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The toolkit for rising the efficiency of heat pump heating system using the accumulation of heat by walls of the building

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This article is devoted to the methods for increasing the efficiency of the heat pump heating system using the effect based on the energy saving principles. The major aim of the study is the analysis of methods for increasing the efficiency of heat accumulation by walls of the building with the account of for climate conditions, which correspond to the requirements of the energy saving technologies. To achieve the aim the mathematical model was proposed and comparative analysis of efficiency of heat accumulation by walls of the heat pump heating system was performed for the consumers of the South regions of the Ukraine. The algorithm of calculation the energy efficiency of the heat pump heating system for heat consumers was developed taking into account the climate conditions. The estimation methods for the energy efficiency of the proposed alternative heat supply schemes were offered. The method for realization was shown using the actual example, and the effectiveness of the alternative heating for consumers was confirmed. The numerical modelling of thermal processes in the elements of building were carried out. The analysis of the results of numerical modelling of thermal processes of heat accumulation by walls for the heat pump installation of heating the of two-story building was presented. The rational ways of increasing the efficiency of the alternative heating system with heat accumulation by walls and with account of climatic conditions were grounded. Results of simulation, conclusions and decisions for the practical application of the heat pump heating system, depending on temperature of the outside air were developed. The significance of the obtained results consists in justification of conditions, which make it possible to use the heat pump heating system using the effect based on the energy saving principles. The most significant results are those recommending the increase in the efficiency of the heat pump systems for the heat supply for the consumers of the Ukraine. The analysis results can be used for designing the heating systems based on the heat pumps using the low-potential energy with heat accumulation by walls of the building. Equations are proposed that are the mathematical model of thermal processes occurring directly in the heat supply facility itself and make it possible to calculate the time-varying thermal power required to meet the needs of the heat consumer and maintain a constant level of the specified microclimate in the building using internal resources of energy consumers.
Keywords: *Heat accumulators; Modelling; Heat pumps; Energy saving; Heat supply systems; Operating modes of heat supply systems; Climatic conditions*

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1. Introduction

At present, the problem of energy saving can be solved both by the thermal losses reduction and assimilation of the innovation technologies of generating, distribution, regulation and consumption of the heat [1]. The global requirement for sustainable energy provision and a political imperative for energy independence have combined to increase interest in the use of renewable energy sources to meet growing energy demands. Therefore, the heat pump systems (HPS) introduce a new path for sustainable systems with clean energy supply and an improved energy efficiency. Current power systems are still dominated by fossil fuel-based electricity generation and operated on supply following the changing demand. Actually, the task of increasing energy efficiency should be realized by implementation of the innovation technologies of production and consumption of energy with the lowest energy losses. The most efficient way of the energy saving is the introduction of heat pumps (HP) with tank accumulators, by virtue of their ability to utilize a renewable energy sources (RES) for heating systems [2]. Even so, the decisions presented in literature, which describe the peculiarities of tools for heat pump system with tank accumulator (TA) for permanent and intermittent heating modes of the public buildings are insufficient [3]. The foreign investigations [4], lack of the methods, which take into account HPS with TA and conditions of their practical application for permanent and intermittent heating modes of the public buildings at the environmental conditions. The features of influence the heat-circuit design solutions and operating modes of HPS on the value of the replacement factor of an alternative heating system haven't been clarified till now. In the last decade, energy generation from HP using RES has seen a sharp rise, but the energy supply from RES is inconstant because it is weather dependent. Thus, the energy production from installations using RES partially satisfies the energy demand. However, the power generation production exceeds the demand during certain time of a day during which has seen a high intensity of energy coming from RES [5]. This excess energy can be used through a power-to-heat technology. Reserves of traditional hydrocarbons such as gas, oil, coal are declining every year. And their use is associated with a negative impact on the environment. Today, there is a need to move to greater use of renewable energy sources, which are inexhaustible and can guarantee energy and environmental security. Among renewable energy sources, the use of low-potential environmental energy, converted to high-potential using heat pumps (HP), is promising. Experience shows that HP is one of the promising types of equipment for creating heat and cold supply systems.

2. Analysis of the latest research on the use of heat accumulation by walls for HP systems throughout the heating season.

The power-to-heat approach refers to the conversion of electricity to heat through HP, innovative boilers accumulators etc. Power-to-heat strategies can be used at the centralized or decentralized level. Heat is produced centrally either with heat generators stand-alone or in combination with heat pumps. Most of the power-to-heat technologies involve the use of an energy storage mechanism [5]. It should be noted that heat pumps are much more energy-efficient than other renewable and conventional technologies. Once installed and operated properly, one unit of electricity used by a heat pump delivers 3…5 units of heat on average over the heating season. By contrast, one unit of electricity used by an electrolyser (Fig.1) to produce hydrogen, which is then combusted, results in 0,6…0,8 units of heat. The efficiency of a high-efficiency biomass boiler is around 0,9 units.

