Research and development of ice storage in building energy supply system

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Abstract. In this work, the most suitable type of heat exchanger for an ice accumulator was determined based on studies of the dynamics of ice growth on heat exchange surfaces of various shapes and its configuration was determined. The calculation of the accumulating capacity of the ice accumulator has been made. The task is set to create a mathematical model in the Ansys Fluent and TRNSYS environment, as well as BIM and BEM models of the main elements of the system. A ready-made design solution for the introduction of an ice storage device into the existing heat supply system of an energy-efficient house with an assessment of the cost of costs and required materials has been developed. An assessment was made of the cost of various solutions for heating a house with a load of 10 kW. A test bench layout has been developed for monitoring and analyzing the operation of the system, as well as the impact on the environment. The functionality of the current system for recording and processing the operating parameters of the equipment allows not only to confirm the correctness of calculations and the operability of the mathematical model, but also to assess the impact of the ice accumulator on the environment.

1. Introduction

In the Russian scientific community, at the moment, more than 68600 articles have been written on the topic "heat pumps" and methods of their application (as requested on Elibrary.ru). However, most of them consider standard solutions for extracting heat from such primary sources as air, ground (vertical and horizontal ground collectors), groundwater, heat from waste water and reservoirs. Each of the previously listed sources has certain advantages and disadvantages. In cases where there are restrictions on the outside air temperature, drilling deep wells, it is possible to use ice accumulators.

In the Russian and foreign scientific community there are already scientific works \([1\text{-}3]\) on a similar topic (for example, Daniel Carbonell (h-index according to Scopus = 8), Daniel Philippen (h-index according to Scopus = 6), Martin Granzotto (h- Scopus index = 9), Michel Y. Haller (Scopus h-index = 14) and Elimar Frank. (h-index = 9), Zmeureanu, Radu G. (Scopus h-index = 22)), but they describe only the principle of operation of this installation, proposed mathematical models describing small units of the system and there is no general model for calculating and designing integral systems.

In addition, the considered mathematical models ignore the effect of temperature on the thermal conductivity of ice, which leads to large errors in calculating the dynamics of ice growth on the heat exchange surface.
For the first time, a patent for this technology was developed by Isocal, but in 2012 the German company Viessmann acquired this organization, and along with it a patent for this technology. Since 2012, this organization has implemented more than 1100 standard solutions for the domestic sector.

The official representative office of the Viessmann organization is located in Russia, which after communicating with the members of the project team is ready to provide technical support in an ongoing study, since the further research of this technology will not only expand the scope of heat pumps, but also increase the company's sales.

It is also worth noting that there is not a single completed object on the territory of the Russian Federation. The project provides for the implementation of the object within 2 years.

2. Application of the ice accumulator
The use of ice accumulators as a low-potential heat source for brine-water heat pumps has not been officially recorded in Russia. The main advantage of this system is that they do not require special building permits, unlike geothermal probes [4]. This helps to solve a number of problems arising at the stages: design, construction and further operation. The main difficulty for some regions is the large depth of soil freezing.

The installation scheme consists of one or two ice accumulators (located at a distance of more than 2 meters from each other), the required number of solar collectors selected according to the design calculation, a reversible heat pump and a buffer tank for preparing hot water [2].

The solar-air absorbers installed on the roof remove heat from the environment and in the daytime from insolation and supply it to the heat pump. If the energy is not taken by the heat pump, it is used to regenerate the ice accumulator or to heat the buffer tank. An ice accumulator with a built-in heat exchanger is installed below the freezing depth of the soil, filled with treated water and used as a low-potential heat source. The heat pump must be able to operate in reversible mode. In the summer, when there is no heating demand and the heat load on hot water supply is minimal, solar collectors supply heat energy to the storage tank. When the heating season begins, heat loads increase and the demand for air conditioning decreases, then the heat pump begins to take heat from the ice accumulator, up to controlled icing at 0 °C. Further there is a phase transition of water from liquid to solid state. In parallel, the process of heat exchange between the ice accumulator and the environment (soil) is carried out in the storage. At the end of the heating period the heating demand of the building decreases and the heat pump switches to reversible operation. In this mode, the ice accumulator is regenerated. The cold is taken from the storage and sent to air conditioning the premises. The ice in the accumulator tank starts to melt and there is a gradual accumulation of heat. Thus, the cycle is closed.

