Ecological Questions 33 (2022) 2: 31–41 http://dx.doi.org/10.12775/EQ.2022.011

Utilization of drainage water heat in flooded urban areas

Yurii Kovalenko[1], Mykhailo Katkov[1], Ievgenii Ponomarenko[1], Myroslav Malovanyy[2], Ivan Tymchuk[2,*]

[1]O.M. Beketov National University of Urban Economy in Kharkiv, Marshal Bazhanov Str., 17, Kharkiv, 61002, Ukraine
[2]Lviv Polytechnic National University, S. Bandera Str., 12, Lviv, 79013, Ukraine
*corresponding author e-mail: i.s.tymchuk@gmail.com

Received: 18 November 2021 / Accepted: 7 February 2022

Abstract. The possibilities of using drainage water from flooded urban areas as a source of energy for heat supply of buildings located in these areas were considered. The use of heating technological workflows based on the utilization of drainage water heat with heat pumps was substantiated. A method was developed for determining the required energy potential of drainage water and for determining technological characteristics of the proposed workflows. A comparative analysis of various workflows was carried out and the advantages of the water-to-water heat pump along with the heat-insulated flooring system over other heat supply workflows are shown.

Keywords: drainage water, heating, flooding, heat pump, urban areas, energy saving.

1. Introduction

Public utility services are one of the significant consumers of thermal energy, which in the context of limited natural resources, their increased cost, and growth of anthropogenic load associated with the use of traditional energy, makes the task of attracting alternative and non-traditional energy sources for heating buildings urgent (Sait et al., 2019; Vranayova et al., 2018).

One of these unconventional energy sources is drainage water discharged from flooded areas. The problem of drainage water treatment is related to its purification from contaminants: ammonium ions (Malyovanyy et al., 2013; Sakalova et al., 2019), phosphates (Tulaydan et al., 2017; Tymchuk et al., 2020; Tymchuk et al., 2021), heavy metals (Kostenko et al., 2017) and their use as non-traditional energy sources.

Significant areas of major cities are flooded in many countries. Flooding of urban areas is typical for Argentina, Bangladesh, China, the Netherlands, the Russian Federation, the USA, Croatia, Japan and other countries (Dobrovicova et al., 2015; Medvedkov & Shtripling, 2017; Sedin et al., 2018).

To reduce the level of flooding, dewatering technologies are used with the discharge of drainage water into sewerage systems or directly into water bodies. At the same time, drainage water is characterized by sufficient flow stability, relative consistency of temperature, which allows the water to be considered a possible source of thermal energy (Kordana-Obuch, 2017; Kordana-Obuch et al., 2019; Akbarzadeh et al., 2018). However, given the low thermal potential of such a source, its effective use for heat supply requires special technological workflows based on the use of heat pumps (Heat pumps in modern…, 2016; Seybold & Brunk, 2017; Zhidovich, 2017; Matsevity et al., 2014; Sirko et al., 2020).

This paper is devoted to the elaboration of such a workflow for utilizing the thermal potential of drainage water for heating buildings and development of the conditions for its use.

2. Analysis of literature data and problem statement

The use of heat pumps in housing and utilities infrastructure as a source of heat supply is one of the global trends and one of the foundations of the energy conservation policy in most economically developed countries. There are various workflows based on the use of heat pumps.

Heat supply systems that use geothermal heat pumps require significant capital costs, which are associated not only with the cost of the heat pump itself, but also with the cost of arranging systems for extracting heat from soil. The latter can be compared with the cost of the heat pumps alone (Sirko et al., 2020). The use of the physical heat of soil requires large volumes of earthworks and, accordingly, large areas for the installation of external heat exchange equipment. The maintainability of underground heat exchange equipment is limited. In addition, the cooling of soil caused by the operation of the geothermal heat pump leads to a decrease in its efficiency during the heating period (Heat pumps in modern…, 2016; Nifontova et al., 2016).

Therefore, despite the relatively low operating costs, such systems have not yet found widespread use in countries with a low level of economic development. And even in economically developed countries in recent years, the implementation of geothermal heat pumps has remained relatively constant, while there has been a steady increase in the number of air heat pumps (Nifontova et al., 2016).

In case of applying heat pumps that use the outdoor air heat, the amount of heat generated by the heat pump decreases on the coldest days of the season, and the heat loss of the building increases, which entails the need to connect additional sources of thermal energy. Freezing of condensate on the external units of heat exchangers reduces the intensity of heat exchange and requires additional heat for defrosting.

In this regard, systems that use groundwater as an energy source are of particular interest, since they provide the highest energy conversion coefficient compared to other low-temperature heat sources and the economically sound potential of this energy source for Ukraine alone is estimated at 800,000 tons of fuel equivalent per year (Sirko et al., 2020).

Apart from groundwater, systems that use surface water bodies and wastewater as a source of low-potential energy provide a sufficiently high efficiency. However, the use of surface water bodies has a number of significant technological and environmental limitations. Technological limitations are associated with the instability of the temperature regime of water bodies, and the lowest temperature, which can reach 0°C, coincides with the peak of energy consumption. Environmental limitations are associated with the necessity to lay several hundred meters of plastic pipes of heat exchanger in the bottom of a water body. This creates a threat of accidental pollution of the water with a heat carrier and requires special measures to increase the reliability of such systems. Also, the use of heat from surface water bodies is limited by the distance between buildings and the coast and the problems of laying networks through the coastal strip and in the bottom of the reservoir.