The efficiency of heat pumps has increased steadily over the past decades due to research, competition, minimum efficiency performance standards and energy labelling schemes. Different types of HP suit different applications and regions. Enhanced design can improve their efficiency even further. In several regions, heat pumps already have a considerable market share due to their beneficial total life-cycle cost. The market share is significant for newly-built houses because heat pumps are often the best option to meet energy performance standards set by new building regulations. Even though the overall penetration is growing, heat pumps are still a rather rare solution for replacing existing heating systems due to higher upfront costs or lack of awareness and know-how among in-stallers and designers. This investigation differs from earlier references presented in this article by systematic approach to analyse for issue the conditions of the efficiencies of various schemes of HP with thermal storage for intermittent heating of the academic buildings which ensure the maximum replacement rate of the thermal load. This reduces the level of fossil fuel consumption in structure of regional energy balance and ensures the substantial energy saving, ecological and economic effects. The recommendations in works [4-6] is insufficient in our case under permanent and intermittent operational modes for justification the scheme-construction solutions in the HP system (HPS) with accumulation by walls for the public buildings.

The coupling of heat accumulation by walls (HA) in the HPS is a rational way to improve the efficiency of the heating system. The tank accumulator can increase the share of use the renewable energy sources (RES) and favouring self-consumption of energy for HPS [6]. The use of tank accumulator for the optimal operation of HPS in different operation modes is analysed in [7]. Nevertheless, fully established criteria for optimal sizing of HP coupled to tank accumulator are not yet obtainable. For rational implementation of HP system with HA, the mathematical model of the energy system is required [8]. The attention payed by the foreign works [2-8] is insufficient, concerning the justification of the choice of the scheme-construction solutions in the alternative system of the heat supply, taking into account the effect of heat accumulation by walls throughout the heating season.

At present, the problem of energy saving can be solved both by the thermal losses' reduction and assimilation of the innovation technologies of generating, distribution, regulation and consumption of the heat with the account of heat accumulation by walls.

3. The aim and tasks of the study

The main aim of the study is to determinate the efficiency of the effect of heat accumulation by walls, taking into account the temperature distribution in the wall during daily changes of ambient air temperature throughout the heating season.

Our work differs from those foreign papers presented earlier in that this article analyses the efficiencies of various schemes of single-step and multi-step HPIs using a low-potential heat sources of subsoil waters for the heating systems with different heat supply units, which ensure the maximum replacement of the thermal load. This makes it possible to perform a rational choice of the conditions for the efficient operation of the heating system in winter period at the outside temperature of t_0 = –18…8 °C typical for the South-Eastern Europe. This reduces the consumption of the hydrocarbon fuel in the structure of the heat balance of the regions and ensures the substantial energy saving effect.

To achieve the goal, it is necessary to solve the following tasks:

– to develop the mathematical model of heat accumulation by walls;

– to justify the possibility of use heat accumulation by walls for heat pump system, taking into account the climatic factors;

– determine the energy saving effect of heat accumulation by walls for the heat pump heating system.

4. Research methodology and data processing

The mathematical model of thermal processes occurring directly in the heat supply facility itself, and make it possible to calculate the time-varying thermal power required Q_T to meet the needs of the heat consumer and maintain a constant level of the specified microclimate in the room

In general, the heat balance equation of the integrated heat pump system IHP heat supply facility is:

$$V_B \cdot C_p \cdot \rho_B \cdot \frac{dT_B}{dt} = \\ = Q_T(t) - \sum Q_{CT}(t) - \sum Q_{OK}(t) - \sum Q_{VENT}(t), \quad (1)$$

where $Q_T(t)$ is the heat flow power for heat supply purposes; $\Sigma Q_{CT}(t)$ is the heat loss through walls; $\Sigma Q_{OK}(t)$ is the heat loss through windows; $\Sigma Q_{VENT}(t)$ is the heat loss through air ventilation.

The specified heat balance equation refers to the air exchange of the interior of a residential building with the environment, where the external, internal walls and ceilings are characterized by the ability to accumulate heat. Depending on the ratio between the values of the temperature of the walls and the ambient air, heat can either be supplied to the walls or removed from the walls into the environment $Q_{CTi} > 0$.

Let's introduce the conditional indices-designations for the external walls of the house $i = 1$; for the ceiling above the upper floor $i = 2$; for the ceiling above the basement $i = 3$; for the internal walls $i = 4$ and for the inter floor ceiling $i = 5$.