3. Main technical tasks

3.1. Design of heat exchanger coils and concrete tank
The first task is to choose the placement of the coils in the tank. The location of the coils determines the uniformity of heat removal, the correct formation of ice on the heat exchange surfaces, and the efficiency of the ice accumulator. Improper backfilling can lead to intense ice formation and damage to the concrete structure.

Despite the fact that ice accumulators have been around for many years. To date, there is no ready developed methodology for calculating the ice accumulator. The main task is to choose the turn-to-turn distance. In [3], practically experiments were carried out aimed at calculating the rate of ice formation on different surfaces. Based on the data obtained in [3], it can be noted that the rate of ice formation on surfaces decreases when a certain ice thickness is reached. In order to ensure uniform formation of ice on the surface of the coil it is necessary to determine the diameter at which a decrease in growth dynamics is observed. Based on the data received, set the turn-to-turn distance.

The second task is to select the material and shape (dimensions) of the concrete structure. The concrete structure must be strong and ensure reliable and safe operation of the installation.
When designing an ice accumulator, it is worth considering that it makes no sense to heat water in a container over 30°C, because there will be significant losses through the enclosing structures of the tank, and this will also lead to a decrease in the moisture content in the soil (decrease in the regenerative function of the soil [5]).

3.2. Installation of a concrete tank

The third challenge is the correct choice of the location and depth of the ice accumulator. Obviously, in order to regenerate and prevent chilling of the tank, it is necessary to mount it to a depth below the freezing of the soil [6].

There are several methods and technologies for installing and using heat accumulators in the heat supply system [5]. Basically, installation is used near the building and under the building (Viessmann has implemented several objects with storage directly under the building). In the second case (introduction into the existing heat supply system), only the installation of the tank next to the building remains.

Since one of the main goals of this work is the development of a design solution for the implementation of a passive house based on a solar collector and a ground heat pump into the existing heat supply system, it is necessary to install a capacity for heat accumulation at an optimal distance from the house and geothermal wells and other communications and pipelines.

4. Development of calculation methods

4.1. Selecting the type of heat exchanger for the ice accumulator

In Figure 1 is presented a graph of the intensity formation of ice on the surface of the heat transfer of different shapes (flat wall, the outer and inner walls of the tube). Analyzing this graph, we can conclude that the rate of ice formation on the inner surfaces of the cylindrical tube is too intense, which can lead to uneven ice formation in the concrete tank (also the concept of an ice accumulator does not allow considering this form of a heat exchanger). The best options are a plate or a coil heat exchanger.

Previous German colleagues [2] has shown that the use of flat coils in this scheme requires compulsory regeneration process, and ice formation rate is high and uneven.

Excluding two types of heat exchangers, only a cylindrical heat exchanger remains (from the outside the coolant is water; through the tubes - brine), which will be immersed in a concrete "barrel".

\[ m \ (kg/m^2) \]

\[ \tau \ (min) \]

**Figure 1.** Graph of the dynamics of the growth of ice mass on the surface of heat exchange of various shapes at the same surface temperatures. 1 - flat surface; 2 - outer cylindrical surface of the tube; 3 - inner cylindrical surface of the tube.
In [7], recommendations are given for the design of coil heat exchangers, but they are applicable only to two states of aggregation (gaseous and liquid). Using the model [3], one can estimate the intensity of the increase in the ice layer on the surface of the heat exchanger. On the basis it should determine when the ice thickness is reached, the rate of ice formation decreases, set the inter-turn distance.

At a constant temperature of the coolant, the thickness of ice that forms on tubes of various diameters is practically the same. We add $2\bar{e}$ to the turn-to-turn distance, which will reduce the intensity of freezing of the heat exchanger and facilitate its regeneration. In "brine water" heat pumps, plastic pipes are used as the material of the soil collector, which are made of low pressure polyethylene (HDPE).

4.2. Requirements for concrete structure

All types of concrete and reinforced concrete structures must meet the following requirements [8]:

- for security;
- for serviceability;
- for durability;
- design requirements.

To meet safety requirements, structures must have characteristics so that under various design influences during construction, installation and operation, there is no threat to the life or health of citizens, property, and the environment.

To meet the requirements for serviceability and durability, the structure must have such characteristics that, under various influences, the formation of cracks and leakage does not occur. It must be taken into account that the concrete structure will:

- installed below the 0.000 m level (it is necessary to provide a foundation);
- filled with water (ensuring the impermeability and tightness of the structure);
- alternate freezing and thawing of water.

