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ADVANTAGES OF ELECTRICAL HEATING SYSTEMS WITH NIGHT HEAT ACCUMULATION IN UKRAINIAN CONDITIONS

Purpose. To develop electrical heating systems with night heat accumulation and to prove its advantages comparable with others possible variants of heating. Methodology. We have purposed a methodology which is based on the current Standards of Ukraine and included few main assumptions: the efficiency of the electric boiler is assumed equal 100 %; the dependence of the building heating load on the outside temperature is linear; all the variants of different energy resources calculating for the system operating correspond to the adequate (depending on weather) regulation. Methodology allows to determine the main technical characteristics of the system taking into account the possibility of switching on the electric boiler in the daytime using the half-loading. On the base of suggested methodology was developed the calculation program for determine the monthly consumption of heat by the building and estimate the cost of heating using different energy sources. This program also allows to compare the payment for centralized heat supply services at the tariff for the consumed heat with a payment for the heated area tariff. Results. We have obtained a method for electrical heating systems with night heat accumulation calculation. Method bases on the current Standards in Ukraine and allows to determine the main technical characteristics of the system taking into account the possibility of switching on the electric boiler in the daytime. On the base of suggested method was developed the calculation program for determine the monthly consumption of heat by the building and estimate the cost of heating using different energy resources. This program also allows to compare the payment for centralized heat supply services at the tariff for the consumed heat with a payment for the heated area tariff. Originality. For the first time we have suggested methodology and developed the calculation program for electrical heating systems with night heat accumulation which is based on the Ukrainian Standards and allows to determine the monthly consumption of heat by the building and estimate the cost of heating using different energy sources. Practical value. We have developed a method and calculation program which allows to design the energy saving electrical heating systems with night heat accumulation. We have demonstrated on the numerical example for the real weather conditions of Kyiv city the economical advance of using electric heating with night heat accumulation comparable with all others options (centralized heat supply, gas heating, pellet heating). For December 2017 tariffs in Ukraine, the cost of electrical heating with night heat accumulation are two times lower than in the case of centralized heat supply with payment for consumed heat. We have proved that the refund period for implementation of electrical heating systems with night heat accumulation instead of centralized heat supply services at the tariff for the consumed heat is less than 3 years, and for centralized heat supply services at the tariff for the heated area tariff is less than 1 year. References 10, tables 4, figures 2.

Key words: **energy saving, electrical heating, night heat accumulation, cost of heating for different energy resources.**

Цель. Цель исследования - разработка системы электрического отопления с ночным аккумулированием теплоты и обоснование ее энергосберегающего характера по сравнению с другими возможными вариантами отопления. Методика. Методика основана на современных стандартах Украины и включает следующие основные допущения: коэффициент полезного действия электрического котла принимается равным 100 %; зависимость отопительной нагрузки здания от внешней температуры считается линейной; для всех расчетных вариантов отопления, использующих различные энергетические ресурсы, режим работы системы отопления отслеживает погодные условия в соответствии с температурой наружного воздуха. Методика предусматривает определение основных технических характеристик системы с учетом возможности включения электрического бойлера в дневное время на половину расчетной нагрузки. Результаты. На основе предложенного метода была разработана расчетная программа для определения ежемесячного теплопотребления здания и расчета стоимости отопления при использовании различных энергетических ресурсов. Эта программа также позволяет сопоставлять стоимости централизованного теплоснабжения как по потребленной теплоте, так и при оплате по величине отапливаемой площади. Научная новизна. Впервые приведены метод и программа расчета систем электроотопления с ночным аккумулированием теплоты, учитывающие действующие стандарты Украины и позволяющие определять основные технические характеристики системы, а также рассчитывать стоимости отопления при использовании различных видов энергетических ресурсов. Практическое значение. Использование предлагаемой методики позволяет проектировать энергосберегающие системы электрического отопления с ночным аккумулированием теплоты. Приведен численный пример для реальных погодных условий г. Киева. Показано, что срок окупаемости перехода на электроотопление для варианта замены централизованного теплоснабжения с оплатой за потребленную теплоту составляет менее 3 лет, для варианта замены централизованного теплоснабжения с оплатой за отапливаемую площадь составляет менее 1 года. Библ. 10, табл. 4, рис. 2.