Let's assume the initial condition according to which the air temperature inside all residential premises is T_B = const, i.e. constant in time and space. This means that the rate of temperature change in time is zero, and therefore for the left-hand side of the heat balance equation (1) we can write:

$$V_B \cdot C_p \cdot \rho_B \cdot \frac{dT_B}{dt} = 0 \quad (2)$$

In practice, this means that under such conditions, the comfort (microclimatic) requirements of the consumer must be constantly maintained at the proper level in the room throughout the entire service life of the heat supply installation [9-11]. Taking into account the maintenance of proper comfortable conditions in residential premises, the heat balance equation (3) takes the form:

$$Q_T(t) = \sum Q_{CT}(t) - \sum Q_{OK}(t) - \sum Q_{BEHT}(t). \quad (3)$$

Let's consider in more detail all the components of the right-hand side of equation (3).

Heat losses through ventilation Q_{VENT}

Since when calculating heat loss through ventilation, we assume that the volume of air in residential premises V_B is a constant value over time and averaged over all premises of a residential building, then, taking into account the constancy of the temperature in the premises T_B = const, the power of the heat flow removed with the ventilated air is a function of the ambient air temperature $T_H(t)$ = var, which varies over time [169]:

$$Q_{VENT}(t) = V_B \cdot C_p \cdot \rho_B \cdot \left[T_B - T_H(t)\right]. \qquad (4)$$

Heat losses through windows Q_{OK}

When calculating heat loss through windows, we will assume that all windows are made using the same technology and do not differ in thermal inertia with respect to incident solar radiation. Then the power of the heat flow removed through the windows is:

$$Q_{OK}(t) = k_{OK} \cdot F_{OK} \cdot \left[T_B - T_H(t)\right], \qquad (5)$$

where k_{OK} is the heat transfer coefficient; F_{OK} – the surface area of all windows in the house.

Heat losses through walls $\sum Q_{OKi}$

The condition of constant temperature in the rooms of the house T_V means that there is no heat exchange between the internal walls and ceilings, i.e. the internal walls and interfloor ceilings inside the house do not accumulate heat. This condition, taking into account the indices-designations, can be expressed as:

$$\begin{cases} Q_{CT4} = 0 \\ Q_{CT5} = 0 \end{cases}. \qquad (6)$$

When determining heat losses through all walls of the house, we assume that the following conditions are met:

• the temperature difference ΔT_p between the air inside the cold room T_h, i.e. in a room that is not heated, and the outdoor air temperature T_H is a constant value, which is expressed by the equation:

$$\Delta T_p = T_h - T_H, \qquad (7)$$

• heat losses in the direction from the ceiling to the basement rooms (i =3) are absent, i.e. Q_{CT3} = 0.

Thus, since the total heat loss through the walls to the environment $\sum_{i=3}^{5} Q_{CT}$ is reduced to heat loss from two sources $\sum_{i=1}^{2} Q_{CTi}$: from the external walls Q_{CT1} and the external ceiling Q_{CT2}, that is, the equation is valid:

$$\sum_{i=1}^{5} Q_{CTi} = \sum_{i=1}^{2} Q_{CTi}. \qquad (8)$$

For the external walls of the house, taking into account their ability to heat accumulation, the heat flow capacity that removed from the walls $\sum_{i=1}^{2} Q_{CTi}$ are [170]:

$$\sum_{i=1}^{2} Q_{CTi} = \sum_{i=1}^{2} \alpha_B \cdot F_{CT} \cdot \left[T_B(t) - T_{CT}(t) \mid B\right], \qquad (9)$$

where α_B is the heat transfer coefficient from the air inside the house to the wall; F_{CT} is the surface area of the walls of the house; $T_{CT}(t)|B$ – the wall temperature from the inside of the house, i.e. from the heated side.

Equation (9) determine the heat flow capacity removed from the walls takes into account the heat exchange between the air inside the room and the walls.

This equation can be solved if the wall temperature $T_{CT}(t)|B$ from the inside, i.e. from the heated side, is known. The specified temperature depends on the temperature field in the wall and the thermophysical characteristics of the heat exchange process between the wall and the environment.

In order to determine the temperature distribution in the wall, taking into account daily changes in the ambient air temperature during the season, in order to determine the effect of heat accumulation by the walls, we will make the following assumptions: the walls have a homogeneous and isotropic structure; non-stationary heat transfer in the walls is one-dimensional; the effect of wall humidity is neglected; the effect of wind is not taken into account.

The adopted simplifications allow us to assume that the model of the wall of the house is a plate of infinite length without internal heat sources and finite thickness δ, which has a uniform temperature distribution over the surface.

Then the temperature field can be determined by the equation of non-stationary heat transfer:

$$\frac{\partial T_{CTi}}{\partial t_{CTi}} = \alpha_{CT} \frac{\partial^2 T_{CTi}}{\partial x_{CTi}^{2}}, \qquad (10)$$

where α_{CTi} is the thermal diffusivity coefficient of the i-th wall; T_{CTi} is the temperature of the i-th wall in the direction along the coordinate axis x. Equation (10) can be solved if all the heat transfer and thermal conductivity coefficients of the internal and external surfaces participating in heat exchange with the environment are known.