The concrete structure of the ice accumulator consists of 2 main parts - a concrete "bowl" and a lid through which the container is inspected and filled.

4.3. Coil heat exchanger design

Problem statement: average water temperature in the ice accumulator during the year $t_b = 5^\circ C$. As pipes, HDPE pipes 32x3 mm are used. From the side of the pipes, a ready-made mixture based on ethylene glycol with corrosion inhibitors down to -20$^\circ C$ is used as a heat carrier. Co-operation with a Buderus Logatherm WPS 11 heat pump (heating power 10.9 kW) in heating mode is provided.

Let's set the diameter of the battery tank:

$$D_{\text{tank in}} = 2.5 \text{ m} - \text{internal diameter of the concrete construction.}$$

In the design of the coil, it is taken into account that the minimum bend radius for pipes DN32 (Uponor GeoPEx, MuoviTech) is 0.32-0.4 m.

Taking into account the data obtained (Figure 3) and recommendations [7], we determine the distance from the pipe to the concrete structure: $a_w = 0.2 \text{ m}$.

$$a_w = 0.2 \text{ m}$$

$$a_b = 0.2 + 0.015 + \frac{(d_n + 2 \cdot \delta_n)}{2}, \quad (1)$$

where:

- $ab$ – is the distance from the pipe to the bottom of the concrete structure,
- $aw$ – is the distance from the pipe to the side walls of the concrete structure,
- $dn$ – is the flow diameter of the pipe, m,
- $\delta_n$ – is the wall thickness of the pipe, m.
Because in the upper part of the concrete bowl, in addition to water, collectors will be located, additional space must be provided:

\[ a_{\text{collector}} = a_b + 0.1, \]  

Determine the diameter of the loop of the first coil:

\[ D_{L1} = D_{\text{tank,in}} - (2 \cdot a_c) = 2.1 \text{ m}, \]  

Determine the turn-to-turn distance:

\[ s_{\text{coil}} = (d_n + 2 \cdot \delta_n) \cdot 3 + 3 \cdot 0.015. \]  

The length of one loop (one complete turn) of the first coil:

\[ l_{1\text{loop}} = \sqrt{\left(\pi \cdot D_{L1}^2 + s_{\text{coil}}^2\right)}. \]  

Let's set the number of turns of the first coil:

\[ n_{\text{coil1}} = 11 \text{ pcs.}. \]  

Determine the length of the first coil (taking into account the installation length of 5 m):

\[ l_{\text{coil1}} = l_{1\text{loop}} \cdot n_{\text{coil1}} + 5. \]  

Let's calculate the surface area of the first coil:

\[ F_{\text{coil1}} = l_{\text{coil1}} \cdot d_{\text{trp,h}} \cdot \pi. \]  

The coil height:

\[ H_{\text{coil1}} = n_{\text{zm1}} \cdot d_n + (n_{\text{coil1}} - 1) \cdot s_{\text{coil}}. \]  

Coil arrangement diagram according to Figure 2.3. The distance between the pipes is 20 cm. By analogy, we make a calculation for all coils (4 pcs.). The calculation results are summarized in Table 1.

**Table 1.** Summary table of geometrical parameters of ice accumulator coils.

| No | Parameter        | Units. | rev | Coil | I  | II | III | IV | Total |
|----|------------------|--------|-----|------|----|----|-----|----|-------|
| 1  | Loop diameter    | m      |     |      | 2.100 | 1.754 | 1.407 | 1.061 | –     |
| 2  | Loop length      | m      |     |      | 3.728 | 3.155 | 2.502 | 1.891 | –     |
| 3  | Coil length      | m      |     |      | 46.03 | 39.27 | 32.52 | 25.81 | 143.63 |
| 4  | Coil area        | m      |     |      | 5.058 | 4.318 | 3.576 | 2.837 | 15.789 |

Figure 2 shows a drawing of a heat exchanger in a concrete structure, as well as the principal location of the supply and return headers.
Knowing the height of the coil, you can determine the height of the water level in the concrete "bowl":

\[ H_w = H_{coil} + a_b + a_{collector} = 2.97 \text{ m}. \] (9)

Let's round the resulting value to 3 m.