A fairly large number of studies are focused on the use of wastewater heat as a source of energy (Zhidovich, 2017). Wastewater as an energy source is characterized by relative ease of access, a fairly high and relatively stable temperature (10–20°C, depending on the wastewater collection point), but it has significant daily flow rate variability, which requires additional engineering solutions for averaging wastewater flow. At the same time, wastewater flow, as a rule, is insufficient to supply heat to buildings without involving other energy sources. In addition, the presence of organic contaminants in wastewater leads to the formation of a biofilm on the heat exchanger, which significantly reduces heat transfer (Heat pumps in modern…, 2016; Kordana-Obuch, 2017; Kordana-Obuch et al., 2019).

Groundwater, despite being slightly colder than wastewater (usually its temperature range is 7-15°C), as a rule, provides a more stable flow rate and is significantly higher in quality (Matsevity et al., 2014). Therefore, its use seems to be quite attractive. However, in this case, additional engineering solutions are required to access this source. The main access workflow is the use of two wells, one of which is used to supply groundwater to the heat exchanger, and the other – to receive the subsequent wastewater. Since the temperature of the wastewater can differ from the temperature of the supplied water by up to 5°C, the waste well shall be located at a distance of at least 30–50 meters from the supply well to exclude their mutual influence. In addition, possible hydrological and environmental impacts must be considered. All this significantly limits the use of such workflows. Drainage waters have a relatively constant temperature, approaching the average annual atmospheric air temperatures in the climatic zone of the object's localization.

For the climatic conditions of the research object, the average annual temperature of the outdoor air and, accordingly, the temperature of the drainage waters was 8°C.

The technologies of using drainage water, which is essentially the same groundwater already extracted while using other technological solutions, are more attractive. One example is the use of mine water (Heat pumps in modern…, 2016; Akbarzadeh et al., 2018). However, given the prevalence of the problem of flooding throughout the world, the water diverted from flooded urban areas is a much more significant source of drainage water. Besides, in many cases, flooded areas are in the immediate vicinity of developed areas, which allows the use of drainage water directly in the places of their formation. However, the use of such a source of low-grade energy in municipal heating systems has not yet received sufficient attention.

Apart from heating, heat pumps can also help reduce the temperature during hot periods of the year and create a comfortable microclimate indoors. At the same time, unlike air-to-water heat pumps capable of operating exclusively in active cooling mode, water-to-water heat pumps are also capable of operating in passive natural cooling mode, which makes energy costs negligible (Akbarzadeh et al., 2018).

Therefore, the analysis of the conditions for the use of such workflows is an urgent task of practical importance.

3. Research aim and objectives

The aim of this paper is to substantiate a technological workflow that allows to utilize the thermal potential of drainage water in flooded areas to heat residential buildings.

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

– to propose technological workflows for utilization of the thermal potential of drainage water;

– to develop a methodology for determining the technological characteristics of the proposed workflows;

– to substantiate the effectiveness of using the proposed workflows for heating buildings.

4. Substantiation of technological workflows for utilization of drainage water thermal energy

4.1. Methodology for assessing the energy potential of discharged drainage water

The feasibility of using heating systems based on the utilization of thermal energy of drainage water is determined by the sufficiency of the energy potential of the water for sustainable provision of the thermal regime of residential premises throughout the year. Therefore, a methodology is needed for comparative analysis of energy needs with the capacity of its source. This methodology was developed on the assumption that the energy consuming building is located directly on the drained flooded area, which makes it possible to neglect the heat losses in the external networks. It was also assumed that the drainage water is continuously discharged.

First, let us consider the issue of heating buildings.

The amount of heat required to heat the object of research during the year (heating season) Q_h, kJ, should correspond to the amount of heat taken from drainage water Q_w, kJ (Zakharov et al., 2021).

$$Q_h = Qw \tag{1}$$

where Q_h is the amount of heat required to heat the object of research during the heating season, kJ;

Q_w is the amount of heat taken from drainage water, kJ.

The amount of heat required to heat the building during the year (heating season):

$$Q_h = 3600 \cdot q \cdot F \tag{2}$$

where Q_h is the amount of heat, kJ; q is the specific annual energy consumption of the building for heating needs, kWh/m^2; F is the area of the heated building, m^2.

The value of the specific annual energy consumption q depends on climatic conditions, structural, thermal characteristics, and the class of the building. Depending on these characteristics, the specific annual consumption of buildings might fluctuate within quite a wide range (DBN V.2.6-31, 2016).

The amount of heat taken from drainage water during the same period

$$Q_w = c_w \cdot m_w \cdot \Delta t_w \tag{3}$$

where Q_w is the amount of heat, kJ; c_w is the specific heat capacity of water, kJ/(kg deg); m_w is the mass flow rate of drainage water used during the heating season, kg; Δt_w is the difference between the initial (before use) and final (after use) temperature of drainage water, deg.