The temperature field in the wall, in a qualitative form, which is characteristic of the case of temperature distribution in an infinitely long uniform plate with a thickness of δ is presented in Figure 1.

Let us consider the initial conditions at the heat transfer boundaries.

In general, the temperature distribution at the initial time $t_0 = 0$ along the x-axis will have the form:

$$T(x_0, t_0) = T_0(x, 0) = f_0(x).$$

We will assume that the temperature distribution in the walls and ceilings at the initial time is linear and we will take the inner surface of the wall (from the heating side) as the starting point for the temperature change along the x-axis.

Taking into account the assumptions and notations made, we obtain the equation for determining the temperature distribution of the i-th wall:

$$T_{0CTi}(x_{CTi}) = f_{0CTi}(x_{CTi}) = T_B - \frac{T_B - T_H(t_0)}{\delta_{CT}} x_{CTi}. \quad (11)$$

On the other hand, the process of heat exchange at the outer and inner boundaries of the wall for an arbitrary moment of time can be represented using boundary conditions of the third kind in the following form:

– boundary condition of the third kind for the i-th inner boundary of the wall, i.e. from the side of the living space:

$$-\lambda_{CTi} \frac{\partial T_{CTi}}{\partial t_{CTi}} | B = \alpha_B \cdot \left[T_B(t) - T_{CTi}(t) | B \right]; \quad (12)$$

– boundary condition of the third kind for the i-th outer boundary of the wall, i.e. from the environmental side:

$$-\lambda_{CTi} \frac{\partial T_{CTi}}{\partial t_{CTi}} | H = \alpha_{Hi} \cdot \left[T_{CTi}(t) | H - T_{Hi}(t) \right]. \quad (13)$$

where λ_{CTi} – coefficient of thermal conductivity of the i-th wall; α_{Hi} – coefficient of heat transfer from the outer boundary of the i-th wall, where, taking into account the indices-designations, $i = 1$ refers to the outer boundary of the wall, and $i = 2$ refers to the outer boundary of the attic ceiling, W/(m·K); T_{Hi} – air temperature, which is taken for the case $i = 1$ and $i = 2$, respectively; $T_{Hi}(t) = T_H(t)$ – temperature at the outer boundary of the wall; $T_{H2}(t) = = T_H(t) + T_h$ – temperature in the attic room under the roof, taking into account equation (7).

The coefficients of thermal conductivity λ_{CTi}, which are part of equations (12-13) and the coefficient of thermal diffusivity α_{CT}, which is part of equation (10), depend on the structural material of the walls of the house. These coefficients can be assumed constant in space and time, as well as the coefficients of heat transfer from the internal air to the wall α_B and from the wall to the external air α_{Hi}. To solve the equation of unsteady heat transfer (10) using equations (11-13), which contain initial boundary conditions and boundary conditions of the third kind, we will use the finite difference method (grid method) [12,13], since this method is an explicit three-parameter method, i.e. theoretically always stable. We approximate the partial derivatives included in the differential equation of heat conduction and boundary conditions in equations (12), (13) by finite differences written for points located at the grid nodes (Figure 2) [14].

Since the differential equation of heat conduction in the form of finite differences connects the value of the desired temperature function, represented in discrete form, with the corresponding coordinates of the grid nodes, the temperature $T(x_i, t_{j+1})$ at the grid node x_i at the selected time level t_{j+1} can be calculated from the temperatures at the neighboring grid nodes corresponding to the time levels t_j and t_{j-1}.

Approximation of the differential equation (10) by finite differences allows us to obtain an equation in the form:

$$\frac{T_1^{j+1} - T_i^{j-1}}{2\Delta t} = \alpha_{CT} \cdot \frac{T_{1+1}^{j} + T_{i-1}^{j} - T_i^{j-1} - T_i^{j+1}}{\Delta x^2}, \quad (14)$$

from which, after transformations, we can present the formula for calculating the desired temperature of the T_{CT} wall in a given time plane, at the node with coordinates (i) and (j+1) from the origin of the grid, in the following form:

$$T_{CTi}^{j+1} = T_{CTi}^{j-1} \cdot \frac{1 - 2\frac{aCT \cdot \Delta t}{\Delta x_{CT}^2}}{1 + 2\frac{aCTi \cdot \Delta t}{\Delta x^2}} + \left(T_{CTi+1}^{j} + T_{CTi-1}^{j} \right) \frac{2\frac{aCT \cdot \Delta t}{\Delta x_{CT}^2}}{1 + 2\frac{aCT \cdot \Delta t}{\Delta x^2}}. \quad (15)$$