Ключевые слова: **энергосбережение, электроотопление, ночная аккумуляция теплоты, расходы на разные виды энергетических ресурсов.**

Introduction. The sharp and uneven rise in the cost of different types of energy used for heating encourages the search for alternative economic solutions.

Reducing heating costs can be achieved by reducing the heat loss by building envelopes as a result of their thermo-modernization [1], as well as through the transition to the use of alternative energy resources.

Among alternatives, primarily for large cities, in recent years, electric heating with night-time heat accumulation [2] and electric heating of the heat-carrier at night at centralized heat supply systems are considered.

In both cases, the effect of equalizing the daily schedule of the electric load of the integrated power system of Ukraine will be achieved, which will have a beneficial effect on its operation due to the more complete loading of the Ukrainian NPPs, which produce the electric power at the lowest cost in comparison with other types of generation. Another positive aspect of the application of electric heating, provided it is sufficiently distributed, is the saving of natural gas.

The simplest version of electric heating was considered - the use of thermal electric heaters, not heat pumps.

Heat pumps, as is known, would allow about three times to reduce the cost of electricity for heating, but at the same time they would have to require thousands of USD investments with a payback period from 3 years and more that in the current economic situation for Ukraine is not acceptable.

The problem of finding effective solutions for different heating systems has been relevant over the past decades and will remain so in the near future and in the foreseeable future.

The number of publications on this subject is tens of thousands. Therefore, let us dwell only on some of them.

Much of the publications are devoted to systems of centralized heating (both from combined heat and power plants and from boiler houses).

Of particular interest to this work are publications, including domestic ones, which deal with issues of heating with the accumulation of heat.

In [3], the search for rational combinations of systems of electric heating with renewable energy sources is carried out, economically justified heating tariffs are given in [4], in [5] possibilities of rational arrangement of heat accumulators with systems of electrical are estimated heating, in [6] the possibilities of taking into account the need of hot water supply in systems of electric heating are shown, in [7] the influence of market factors on the efficiency of systems of electric heating is estimated, [8] the possibilities of efficient use of heat accumulators as for electric heating, and hot water supply are shown.

In contrast, in this paper, the emphasis is not on the theoretical description of the calculation of the heating systems itself, but on the practical results of such calculations.

Hence, the following problem arises - the determination of the required heating load of the building (regardless of the specific type of indoor heating system used), comparisons on this basis of various possible options for the supply of heat to the building and the choice of the most economical of them.

The goal of the investigation is the substantiation of the energy saving nature of the electric heating system with night-time accumulation of heat in comparison with other possible variants of heating.

To achieve the goal, the following tasks must be solved:

- to develop a method and a calculation program to determine the main technical characteristics (useful volume of the tank-accumulator of hot water and the power of the electric heater) of the electricity system of heating with an accumulator of heat and electricity accounting for a three-zone tariff;
- to compare the cost of district heating with gas heating, with round-the-clock electric heating at electricity accounting for a single-zone tariff, as well as with pellet heating;
- to bring a numerical example of the calculation and a comparative analysis of the cost of heating the office building located in the city of Kyiv (under the actual weather conditions in this city) and show the advantages of a heating system with nightly heat accumulation.

Brief description of the system of heating with an accumulator of heat. Charging the heat accumulator [9] (Fig. 1) is performed when the electric boiler and circulation pump of the charging circuit are switched on, mainly at night.

The supply of heat-carrier to the heating devices of the building is provided by the circulating pump of the flow path continuously throughout the heating season.

