 \cdot (n-1) + t_2}{n}. \tag{11}$$

In accordance with the calculations on dependence (11), after the end of the first cycle of the coolant circulation, provided that $M_b = 10M'_o$ the water temperature in the tank will decrease from the initial 95°C to 93°C. If the volume of the tank is lied to $M_b = 5M'_o$, then the water temperature after the first circle of circulation will be set at a level of 91°C with a further continuous decrease in temperature in the tank during the subsequent circulation.

Thus, it is possible to create a graph of the dependence of the necessary capacity of the tank-accumulator on the temperature of the outdoor air, provided that the installed schedule

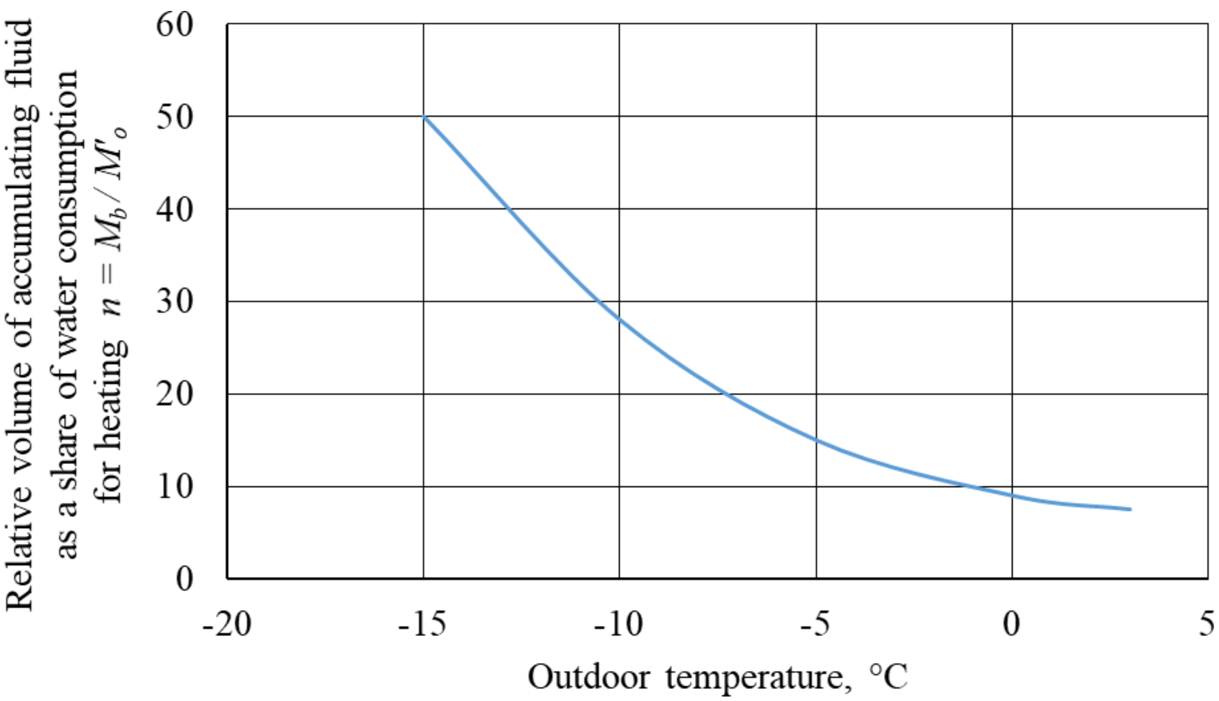

Figure 5. Dependence of the relative capacity of the accumulator tank "n" of the electric storage system on the outside air temperature, to which it is possible to operate the heating system to ensure comfortable microclimate parameters without additional consumption of electrical energy in the heating system during the daytime hours at an increased tariff.

of heat flow and maintain the optimal microclimate parameters in the premises. The condition for constructing the graph is also that continuous selection of the coolant from the tank is made without replenishment of energy from the outside in the daytime period of the day for an increased tariff for electric energy.

Figure 5 shows such a graph, which was obtained during the experimental stage of the research. It is built for a calculated temperature difference in the supply and return lines of the heating system $\Delta t = 20°\text{C}$.

The studies were carried out for an accumulation heating system of a residential building with a calculated heat consumption for heating of 250 kW without replenishing energy up to an outside air temperature of -10°C. The required capacity of the accumulation tank in accordance with the obtained schedule was no less than $V_b = 25V_b'$ or 134 m^3. Figure 6 shows a photo of such a tank for an accumulation heating system.

Placing a tank of this size in a building caused understandable problems. Therefore, it was placed outside and was carefully insulated. The heat supply system provided heat to the building of a sanatorium in the city of Mirgorod, Poltava region (Ukraine). A significant reduction in the size of the storage tank is possible by performing thermal modernization of the building and reducing the need for heat for heating. So, for example, for the estimated heating requirement of a building of about 40 kW, the volume of the tank is reduced to 34 m^3.

To reduce the building's need for heat, it is necessary to carry out a set of works on thermal

Figure 6. Storage capacity for a heating system with an estimated heat demand (thermal power) of 250 kW.

modernization of the building – increase the thermal resistance of external fences from 1 m^2g/W to 5 m^2g/W, use energy-efficient translucent fences, introduce a ventilation system with heat recovery, install an automated individual weather control system in the building heating point.

Experimental studies on the arrangement of a heating system with water storage tanks confirmed the obtained research results. However, it is noted that placing accumulation tanks of significant size in the premises of a building will require some structural work and significant costs.

4. Conclusions

The paper presents a methodology for determining the main design parameters of an electric storage heating system with water storage tanks.

Dependencies were obtained to determine the required volume of storage tanks and the required power of electric heaters of the electric storage heating system depending on the outside air temperature.

The results of calculations based on the given methodology indicate the possibilities of using electric storage heating systems and give an idea of the limitations that occur when implementing such systems.

As a result of the studies performed, it was shown that the tank capacity and the power of the system's electric heaters depend on the magnitude of the building's heating needs. In this regard, one of the conditions for the successful implementation of electric storage heating systems is the thermal modernization of buildings to a level that meets modern requirements for thermal protection of buildings. Carrying out work on thermal modernization of heat supply facilities and reducing the need for heat for heating significantly increases the efficiency of electric storage systems.

Acknowledgments

The people behind the article would like to express their heartfelt gratitude to the courageous individuals who are working hard to uphold and bring back peace in Ukraine. Additionally, they want to extend their sincere appreciation to IOP Publishing for being in solidarity with the Ukrainian people and for the outstanding assistance that they have provided to Ukrainian scientists.

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