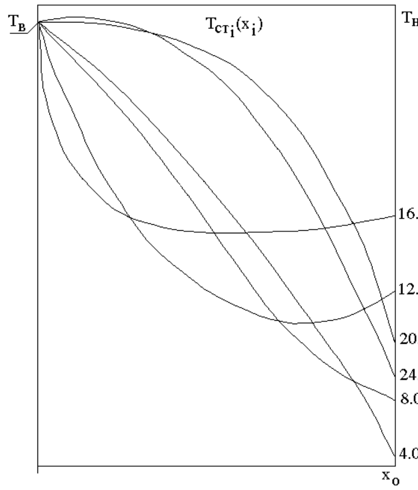

Figure 1 *– Temperature field over time inside the wall of the building*

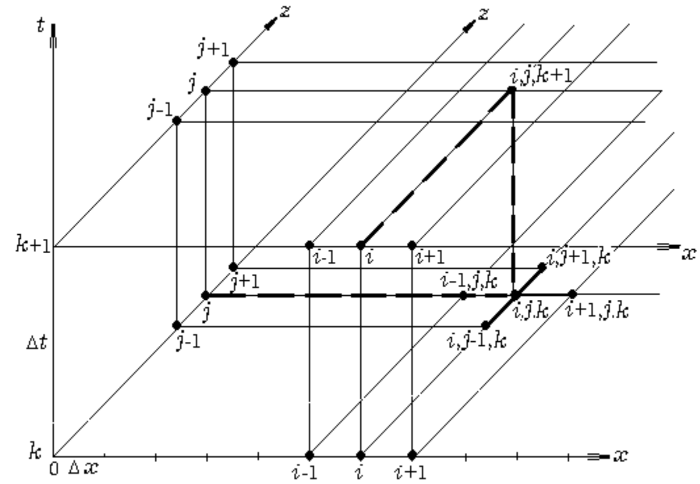

Figure 2 *–Elementary volume in the form of a spatiotemporal grid*

Let's introduce the notation $A_{CT} = 2\cdot(a_{CT}\Delta t)/(\Delta x^2_{CT})$, then, for this temperature of the wall, we obtain equation (15) in the simplified form:

$$T_{CTi}^{j+1} = T_{CTi}^{j-1} \cdot \frac{1 - A_{CT}}{1 + A_{CT}} + \left(T_{CTi+1}^{j} + T_{CTi-1}^{j}\right)\frac{A_{CT}}{1 + A_{CT}}. \quad (16)$$

To solve the equation (16), it's necessary to introduce the appropriate boundary conditions. Let's present the temperature function at the nodes on the inner and outer boundaries in the form of a Taylor series expansion in the vicinity of the corresponding nodes. Thus, for the internal boundary ($x = x_0$), we present the temperature function $T(x, z)$ in the neighborhood of nodes close to the boundary in the form of a Taylor series expansion. Then the first derivative of the T_{CT} temperature function at time t^{l+1} in node i can be calculated using the expression:

$$T_i^{j+1} = \frac{\partial T}{\partial x \mid x = x_0} = \frac{4T_2^{j+1} - 3T_i^{j+1} - T_2^{j+1}}{2\Delta x}. \quad (17)$$

By substituting the value of the first derivative function of the temperature T′ in the node (j+1, i) from the discrete equation (17) into the expression for the boundary conditions (12), we obtain the relation for determining the T_{CT} temperature on the inner surface for the time plane (j+1) in the form:

$$T_{CTi}^{j+1} = \frac{T_B + \dfrac{\lambda_{CT}}{\alpha_B 2\Delta x_{CT}}\left(4T_{CT2}^{j+1} - T_{CT3}^{j+1}\right)}{1 + \dfrac{3\lambda_{CT}}{\alpha_B 2\Delta x_{CT}}}. \quad (18)$$

Similarly, by approximating the boundary conditions (12) on the outer surface of the wall with finite differences, we obtain the value of the T_{CT} temperature at node n for the time plane (j+1) in the form:

$$T_{CTn}^{j+1} = \frac{T_H + \dfrac{\lambda_{CT}}{\alpha_B 2\Delta x_{CT}}\left(4T_{CTn-1}^{j+1} - T_{CTn-2}^{j+1}\right)}{1 + \dfrac{3\lambda_{CT}}{\alpha_H 2\Delta x_{CT}}}. \quad (19)$$

Numerical modelling of thermal processes in barriers, determination of the non-stationary temperature field, carried out for a period 240 s. Heat losses through the walls and ceiling were calculated according to the formula (18) with an interval of 1 hour.