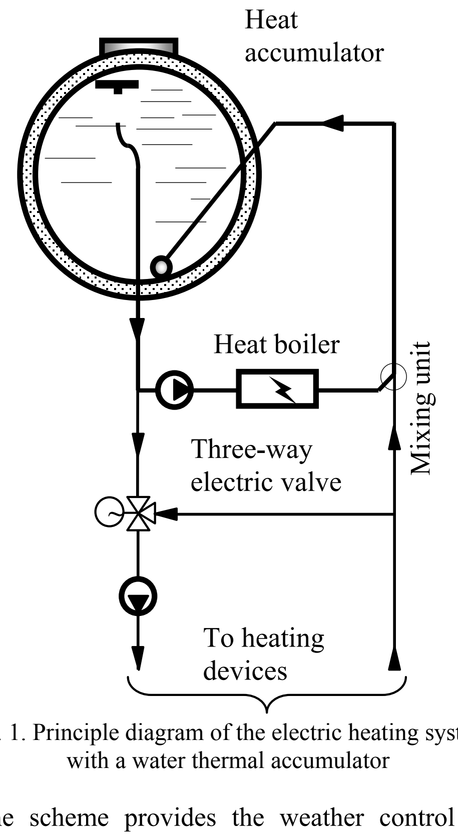

Fig. 1. Principle diagram of the electric heating system with a water thermal accumulator

The scheme provides the weather control of the temperature of the heat-carrier supplied to the heating devices by mixing the part of the rotary heat-carrier with a three-way electric valve.

Thus, it provides energy-saving mode of operation and the required heating load of the system, depending on the temperature of the outside air.

Method of calculation. The following assumptions are accepted in the calculation:

- the heat accumulator and the electric boiler are located directly in the heating room, therefore the loss of heat through thermal insulation of the accumulator and through the surface of the electric boiler is not taken into account;
- the efficiency of the electric boiler is taken equal to 100 %;
- the dependence of the heating load of the building on the temperature of the outside air is linear: the external temperature +18 °C corresponds to the zero heating load, the minimum design temperature of the outside air corresponds to 100 % of the heating load of the building in accordance with the statistical climatic data [10]; heating operates only at ambient temperatures below +8 °C;
- it is assumed that in all variants of use of different energy resources the system operates in the mode of adequate weather regulation;
- the useful temperature difference of the heat-carrier in a fully charged thermal accumulator and completely discharged one is 35 K;
- calculation of the current value of the temperature of the heat-carrier in the volume of the heat accumulator during operation of the system is carried out on the model of perfect mixing, without taking into account temperature stratification;
- tariffs and prices for various energy resources are taken in accordance with [10] as of December 2017.

The method of calculation takes into account the possibility of switching on the electric boiler in the daytime, in the semi-peak period of the load of the power system, at ambient temperatures below the set temperature of only night electricity consumption t^{night}, while also envisaging the switching on of the electric boiler for incomplete power.

At the linear relationship between the temperature of the outside air and the heating load of the building, the proportion of the total heating load of the building, depending on the temperature of the outside air, will be:

$$q/q^{calc} = \varphi^{q} = (t_{in}^{calc} - t)/(t_{in}^{calc} - t^{calc}), \qquad (1)$$

where q is the specific heating load of the building, W/m^2, at the current value of the temperature of the outside air t, °C; q^{calc} is the specific maximal heating load of the building, W/m^2, at the normative minimal value of the temperature of the outside air, °C; t_{in}^{calc} = +18 °C is the calculated air temperature at which the heating load equals to zero; t^{calc} is the normative minimal value of the temperature of the outside air, for Kyiv t^{calc} = –22 °C.