The volume of water in the concrete "bowl":

\[ V_w = H_w \cdot \frac{\pi}{4} \cdot D_{tank, total} - l_{col, total} \cdot \frac{\pi}{4} \cdot d_n. \] (10)

Since the density of ice at a temperature of -5 °C is 917.5 kg m\(^{-3}\) (the density of water at 0.01 °C is 999.8 kg m\(^{-3}\)), when designing the bowl, it is necessary to take into account that the volume will increase to 15.75 m\(^{3}\) (an increase in volume by 8%, water level rise by 0.16 m). To avoid overflow, it is necessary to increase the height of the concrete structure:

\[ H = H_w + 0.3 \] (11)

4.4. Coil heat exchanger design

According to the research [8] and the requirements [9], to ensure the reliability of a concrete or reinforced concrete structure, it is necessary to make a calculation using the semi-probabilistic method, assessing the acting loads and operating conditions. In addition, it is necessary to consider the possibility of transportation (if necessary), or pouring on site. The concrete structure should consist of 4 elements: a concrete ring, bottom, cover and foundation.

Previously, the main parameters of the concrete structure were set, namely the inner diameter and height of the bowl, which corresponds to \(D = 2.5\) m and \(H = 3.30\) m. The calculation of the parameters and reliability of the ring concrete structure was performed using the Perpendicular.pro software. The cover for this tank can be used the same as for drainage wells.

4.5. Calculation of the maximum storage capacity of the ice accumulator

The calculation will be made by analogy with the article [10]. Let's write down the formula for calculating the accumulating capacity of the ice accumulator when it is discharged:

\[ Q_a = Q_I + Q_H + Q_{II} - Q_{loss} + Q_{reg} + Q_{sol}, \] (12)
where:
- $Q_I$ - heat extraction from the ice accumulator (from 15°C to 0.1°C),
- $Q_{II}$ - phase transition,
- $Q_{III}$ - ice supercooling (0),
- $Q_{loss}$ - losses through the concrete structure,
- $Q_{reg}$ - the regeneration of the ice accumulator,
- $Q_{sol}$ - heat gains from the solar collector (if available).

\[
Q_I = V_w \cdot c_p \cdot \Delta t_1 \cdot \rho_w = 250 \text{ kWh}, \tag{13}
\]
\[
Q_{II} = V_w \cdot \rho_w \cdot L = 1338 \text{ kWh}. \tag{14}
\]

The project does not provide for ice supercooling below -0.1°C

\[
Q_{III} = 0
\]

Before proceeding with the calculation of heat losses through the enclosing structures, we will calculate the required time of continuous operation of the heat pump to extract heat from the ice accumulator (cooling capacity according to the passport is 8.6 kW).

\[
\tau_I = \frac{Q_I}{Q_c \cdot 3600} = 29 \text{ h 5 min}, \tag{15}
\]
\[
\tau_{II} = \frac{Q_{II}}{Q_c \cdot 3600} = 155 \text{ h 34 min}. \tag{16}
\]

The total operating time for a complete discharge of the tank (excluding regeneration from the ground and solar collectors) is 184 hours and 39 minutes. Let's calculate the losses and heat inflows through the walls for the given duration of work.

\[Q_{loss} = 58 \text{ kWh} \]
\[Q_{reg} = 516 \text{ kWh} \]

Since the sun is often the main source of heat for such ice accumulators [11], the $Q_a$ value was calculated using the T * Sol Pro 5.5 program. The system of solar collectors was specified, consisted of 15 Vitosol 100-F flat panels, with a total area of 37.77 m$^2$ (active area 34.94 m$^2$). Due to the fact that the program is given standard schemes, the heating scheme of the open pool was chosen as the calculated one (the dimensions of the pool correspond to the dimensions of the ice accumulator).

\[Q_a = 2686 \text{ kWh} \]

5. **Object of design and implementation of technical solutions**

5.1. **Design object**
The design object is an existing energy efficient house located in the Moscow region. The total area of the building is 205 m$^2$ (living area 167 m$^2$, plot area 1 264 m$^2$). Building dimensions – the building length 12 m, the width 11 m, the height to the ridge of the roof - 10 m. Description of the house is presented in works [12-14].