Taking into account the accepted assumptions, as well as equations (14), (15), (19), which are the basis of the solution of the balance equation of the heat supply object (13), the ratio for determining the heat flow capacity for the purposes of heat supply is obtained in the form:

$$Q_T(t) = \left[V_B \cdot C_p \cdot \rho_B \cdot a + k_{OK} \cdot F_{OK}\right] \cdot \left[T_B - T_H(t)\right] + \\ + \left\{\alpha_B \cdot F_{CT1} \cdot \left[T_B - T_{CT1}(t) \mid B\right]\right\} + \\ + \left\{\alpha_B \cdot F_{CT2} \cdot \left[T_B - T_{CT2}(t) \mid B\right]\right\}. \quad (20)$$

The resulting equation can be solved with a known temperature distribution in time $T_{CT1}|B$ on the surface of the external wall from the side of the heated room and the temperature $T_{CT2}|B$ on the surface of the external ceiling from the side of the heated room. In turn, to determine these temperatures, it is necessary to know the temperature distribution in this barrier taking into account the boundary and initial conditions. Equations (9)-(20) are a mathematical model of thermal processes occurring in a heat supply facility. These equations allow calculating the time-varying thermal power Q_T, which is necessary to meet the needs of the heat consumer and maintain a constant level of the specified microclimate in the room.

5. Results of simulation, conclusions and decisions

Numerical modelling of heat exchange processes in a heat supply facility, which is a typical individual house, is reduced to calculating the dynamics of heat losses during the heating season [14], which are included in the heat balance equation of the heat supply facility (3) and allows to calculate the changes in the heat load of the system.

Let's analyse the results of numerical modelling using the example of calculation for the middle October. The average daily distribution of the outdoor air temperature of the heat supply facility in the mid-October is shown in the Figure 3.

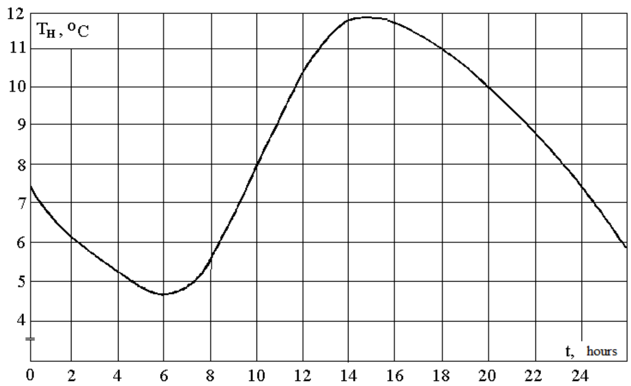

***Figure 3** – The average daily outdoor air temperature T_H in the mid-October*

Results of calculation of the heat load of the heat supply facility and its components – total heat losses through ventilation and through windows $Q_{VENT+OK}$, through walls Q_{CT} and thermal power of the building Q_T with and without taking into account heat accumulation by the walls are shown in the Figure 4.

The specified heat losses are a function of the external air temperature T_H.

For the purpose of comparison, results of simulation of the heat load of the system with account the heat accumulation by walls Q_{CT} and through the ceiling $Q_П$ and similar values without taking into account accumulation Q_{CT} and $Q_П$ are presented.

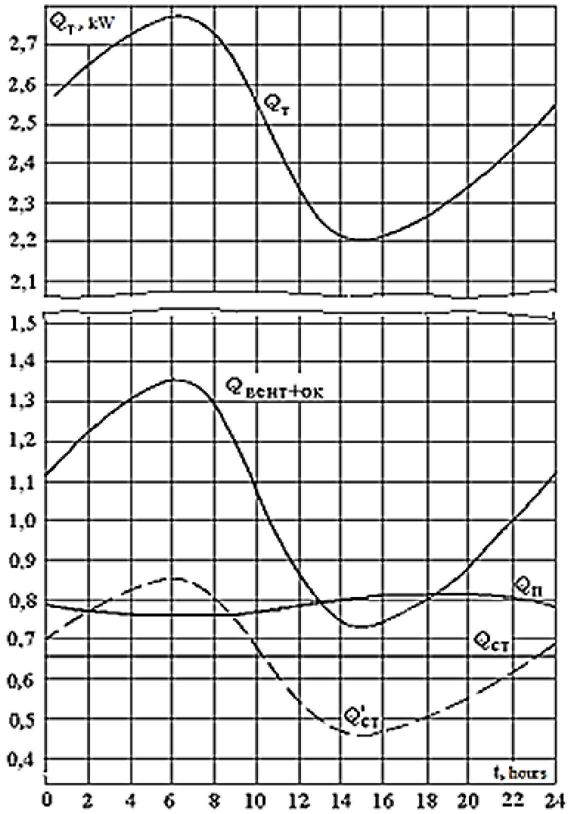

***Figure 4** – Heat losses and daily heat load in October*

The analysis shows that the accumulation of heat by the walls has a mitigating effect on the nature of the heat exchange process, i.e. the graphs of fluctuations of heat losses through walls Q_{CT} and ceiling $Q_П$ are characterized by small amplitude over time, which is clearly visible from the curves of changes of heat flow capacity that lost from the interior of the building to environment through the walls and ceilings.