Specific normative losses of heat in a building during the heating season are the sum of monthly losses of heat during the heating season:

$$Q_{year}^{norm} = q_{oct} + q_{nov} + q_{dec} + q_{jan} + q_{feb} + q_{mar} + q_{apr}, \text{ kW·h/m}^2, \qquad (2)$$

where q_{oct} ... q_{apr} are the monthly specific losses of heat, kW·h/m^2, which taking into account (1) can be represented as:

$$q_{oct} = \varphi^{q}_{oct} \cdot q^{calc} \cdot \tau_{oct} = (18 - t_{oct}) \cdot q^{calc} \cdot \tau_{oct}/(18 - t^{calc}),$$

$$q_{apr} = \varphi^{q}_{apr} \cdot q^{calc} \cdot \tau_{apr} = (18 - t_{apr}) \cdot q^{calc} \cdot \tau_{apr}/(18 - t^{calc}),$$

where φ^{q}_{oct} … φ^{q}_{apr} are the shares of the total heating load at the average monthly temperatures of the outside air of the respective month of the heating period; τ_{oct} … τ_{apr} are the number of hours in the respective month of the heating period, h; q^{calc} is the specific losses of heat of the building, kW/m^2, at the normative minimum calculated temperature of the outside air t^{calc}, °C; t_{oct} … t_{apr} are the average monthly air temperatures in the corresponding month, °C.

Then:

$$q_{year}^{norm} = q^{calc} \cdot [\tau_{oct} \cdot (18 - t_{oct}) + \tau_{nov} \cdot (18 - t_{nov}) + \tau_{dec} \cdot (18 - t_{dec}) + \tau_{jan} \cdot (18 - t_{jan}) + \tau_{feb} \cdot (18 - t_{feb}) + \tau_{mar} \cdot (18 - t_{mar}) + \tau_{apr} \cdot (18 - t_{apr})]/(18 - t^{calc}), \text{ kW·h/m}^2.$$

Consequently, the maximum calculated specific heat losses of the building, kW/m^2, at the normative minimum calculated temperature of the outside air, are:

$$q^{calc} = (18 - t^{calc}) \cdot q_{year}^{norm}/[\tau_{oct} \cdot (18 - t_{oct}) + \tau_{nov} \cdot (18 - t_{nov}) + \tau_{dec} \cdot (18 - t_{dec}) + \tau_{jan} \cdot (18 - t_{jan}) + \tau_{feb} \cdot (18 - t_{feb}) + \tau_{mar} \cdot (18 - t_{mar}) + \tau_{apr} \cdot (18 - t_{apr})], \text{ kW/m}^2.$$

The maximum calculated heating load of the building at the normative minimum calculated temperature of the outside air t^{calc} corresponds to the value φ^{q} = 1 and equals:

$$\Phi^{calc} = A \cdot q^{calc}, \text{ kW}, \qquad (3)$$

where A is the total heating area of the building, m^2.

Daily heat consumption of the building at the normative minimum calculated temperature of the outside air t^{calc}:

$$Q^{calc} = 24 \cdot \Phi^{calc}, \text{ kW·h/day}. \qquad (4)$$

At the minimum calculated temperature of the only nightly electricity consumption t^{night}, °C, heating load Φ^{night} and daily heat consumption of the building Q^{night} will be:

$$\Phi^{night} = \Phi^{calc} \cdot \varphi^{qnight} = \Phi^{calc} \cdot (t_{in}^{calc} - t^{night})/(t_{in}^{calc} - t^{calc}), \text{ kW}; \qquad (5)$$

$$Q^{night} = 24 \cdot \Phi^{night}, \text{ kW·h/day}. \qquad (6)$$

During the time of preferential night electricity consumption (within 7 hours) at a temperature t^{night} it is necessary to carry out a full charge of a water thermal accumulator simultaneously with the supply of heat for heating the building.

In this case, the supply of heat accumulated in the heat accumulator should provide heating of the building for a full day period of 17 hours.

Consequently, the total amount of heat in the heat accumulator will be:

$$Q^{acc} = 17 \cdot \Phi^{night}, \text{ kW·h}. \qquad (7)$$

Since the heat accumulator must be charged for 7 hours at the same time as the heat supply for heating the building, the electric power of the boiler will be:

$$N = \Phi^{night} + Q^{acc}/7, \text{ kW}. \qquad (8)$$

Useful volume of heat accumulator:

$$V^{acc} = Q^{acc}\cdot 3600/(c_p\cdot\rho\cdot\Delta T^{acc}),\ \text{m}^3, \quad (9)$$

where c_p = 4.19 kJ/(kg·K) is the specific isobaric heat capacity of water; ρ = 1000 kg/m^3 is the density of water; ΔT^{acc} = 35 K is the useful temperature difference in the heat accumulator.