Design and construction work was carried out using Passive House technologies [15]. That is why the shape of the building is close to a cube, because this solution allows to reduce heat losses of the
building through the building envelope. The roof is gable, the roof area on the south side is 130 m² (this area is used to accommodate solar collectors). There is a hinged veranda on the south side. It is designed in such way that in summer it limits the flow of heat due to insolation, but in winter, on the contrary, when the sun is low, the sun's rays freely illuminate the window and glass door, thereby providing heating of the internal air in winter.

The main calculation of the thermal loads of this object was carried out in the PHPP software package and is described in [12-14]. Based on the results obtained by the program, the thickness of the layers of the enclosing structures was determined. Later, these results were used in [16] for comparative analysis of various software.

5.2. Existing heat supply system
The phased implementation of equipment is underway at the projected facility. Schematic diagram heating detail is described in the work [12-14]

To date, 2 wells have been drilled and geothermal probes installed in them. The operation of the heat pump shown that at long operation (long cycles described in [17]), there is a drop temperature feedback line below -1 °S, that indicates the low productivity of the well. This operating mode limits the operating time of the heat pump and does not allow full use of the night electricity tariff. In this connection, it was decided to use the ice accumulator as an additional source of heat. This was done based on research about joint work [18].

To determine the effectiveness of the application of the introduced technology was determined COP for three cases: the heat pump with the existing geothermal probes, a heat pump with ice accumulator’s volume of 14.5 m³ and a heat pump with the ice accumulator’s volume of 50 m³. The results were determined according to the COP calculation method proposed by the manufacturer of the Buderus Logatherm WPS11 heat pump. The data for calculating the COP of the heat pump in the existing scheme was taken from the existing monitoring system [19]. The heating circuit flow temperature is 35 °C.

| №   | Scheme                                      | COP   |
|-----|--------------------------------------------|-------|
| 1   | Heat pump with 2 geothermal probes         | 6.0 – 3.8 |
| 2   | Heat pump with ice storage volume 14.5 m³ | 6.5 – 4.4 (4.7) |
| 3   | Heat pump with ice storage volume 53.4 m³ | 6.5 – 4.4 (5.5) |

The data are presented in Table 2 and listed with the range. For the first scheme, this range means the maximum possible initial COP and the minimum at the end of one cycle of work. For the second and the third schemes, the operating range is presented from the maximum design mode of the ice accumulator (the water temperature in the ice accumulator is 15 °C higher) to the moment of complete crystallization (the water temperature is -0.1 °C, without ice overcooling). The value in the brackets indicates the average operating factor coefficient power.

6. Conclusion
It was shown that in the current practice there is no model and software for calculating the ice accumulator, which could allow for a reliable calculation. All models have a number of assumptions that introduce large errors in the final result.

The paper proposes a simplified method for designing an ice accumulator. Recommendations for design were developed, namely:

- choice of turn-to-turn distance based on the existing recommendations for the design of coil heat exchangers and the maximum rate of ice layer growth on the coil surface;
the recommended number of turns - 9 - 11 pcs. With an increase in the number of coils, the height of the ice accumulator and the depth of its installation increase. If groundwater is located nearby, it can lead to the impossibility of installing an ice accumulator;

- the walls of the ice accumulator should not be insulated, because this will lead to a decrease in the regeneration of the ice accumulator (regeneration will occur only due to solar collectors and the reversible mode of the heat pump);

- the principle of connecting a heat pump to an icemaker is completely similar to geothermal collectors. Their joint work is allowed;

- it is not recommended to maintain and strive for the temperature in the ice accumulator above 15 °C, because this mode will lead to an increase in heat loss and a waste of the received solar energy;

- it is not recommended to raise the temperature of the brine in the wells above 30 °C. This can lead to a decrease in the amount of moisture in the soil, which will lead to a decrease in the amount of heat that can be taken away.

The second fulfilled goal is a ready-made design solution for implementation into the existing heat supply system of a passive house. Based on the existing problem with wells chilling during long-term operation, it was necessary to increase the number of wells or to develop an alternative solution to the problem. The solution to this problem will be the introduction of an ice accumulator. It will allow you to avoid chilling wells, as well as accumulate additional energy. In the work, the calculation of the concrete structure was made, the composition of concrete and the section of reinforcement were selected to increase the strength of the structure. The heat exchanger of the ice accumulator was designed and the turn-to-turn distance was chosen, which makes the dynamics of ice growth the same throughout the entire volume of the ice accumulator.

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