Heat losses through the ceiling $Q_П$ practically don't change during the day but fluctuations of heat losses through the walls Q_{CT}, taking into account accumulation, are smoothed out and their average value for October are equal $Q_{CT} = 0{,}66$.

For comparison in the Figure 4 the dotted line shows a graph of total losses through walls and ceilings $Q'_{CT+П}$ without taking into account heat accumulation by walls. The graph of heat losses through walls and ceilings $Q'_{CT+П}$ has a clearly pronounced sinusoidal character, opposite in phase to the graph of changes in ambient air temperature T_H during the day (Figure 3), the phase delay is approximately 12 hours.

During the night period, the graph of heat losses Q'_{CT} changes is similar to the sinusoidal curve of heat loss changes through ventilation and through windows $Q_{VENT+OK}$, which is explained mainly by the changes of the ambient air temperature T_H. It is obvious that the value of specified heat losses reaches its maximum value during the night period, which leads to a corresponding increase of thermal load of the system Q_T.

Analysis of calculations shows that when heat is accumulated by walls at night, heat losses Q_{CT} caused by fluctuations of the ambient air temperature T_H are relatively smaller, since the amplitude of fluctuations in the consumer's requirements in thermal power Q_T is smoothed. Thus, the changes in heat losses taking into account heat accumulation by walls Q_{CT}, which depends on ambient temperature T_H, is less pronounced for fluctuations in consumer's requirements of the thermal power Q_T.

In the Figure 5 the heat load changes in October are shown, taking into account the accumulation of Q_T and excluding the accumulation of heat by the walls of the house Q'_T. The solid line shows the change of the heat capacity, and the dotted line refers to the case of heat load without taking into account the accumulation of heat by the walls. The graphs clearly show the influence of the accumulation of heat by the walls on the amplitude of fluctuations in the heat load – the amplitude of fluctuations of Q_T decreases. In this case, the maximum amplitude is observed before sunrise (at the minimum outdoor air temperature T_H), and the minimum – around noon, approximately at 14.30, i.e. at the maximum temperature T_H.

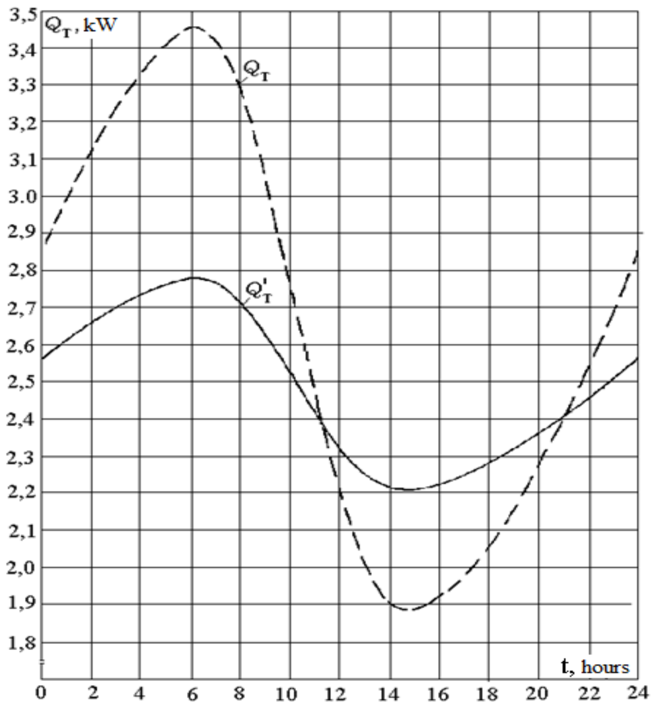

Figure 5 – Changes of the heat load in October with accumulation of heat Q'_T and without accumulation of heat Q_T by the walls

The dynamics of the non-stationary process of heat exchange between the wall of the house and the environment, taking into account the accumulation of heat by the walls, can be clearly seen in Figure 6, which presents graphs of changes in the temperature field in the outer wall for the given period of the day. The results of the calculations presented were performed with an interval of 6 hours and refer to mid-October, but it is worth noting that the temperature field in the walls of the house for other months of the heating period has a similar character.