Using (1) – (3), we obtain the ratio for determining the required mass flow rate of drainage water for the heating season:

$$m_w = \frac{3600 \cdot q \cdot F}{c_w \cdot \Delta t_w}. \tag{4}$$

Then the average daily mass flow rate of drainage water can be determined by the ratio:

$$m_{wd} = \frac{m_w}{\tau} = \frac{3600 \cdot q \cdot F}{\tau \cdot c_w \cdot \Delta t_w}, \tag{5}$$

where m_{wd} is the average daily mass flow rate of drainage water, kg/day; τ is the duration of the heating season during the year, days.

Ratio (5) allows to determine the required average daily drainage water flow for the conditions of the average difference between the temperatures of the heated premises and outdoor air within the heating season. That is, it does not take into account the variability of outdoor air temperature during different periods of the heating season.

At the same time, in the coldest periods of the year, the heat loss of the building and, accordingly, the demand for the resource increases significantly, therefore, it is necessary to determine the minimum required drainage water consumption to heat the building during the coldest period of the year.

Let us define q_i, kJ/(day·m^2·deg) as the specific average daily energy consumption for building heating given a difference between temperatures of the outdoor air and the heated premises of 1°C.

Q_h is the amount of heat required to heat the object of research during the heating season, kJ:

$$Q_h = q_i \cdot F \cdot \sum_i \Delta t_i \cdot \tau_i, \quad (6)$$

where q_i, kJ/(m^2·deg) is the specific average daily energy consumption for building heating given a difference between temperatures of the outdoor air and the heated premises of 1°C; Δt_i is the temperature difference between the outdoor air and the heated premises, °C; τ_i is the time interval of the heating period, during which the temperature difference between the outdoor air and the heated premises is Δt_i, days.

Then considering (2) and (6), the specific average daily energy consumption for building heating given a difference between temperatures of the outdoor air and the heated premises of 1°C amounts to:

$$q_i = \frac{3600 \cdot q}{\sum_i \Delta t_i \cdot \tau_i}, \quad (7)$$

Based on the climatic conditions of the location of the object, we determine the minimum average daily temperature of outdoor air. Let us denote the difference between the minimum average daily temperature of outdoor air and the air in the heated premises as Δt_{max}.

Then the amount of heat required to heat the object during the day with the minimum average daily temperature is:

$$Q_{h\max} = q_i \cdot F \cdot \Delta t_{\max} \quad (8)$$

The amount of heat that must be taken from the drainage water during the day under conditions of the minimum average daily temperature of outdoor air is:

$$Q_{w\max} = c_w \cdot m_{w\max} \cdot \Delta t_w \quad (9)$$

where m_{wmax} is the drainage water consumption required to heat the building at the minimum average daily temperature of outdoor air, kg.

Considering (8) and (9), the drainage water flow required to heat the building under the conditions of the minimum average daily outdoor air temperature amounts to:

$$m_{w\max} = \frac{q_i \cdot F \cdot \Delta t_{\max}}{c_w \cdot \Delta t_w}, \quad (10)$$

In the absence of information on the value of the actual specific energy consumption of the building, this value can be determined by calculation based on the heat balance of the premises. We neglect the heat input due to solar radiation, considering its insignificant amount during the coldest days of the heating season in countries of the temperate climate zone. Then, considering heat losses due to heat transfer through external enclosing structures and infiltration, we write down:

$$Q_{h\max} = \left(\sum_i k_i \cdot f_i \cdot 10^{-3} + c_a \cdot m_f \right) \cdot \tau_d \cdot \Delta t_{\max}, \quad (11)$$

where c_a is the mass heat capacity of air, kJ/(kg, deg); m_f is the mass flow rate of air entering the premises with infiltration, kg/s; τ_d is the duration of a given time interval, s; f_i is the area of the i-th element of enclosing structures, including external walls, windows, floors, ceilings, doorways, m^2;

k_i is the heat transfer coefficient of the i-th element of enclosing structures, including external walls, windows, floors, ceilings, doorways, W/(m^2 deg).

The value of k_i is determined by the formula:

$$k_i = \frac{1}{\frac{1}{\alpha_1} + \sum_i \left(\frac{h_i}{\lambda_i} \right) + \frac{1}{\alpha_2}} \quad (12)$$

where α_1 is the coefficient of heat transfer from the wall to the indoor air, W/(m^2 deg); α_2 is the coefficient of heat transfer from the wall to outdoor air, W/(m^2 deg); h_i is the thickness of the i-th layer of the enclosing structure, m; λ_i is the thermal conductivity coefficient of the i-th layer of the enclosing structure, W/(m deg).