Calculated duration of operation of an electric boiler during daytime during the day at the normative minimum calculated temperature of the outside air:

$$\tau^{day} = (Q^{calc} - Q^{night})/N,\ \text{h}. \quad (10)$$

According to the calculations, τ^{day} should be less than the duration of the half-peak period to exclude the operation of the electric boiler during the peak day period with the most expensive tariff.

On the basis of expressions (1-10) a program has been prepared in MS Excel for variant comparative calculations of systems of electric heating with thermal accumulator.

Below is an example of the calculation of such a heating system of an office building located in the city of Kyiv.

Results of comparative calculation of heating systems and their discussion. Output data and calculation results are given in Table 1 for an office building with an area of 1000 m^2 with a maximum specific calculated heating load of q^{calc} = 40 W/m^2, which corresponds to a well-insulated building.

Estimated total power of the thermal electric heaters of the electric boiler is (at operation mostly at night) 102.9 kW, with a useful volume of thermal accumulator 12.52 m^3, while the calculated power of the electric boiler, at a 24-hour operation without a thermal accumulator, is equal to 40 kW.

The calculation is made for the case when at the temperature of the outside air below –12 °C the electric boiler will be switched on at 50 % of the power for heating the heat-carrier in daylight hours.

At minimum calculated temperature, the duration of day-time switching on the electric boiler will not exceed 5 hours.

Table 2 presents the results of calculations of monthly costs for building heating using different energy resources and forms of payment.

Table 3 and Fig. 2 show the results of calculations of total seasonal costs for building heating using different energy resources.

According to the calculation, the total heat consumption of the building during the heating season is 83.9 MW·h, which corresponds practically to the regulatory level of 83 MW·h, hence, the calculated maximum 40W/m^2 of the specific heating load corresponds to the normative thermal losses of the building.

The smallest seasonal heating costs in the amount of 41.2 thousand UAH are provided with the use of electric heating with night-time accumulation of heat and with the use of three-zone accounting of electricity consumed. Relatively small expenses of 50.6 thousand UAH correspond to the heating with pellets, but considering the concomitant factors associated with the need for periodic delivery, storage of pellet and waste disposal, the electrical heating is much better.

When using a gas boiler, seasonal expenses will amount to 83.5 thousand UAH, which is twice much as when electrical heating with night-time heat accumulation.

In the case of district heat supply, payment for its services in the amount of 92.8 thousand UAH during the heating season is not much higher than the cost of gas heating.

The largest seasonal heating costs in the amount of 210 thousand UAH arise in the case of monthly payment for district heating services at the tariff 30 UAH for each square meter of heating space during the heating season, that is, in the absence of a registered heat meter.

If you use electric heating without thermal accumulation, then, subject to adequate weather regulation, seasonal costs will be 164.7 thousand UAH, which is less than with district heating with payment for services for the tariff for the heating area.

Table 1

Initial data and technological calculation results

Total heating area of the building, m^2	1000
Maximum specific heating load of the building, W/m^2	40
Normative maximum seasonal heat losses of the building by ДБН В2.6-31:2016, kW·h/m^2	83
The minimum external temperature of only night-time electricity consumption (at lower temperatures there is a day-time switching on of the electric coil), °C	–12
The share of electrical power in the daytime operation of the electric boiler, %	50
Calculated total power of the thermal electric heaters of the electric boiler, kW	102.9
Calculated power of the thermal electric heaters of the electric boiler with round-the-clock operation without thermal accumulation, kW	40
Useful difference of temperature of water in a thermal accumulator, K	35
Useful calculated volume of the thermal accumulator, m^3	12.52
Basic electricity tariff excluding VAT, kopeck/(kW·h)	163.545
Cost of consumed heat at centralized heat supply, UAH/Gcal	1286.07
Cost of district heating at paying for a unit of heating space, UAH/(m^2·month)	30
Cost of natural gas for an industrial boiler-house, UAH/thousand m^3	9692.4
Cost of natural gas in the composition of the consumed heat at district heat supply, taking into account the efficiency of the gas boiler, UAH/Gcal	1156.6
Cost of pellets, UAH/t	2410
Heating capacity of pellets, MJ/kg	18
Cost of pellet heat, taking into account the efficiency of the pellet boiler, UAH/Gcal	700.7
Cost of heat for round-the-clock heating without a thermal accumulator, UAH/Gcal	2282.4