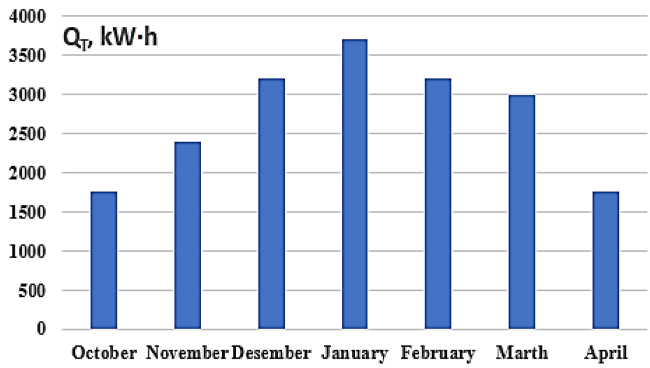

Figure 6 *– Diagram of the thermal capacity Q_T*

Analysis of the graphs of the temperature function $T_{CTi}(x)$ along the wall thickness δ shows that for 13:00 it has the greatest curvature especially near the outer wall of the house, but over time it takes the form of a straight line, which becomes most pronounced in the evening. The graphs characterize the features of non-stationary heat exchange processes in the wall, where the temperature through its thickness decreases from the inner boundary to the outer, in accordance with the change in the temperature difference between the environment and inside the house. After noon at 13:00, an increase of temperature is observed near the outer boundary, which is explained by the ability of the wall to accumulate heat.

It is obvious that the nature of the temperature field in the walls affects the microclimate parameters inside the house, which, according to generally accepted standards, must be maintained at a proper constant level over time, which causes a corresponding fluctuation in the thermal power of the HPS.The results of the heat load calculations for the heat supply facility of IHP during the heating season are presented in the form of a generalized diagram at Figure 6.

5. Conclusions

Analysis of the diagram shows that maximum monthly heat load of HPS is 3700 kWh and is typical for January. That is typical for climate conditions of

Odessa, for HP heating system of two-story building with an area 100 m^2. In December and February, the heat capacity requirements are also high – 3200 kWh, but less than in January. However, the average daily heat capacity in February – 114 kWh is greater than in December – 103 kWh in October and April, the heat load of HP heating system is minimal –1750 kWh. Numerical modeling of heat supply facility allowed us to establish the heat capacity of HPS for warm 6500 kWh and cold 12500 kWh months of the season, respectively.

CRediT author statement

Alla Denysova: Methodology, Development of the mathematical model, Writing – Original Draft, Project administration, Supervision. **Mykola Serheiev**: Numerical modelling, Analysis of results of simulation, Resources, Software.

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Інструментарій для підвищення ефективності теплонасосної системи опалення за рахунок акумуляції тепла стінами будівлі

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Дана стаття присвячена методам підвищення ефективності теплонасосної системи опалення з використанням ефекту, що базується на принципах енергозбереження. Основною метою дослідження є аналіз методів підвищення ефективності акумулювання теплоти стінами будівлі з урахуванням кліматичних умов, які відповідають вимогам енергозберігаючих технологій. Для досягнення поставленої мети запропоновано математичну модель та проведено порівняльний аналіз ефективності акумуляції тепла стінами будівлі при використанні теплонасосної системи опалення для кліматичних умов України. Розроблено алгоритм чисельного моделювання енергоефективності теплонасосної системи опалення з урахуванням кліматичних умов. Запропоновано методи оцінки енергоефективності альтернативної схеми теплопостачання. На конкретному прикладі показано спосіб реалізації та підтверджено ефективність системи альтернативного опалення. Виконано чисельне моделювання теплових процесів в елементах будівлі з урахуванням акумулювання теплоти стінами. Наведено аналіз результатів чисельного моделювання теплових процесів акумулювання тепла стінами при роботі теплонасосної установки для цілей опалення двоповерхової будівлі. Обґрунтовано раціональні шляхи підвищення ефективності альтернативної системи опалення при акумулюванні теплоти стінами з урахуванням кліматичних умов. Виконано аналіз результатів моделювання та запропоновано рішення для практичного застосування результатів дослідження. Значимість отриманих результатів полягає в обґрунтуванні умов, які дають засадах енергозбереження. Найбільш вагомими результатами є висновки щодо підвищення ефективності теплонасосних систем теплозабезпечення споживачів, які можуть бути використані для проектування систем опалення на основі теплових насосів з урахуванням акумулювання теплоти стінами будівлі. Запропоновано рівняння, які є математичною моделлю теплових процесів, які відбуваються безпосередньо в самому об'єкті теплопостачання, дозволяють розрахувати теплову потужність теплонасосної системи, яка необхідна для задоволення потреб споживача тепла та підтримки постійного рівня заданого мікроклімату в будівлі з використанням внутрішніх ресурсів споживачів енергії.

Ключові слова: *Акумулятори теплоти; Моделювання; Теплові насоси; Енергозбереження; Системи теплопостачання; Режими роботи систем теплопостачання; Кліматичні умови*

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