Based on (8) and (11) we obtain a relation for determining the specific daily average energy consumption values for building heating given a difference between temperatures of the outdoor air and the heated premises of 1°C:

$$q_i = \frac{\left[\sum_i (k_i \cdot f_i) \cdot 10^{-3} + c_a \cdot m_f \right] \cdot \tau_d}{F} \quad (13)$$

Based on (10) and (13), we obtain a ratio that allows us to determine the drainage water flow required to heat the building under the conditions of the minimum average daily outdoor temperature in the absence of information on the value of the actual specific energy consumption of the building:

$$m_{w\max} = \frac{\left[\sum_i (k_i \cdot f_i) \cdot 10^{-3} + c_a \cdot m_f \right] \cdot \tau_d \cdot \Delta t_{\max}}{c_w \cdot \Delta t_w} \quad (14)$$

Considering that the water-to-water heat pump is capable of operating in the passive natural cooling mode, let us estimate the amount of drainage water required to remove excess heat from the premises on the warmest days of the year.

If the amount of heat to be removed from the object of research in summer during the days with the highest average daily temperature corresponds to the amount of heat transferred to the drainage water,

$$Q_{hs} = Q_{ws} \tag{15}$$

where Q_{hs} is the amount of heat to be removed from the object of research in summer during the days with the highest average daily temperature, kJ; Q_{ws} is the amount of heat transferred to drainage water, kJ.

Taking into account the inflow of heat to the building due to heat transfer through the external enclosing structures and infiltration, we obtain a dependency similar to (14):

$$m_{ns} = \frac{\left[\sum_i (k_i \cdot F_i) \cdot 10^{-3} + c_a \cdot m_f\right] \cdot \tau_d \cdot \Delta t_{ns}}{c_w \cdot \Delta t_w} \tag{16}$$

where m_{ns} is the amount of drainage water required to remove excess heat from the premises on the warmest days of the year, kg; Δt_{ns} is the temperature difference between outdoor air and the air in the cooled premises on the warmest days of the summer season, °C.

The minimum required amount of drainage water is taken as the larger of the values obtained from ratios (14) and (16).

4.2. Methodology for assessing the energy characteristics of drainage water heat utilization workflows using a heat pump

The amount of heat energy that needs to be supplied to a heat pump is determined by the amount of heat needed to heat the building and the efficiency of the heat pump.

The method for determining the amount of heat for heating a building is given in the previous section.

The efficiency of a heat pump ε is estimated by the heating coefficient (it is also often called the efficiency factor of energy use, power factor, COP (Coefficient of Performance) conversion factor) (Kirillini et al., 1979):

$$\varepsilon = \frac{q_1}{l_c}, \tag{17}$$

where q_1 is the amount of heat transferred to the heated object, kJ; l_c is the amount of heat consumed during the cycle of work, kJ.

If the reverse Carnot cycle is carried out in the heat pump, then the theoretical value of the heating coefficient of the heat pump will be:

$$\varepsilon = \frac{T_1}{T_1 - T_2} \tag{18}$$

where T_1 is the temperature of the supplying circuit of the heat carrier, K; T_2 is the outdoor temperature, K.

The actual COP of a heat pump is much lower.

During the design of heat pumps, the approximate value of the power factor ε for modern devices may be determined using the empirical formula (Madramootoo et al., 1997):

$$\varepsilon = 0.5\left(\frac{T_1}{T_1 - T_2}\right) \tag{19}$$

Then at a given average daily temperature

$$Q_{h2} = \frac{Q_{h1}}{\varepsilon} \tag{20}$$

where Q_{h1} and Q_{h2} is the daily the amount of energy transferred to the heated object and the daily amount of energy consumed during the cycle, respectively, kJ.

Considering (19), we get:

$$\varepsilon = 0.5\left(\frac{273 + t_{wv}}{t_{wv} - t_{wn}}\right) \tag{21}$$

where t_{wv} is the temperature of the supplying circuit of the heat carrier, °C; t_{wn} is the temperature of the external heat carrier circuit, °C.

The amount of energy transferred to the heated object at a given average daily temperature, similarly to formula (8), is defined as:

$$Qh_1 = q_i \cdot F \cdot (t_{av} - t_{an}) \tag{22}$$

where t_{av} is the air temperature in the heated premises, °C; t_{an} is the outdoor air temperature, °C.

Considering (20) – (22), we get:

$$Q_{h2} = \frac{2q_i \cdot F \cdot (t_{av} - t_{an}) \cdot (t_{wn} - t_{wn})}{(273 + t_{wn})} \tag{23}$$

5. Study results

5.1. Determination of drainage water flow rate for building heating using a heat pump

The methodology described in Section 4.1 was used to assess the efficiency of utilizing physical heat of drainage water using a heat pump to heat a residential building located in a flooded area equipped with a drainage system with a continuous groundwater disposal with a flow rate of m_{wf} = 1500 kg/h.

The heated premises area is F = 100 m^2.

The drainage water temperature, corresponding to the annual average temperature in the region is t_{wn} = 8°C. To prevent water freezing, it is necessary to cool the drainage water with the outer contour of the heat pump to at least 4°C and to heat it to 12°C when cooling the building during summer period.

Specific energy consumption for building heating is q = 120 kWh/m^2 per year.

The climate of the area where the building is located is temperate continental (Dfb according to the Köppen-Geiger climate classification), the average January temperature is −5°C, the duration of the heating season is τ = 180 days, for average temperatures within the heating season see Table 1.