Let us consider also expediency of reconstruction of existing heating systems by replacing the heat source with electric heating with a thermal accumulator at a three-zone tariff. The comparison is made with the most widespread heat supply in large cities of Ukraine – centralized (district) heat supply both with payment for consumed heat, and with payment for the heating area.

Table 2

Seasonal heating costs at using various energy resources

The heat consumed for the season, Gcal	72.2
The heat consumed for the season, MW·h	83.9
Normative maximum seasonal heat losses for a building by ДБН В2.6-31:2016, not more, MW·h	83
Cost of electricity consumed during the heating season in the presence of adequate weather regulation, thousand UAH	41.2
Cost of electricity consumed during the heating season at round-the-clock heating without a thermal accumulator, but in the presence of adequate weather regulation, thousand UAH	164.7
Cost of district heating during the heating season at the tariff for the released heat in the presence of adequate weather regulation, thousand UAH	92.8
Cost of district heating during the heating season with the tariff for the heated area, thousand UAH	210
Total amount of consumed gas during the heating season, in the presence of adequate weather regulation, thousand m^3	8.6
Cost of consumed natural gas during the season for heating, thousand UAH	83.5
Cost of pellet heating in the presence of adequate weather regulation, thousand UAH	50.6

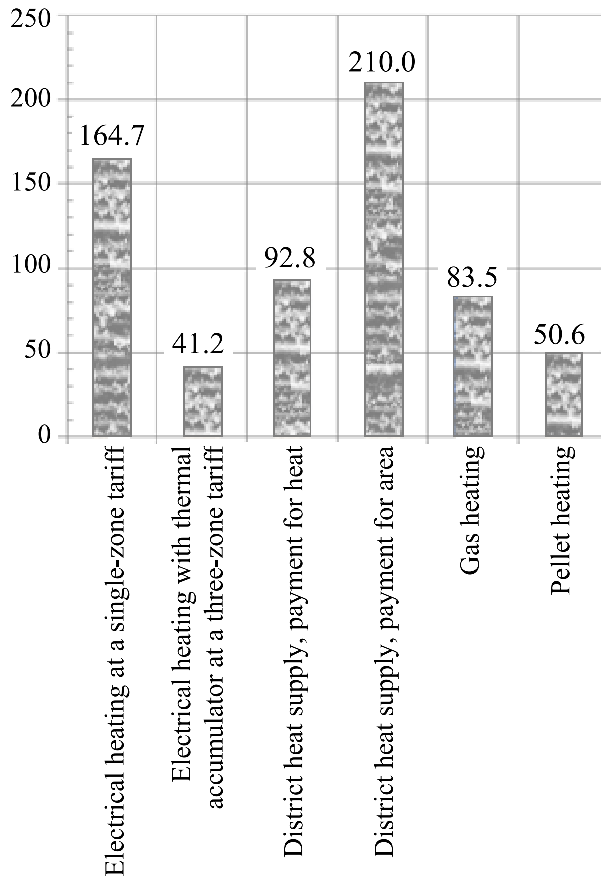

Fig. 2. Seasonal heating costs at using various energy resources, thousand UAH

Table 3

Monthly heating costs when using different energy resources

Month	Oct.	Nov.	Dec.	Jan.	Feb.	March	April
Average temperature, °C	7.5	1.2	–3.5	–5.9	–5.2	–0.4	7.5
Consumed heat, Gcal/month	3.84	10.40	13.75	15.29	13.41	11.77	3.71
Consumed heat, kW·h/month	4464	12096	15996	17782	15590	13690	4320
Cost of consumed electricity, thousand UAH/month	2.19	5.93	7.85	8.72	7.65	6.72	2.12
Cost of consumed electricity at round-the-clock electrical heating without thermal accumulator, thousand UAH/month	8.76	23.74	31.39	34.90	30.60	26.87	8.48
Cost of district heating when paying for released heat, thousand UAH/month	4.94	13.38	17.69	19.66	17.24	15.14	4.78
Cost of district heating when paying for heating area, thousand UAH/month	30	30	30	30	30	30	30
Cost of the equivalent gas consumed for heating, thousand UAH/month	4.44	12.03	15.91	17.68	15.50	13.61	4.3
Cost of pellet heating, thousand UAH/month	2.69	7.29	9.64	10.71	9.39	8.25	2.6

Calculations of the electrical heating system are presented in the summarized Table 4. Comparison of the total cost of the proposed system of heating (Table 4) with annual costs for district heating (Fig. 2) shows that the payback period for switching to electrical heating from district heating with payment for consumed heat is 2.7 years, and with payment for heating space – 0.83 years.