Table 1. Average monthly temperatures during the heating season

Heating season period	October	November	December	January	February	March	April
Average temperature, °C	+8	+1	−4	−5	−4	0	+8

The minimum value of the average daily temperature is -15°C.

The maximum value of the average daily temperature is +28°C.

The average annual temperature of outdoor air is +8°C.

The temperature inside the heated premises is +20°C.

At this object of research the specific average daily energy consumption for building heating given the difference in temperatures between the outdoor air and the heated space is 1°C, based on (7) will be:

$$q_i = \frac{3600 \cdot 120}{(20\text{-}8)\cdot(15+15)+(20\text{-}1)\cdot 30+ +(20+4)\cdot(31+28)+(20+5)\cdot 31} = 138\ kJ/(day \cdot m^2 \cdot \deg)$$

For further calculations, we will take into account the following factors:

- the temperature of drainage water is relatively constant and approaches the average annual air temperatures (Madramootoo et al., 1997);
- specific heat capacity of drainage water is c_w = 4.19 kJ/(kg×°C).

To ensure reliable heating over the entire heating season, it is necessary to ensure sufficient heat supply at the lowest average daily temperature.

Based on this, the expression (10) takes the following form:

$$m_{w\max} = \frac{q_i \cdot F \cdot (20 - t_{an})}{4.19(t_{cp} - 4)} \tag{24}$$

where t_{an} is the minimum average daily temperature, °C; t_{cp} is the average annual temperature of outdoor air, °C.

The drainage water flow required to heat the building at the lowest average daily outdoor air temperature amounts to:

$$m_{w\max} = \frac{138 \cdot 100 \cdot (20+15)}{4.19 \cdot (8\text{-}4)} = 28800\ kg. \tag{25}$$

The amount of drainage water required to remove excess heat from the premises on the warmest days of the year based on the same dependency amounts to:

$$m_{ns} = \frac{138 \cdot 100 \cdot (28-20)}{4.19 \cdot (12-8)} = 6590\ kg. \tag{26}$$

Accordingly, the hourly consumption of drainage water required to dispose excess heat from the premises during the warmest days of the year M_{ns} will be 274 kg.

As it follows from the calculation results, the amount of drainage water required to heat the building at the lowest average daily outdoor temperature is significantly greater than the amount of drainage water required to remove excess heat from the premises on the warmest days of the year.

The actual amount of discharged water equal to 1500 kg/h exceeds the required one, which allows us to conclude that application of this workflow is possible and to initiate a comparative assessment of energy efficiency.

In practice, it is often necessary to determine the area of premises that can be heated by utilizing the physical heat of drainage water, knowing the amount of drainage water discharged from the flooded area.

Based on ratios (7) and (24), we assessed the drainage water consumption required to heat buildings, depending on their area and specific energy consumption, given the climatic conditions of the location of the object of research.

The calculation results are shown in Figure 1.

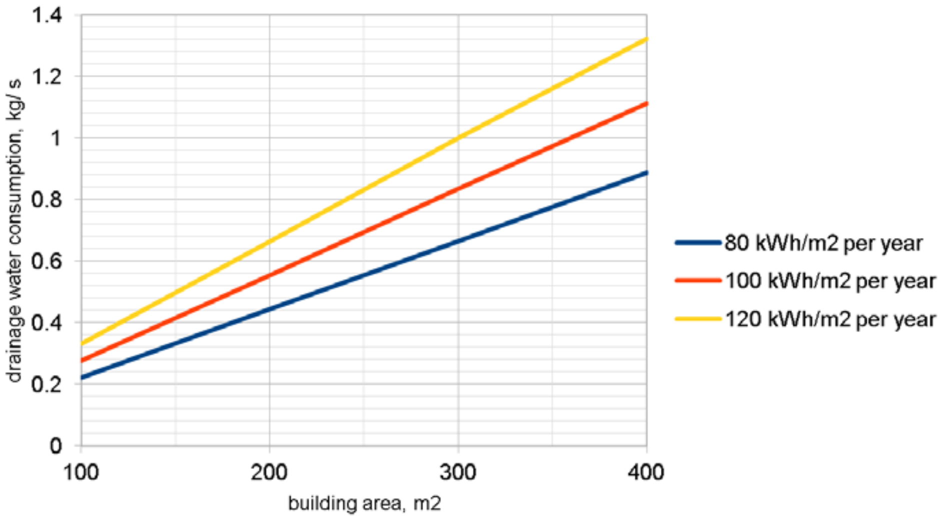


Figure 1. Drainage water consumption for heating the buildings, depending on the area with different specific energy consumption

5.2. Comparative assessment of the efficiency of the proposed building heating workflow

Various heating workflows were analyzed for the object described in the previous section. The following were considered options for heat pump-based heating of buildings:

- use of a heat pump of air-to-water type; the heated premises are equipped with radiators;
- use of a heat pump of air-to-water type; the heated premises are equipped with heat-insulated flooring;
- use of a water-to-water heat pump that utilizes drainage water heat; the heated premises are equipped with radiators;
- use of a water-to-water heat pump that utilizes drainage water heat; the heated premises are equipped with heat-insulated flooring;

Alternatively, an electric boiler-based heating workflow without a heat pump was considered.

Let us compare the energy consumption for heating the object of research under the given climatic conditions for the cases of using an air-to-water, drainage water-to-water heat pump, and an electric boiler.

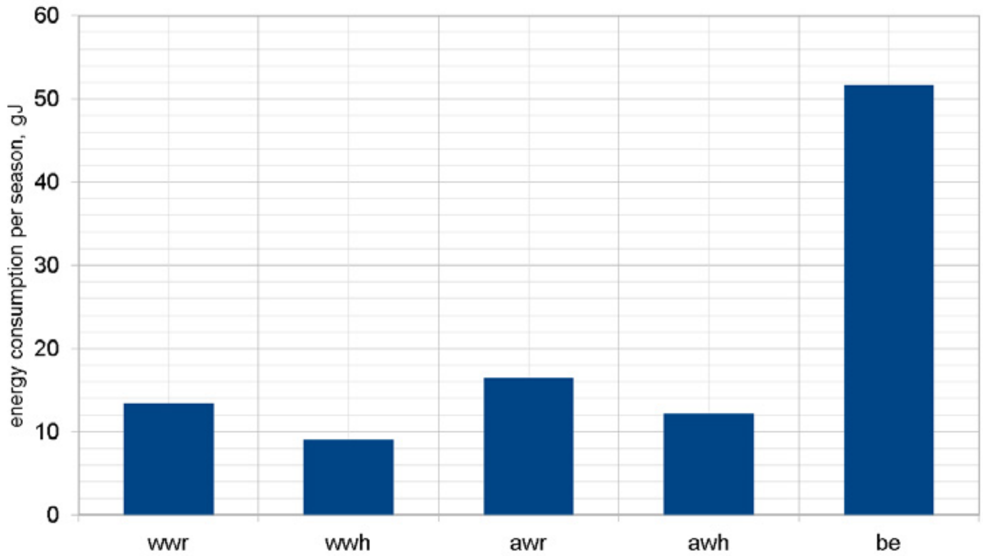
We will use the ratio (23) to determine the amount of energy spent for each month of the heating season at a given average monthly temperature Q_{hm2}, kJ/day, and determine the total amount of energy spent during the heating season.

The results of calculating the amount of energy to heat the object of research supplied monthly and during the heating season for air-to-water and water-to-water heat pumps using radiator heating along with the heat-insulated flooring and for an electric boiler are shown in Table 2.

For the results of calculating the energy consumption for heating the object of research during the heating season using an electric boiler or a heat pump, in cases where the heated premises are equipped with radiators and a heat-insulated flooring system see Figure 2.

Table 2. Values of the amount of energy consumed for each period of the heating season at a given average monthly temperature, Q, GJ

Heating circuit		Heating season period							
		October	November	December	January	February	March	April	Heating season
Electric boiler		2.48	7.87	10.27	10.7	9.27	8.56	2.48	51.63
Air-to-water heat pump	Radiator	0.64	2.38	3.43	3.64	3.1	2.65	0.64	16.48
	Heat-insulated flooring	0.44	1.74	2.67	2.78	2.35	1.75	0.44	12.17
Water-to-water heat pump	Radiator	0.64	2.04	2.67	2.78	2.41	2.22	0.64	13.4
	Heat-insulated flooring	0.44	1.38	1.8	1.88	1.63	1.5	0.44	9.07



wwr – use of a water-to-water heat pump that utilizes drainage water heat; the heated premises are equipped with radiators;
wwh – use of a water-to-water heat pump that utilizes drainage water heat; the heated premises are equipped with heat-insulated flooring;
awr – use of an air-to-water heat pump; the heated premises are equipped with radiators;
awh – use of an air-to-water heat pump; the heated premises are equipped with heat-insulated flooring;
be – use of an electric boiler

Figure 2. The results of calculating the energy consumption for heating the object of research. The figure uses the following designations:

As a result of the comparative assessment, we found that for the climatic conditions of the object of research, the use of a "water-to-water" heat pump, utilizing the drainage water heat, and equipment of the heated premises with the heat-insulated flooring system reduces energy consumption for heating during the heating season by 5.7 times as compared to the use of an electric boiler and by 1.34 times as compared to the use of an air-to-water heat pump.

In case of equipping the heated premises with a radiator heating system, the energy savings are somewhat less, and are reduced, respectively, by 3.85 and 1.23 times.

The results of calculating the energy consumption for heating the object of research during the heating season when using an electric boiler, a heat pump, for the case when the heated premises are equipped with radiators are shown in Figure 3.

The blue color in the figure shows the average energy cost for each month of the heating season for heating the research object when using an electric boiler.

Red – an air-water heat pump that uses the heat of the outside air when it provides the heated space with radiators.

Yellow – a heat pump that uses the heat of waste water when the heated space is equipped with radiators.

From the figure it is clear that the use of a heat pump ensures a reduction in energy costs throughout the heating season.

The advantages of the proposed scheme for the use of drain water heat are visible in the coldest months of the heating season.

At the beginning and end of the heating season, when the air temperature differs only slightly from the average annual air temperature and the temperature of the drain water, the benefits of the proposed scheme are minimal.