Thus, the use of electrical heating systems with night-time heat accumulation is not only appropriate for new heating systems, but also for existing ones.

Table 4

Characteristics of the system of electric heating with thermal accumulator

Initial data for calculation		
Calculated total power of thermal electric heaters	102.9 kW	
Useful calculated capacity of the heat accumulator	12.52 m^3	
Calculated temperature difference in the charging circulation circuit	5 K	
Estimated temperature difference in the consumption circulation circuit	10 K	
Water speed in the charging circulation circuit	1.5 m/s	
Water speed in the consumption circulation circuit	1.5 m/s	
Water speed in the mixed circulation circuit	1 m/s	
Results of calculation of main technological characteristics of the heating system		
Calculated water consumption in the charging circulation circuit	4.913 kg/s	17.69 t/h
Calculated water consumption in the consumption circulation circuit	0.955 kg/s	3.44 t/h
Tube diameter of the charging circulation circuit	0.0646 m	64.6 mm
Tube diameter of the consumption circulation circuit	0.0285 m	28.5 mm
Diameter of branch pipes of heat accumulator	0.0864 m	86.4 mm
Cost indicators of the heating system		
	cost, UAH	
Electrical boiler	15000	
Circulation pump of the charging circuit	8300	
Circulation pump of the consumption circuit	2900	
Heat tank-accumulator	18000	
Heat insulation	10000	
Three-way regulating valve Ду32	1700	
Servo drive for three-way regulating valve Ду32	2500	
Automatic control unit	16000	
Locking valves, pipes, tees, fittings, heat insulation of communications	20000	
Construction works	45000	
Total cost	139400	

Conclusions.

1. A method and program of calculation of systems of electric heating with night accumulation of heat is given.

The method takes into account the current Standards of Ukraine and allows to determine the basic technical characteristics of the system, taking into account the possibility of switching the electric boiler into half of the calculated power in daylight hours.

2. The proposed method and developed program allow determining the monthly heat consumption of buildings and calculating the cost of heating using different types of energy resources, as well as comparing the costs of district heating with payment for consumed amount of heat and when paying for the heating area.

3. A numerical example for real weather conditions in Kyiv city has shown the economic benefits of using electric heating with night-time heat accumulation.

According to the Ukrainian tariffs for December 2017, the cost of heating with a nightly accumulation of heat is two times lower than for district heat supply with payment for consumed heat.

4. It is proved that the payback period for switching to electrical heating for the option of replacing district heating with payment for the consumed heat is less than 3 years, and for a variant of the replacement of district heating with payment for the heating area is less than 1 year.

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