The results of calculating the energy consumption to heat the object of research during the heating season when using an electric boiler, a heat pump, for the case where the heated premises are equipped with the heat-insulated flooring system are shown in Figure 4.

The average energy cost for each month of the heating season for heating the research object with an electric boiler remained the same as in the case of equipping a heated room with radiators.

The energy costs for heating the research object when using a heat pump, if the heated space is equipped with a "warm floor" system, decreased in comparison with the option of equipping the heated space with radiators.

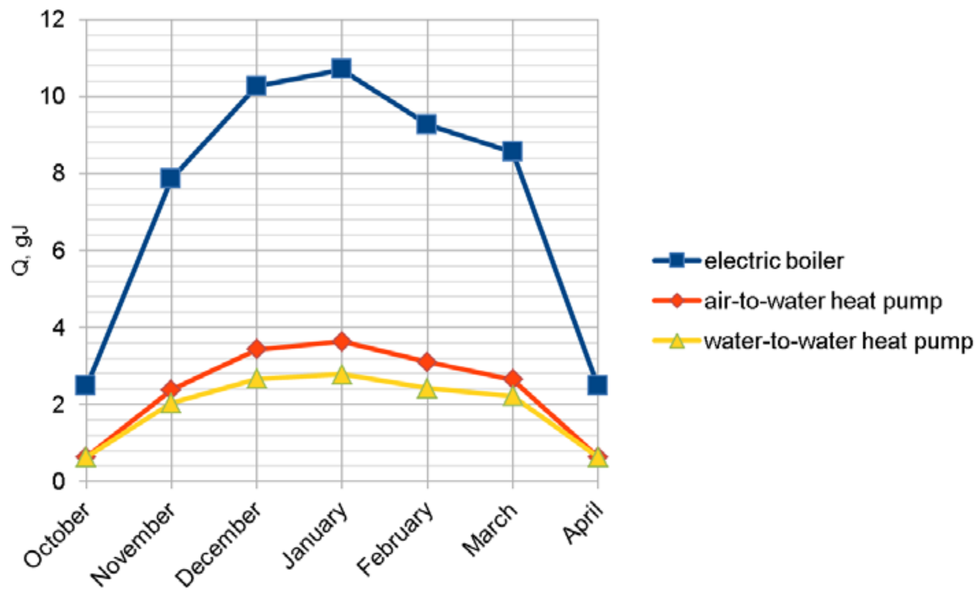


Figure 3. The results of calculating the energy consumption for heating the object of research when using an electric boiler, a heat pump, and given the premises are equipped with radiators

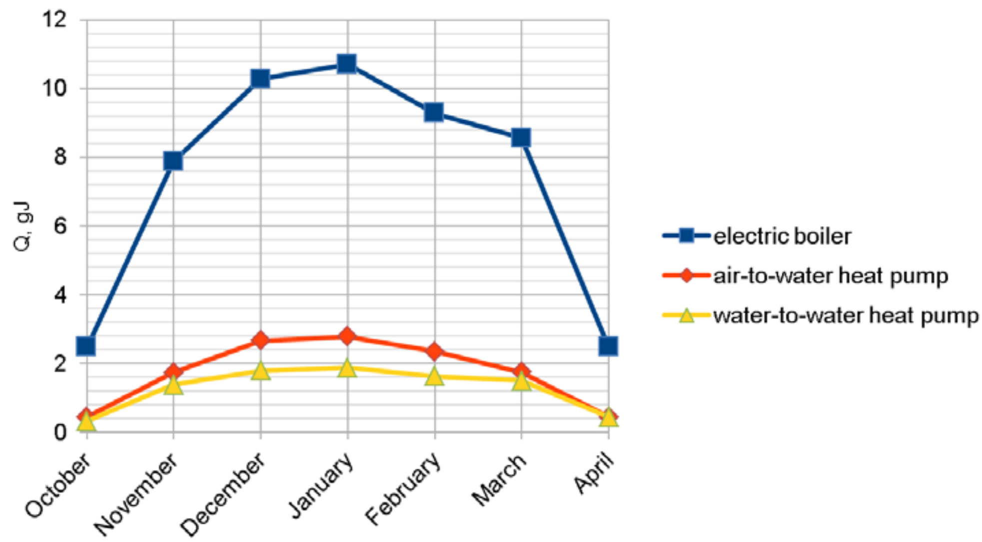


Figure 4. The results of calculating the energy consumption for heating the object of research when using an electric boiler, a heat pump, and given the premises are equipped with radiators

The maximum reduction in energy costs occurs when using a heat pump that uses the heat of the wastewater and when the heated space is equipped with a "warm floor" system.

6. Discussion

The results of the study make it possible to determine the minimum required average daily consumption of drainage water to heat a building, taking into account the thermal characteristics of the building and climatic conditions.

Based on the comparative assessment we found that for the climatic conditions of the object of research, application of a "water-to-water" heat pump utilizing the drainage water heat, and equipping the heated premises with the heat-insulated flooring system reduce energy consumption for heating during the heating season by 5.7 times as compared to the cases of using an electric boiler and by 1.34 times as compared to the cases of using an air-to-water heat pump.

In case of equipping the heated premises with a radiator heating system, the energy savings are somewhat less, and are reduced, respectively, by 3.85 and 1.23 times.

The "drainage water-heat pump-heat-insulated flooring" workflow allows to reduce the energy consumption by 1.48 times as compared to the use of the air-to-water heat pump in the coldest month of the heating season, and by 2.3 times during the period of minimum values of average daily temperatures.

Depending on the thermal characteristics of the building and the climatic conditions the obtained results allow to determine the value of the required drainage water flow rate to heat the building.

Conclusions and recommendations

The technological workflow was substantiated, which makes it possible to utilize the thermal energy of drainage water discharged from flooded urbanized areas for heating residential buildings.

A comparative assessment of the energy efficiency of the proposed and traditional heating systems was carried out. We found that the use of a heat pump in combination with the heat-insulated flooring system reduces energy consumption by 5.7 times.

A comparative assessment of the energy efficiency of the proposed heating workflow and the efficiency of widely used air-to-water heat pumps in combination with the heat-insulated flooring system was carried out. We found that the use of the proposed heating workflow reduces energy consumption by 2.3 times.

References

Akbarzadeh P., Nejad A.A., Movahed F. & Zolfaghari S., 2018, A new approach to numerical investigation of gfx and power-pipe drain water heat recovery (dwhr) systems in buildings. Heat Transfer Research 49(14): 1339-1352. doi:10.1615/HeatTransRes.2018016060

DBN V.2.6-31, 2016, Thermal insulation of construction DBN V.2.6-31, 2016, Minregion of Ukraine, Kyiv. https://www.minregion.gov.ua/wp-content/uploads/2017/02/DBN-V.2.6-31-2016-Teplova-izolyatsiya-budivel.pdf (in Ukrainian).

Dobrovicova S., Dobrovic R. & Dobrovic J., 2015, The economic impact of floods and their importance in different regions of the world with emphasis on Europe. Procedia Economics and Finance 34: 649-655. (in Russian).

Heat pumps in modern industry and communal infrastructure. Informational – methodical edition, 2016, Publishing House "Pero", Moscow 204 pp. https://mpei.ru/personal/Lists/CadrePapers/Attachments/2000/%D0%92 %D0%B5%D1%80%D1%81%D1%82%D0%BA%D0%B0%20%D1%87%D0%B8%D1%81%D1%82%D0%BE%D0%B2%D0%B0%D1%8F.pdf (in Russian).

Kirillini V.A. Sychev V.V. & Sheindlin A. E., 1979, Technical thermodynamics: monograph. Nauka, Moscow, 512 pp. (in Russian).

Kostenko E., Melnyk L., Matko S. & Malovanyy M., 2017, The use of sulphophtalein dyes immobilized on anionite Ab-17X8 to determine the contents of Pb(Ii), Cu(Ii), Hg(Ii) and Zn(Ii) in liquid medium. Chemistry & Chemical Technology 11(1): 117-124. doi:10.23939/chcht11.01.117.

Kordana-Obuch S., 2017, SWOT analysis of wastewater heat recovery systems application. Paper presented at the E3S Web of Conferences, 17. doi:10.1051/e3sconf/20171700042

Kordana-Obuch S., Pochwat K., Słyś D. & Starzec M., 2019, Opportunities and threats of implementing drain water heat recovery units in Poland. Resources 8(2): 88. doi:10.3390/resources8020088

Madramootoo Ch.A., Johnston W.R. & Willardson L.S., 1997, Management of Agricultural Drainage Water Quality. Food and Agriculture Organization of the United Nations, Rome, 94 pp.

Malyovanyy M., Sakalova, G., Chornomaz N. & Nahurskyy O., 2013, Water sorption purification from ammonium pollution. Chemistry and Chemical Technology 7(3): 355-358. doi:10.23939/chcht07.03.355

Matsevity Yu.M., Chirkin N.B. & Klepanda A.S., 2014, About the use of heat pumps in the world and what hinders their large-scale implementation in Ukraine. Energy saving. Energy. Energy audit No. 2(120): 2-16. (in Russian).

Medvedkov K.S. & Shtripling L.O., 2017, Analysis of the flooded area using the example of groundwater in the city of Nazyvaevsk. Bulletin of the Tomsk Polytechnic University. Engineering of Georesources Vol. 328, No. 4: 85–93. (in Russian).

Nifontova L.S., Rudi D.Yu. & Khalitov N.A., 2016, Analysis of the types of heat pumps. Technical Sciences 5(47), Part 3: 145-149. (in Russian).

Sakalova H., Malovanyy M., Vasylinych T. & Kryklyvyi R., 2019, The Research of Ammonium Concentrations in City Stocks and Further Sedimentation of Ion-Exchange Concentrate. Journal of Ecological Engineering 20(1): 158-164. doi: 10.12911/22998993/93944

Sait M.A., Chigbu U.E., Hamiduddin I. & De Vries W.T., 2019, Renewable energy as an underutilised resource in cities: Germany's 'energiewende' and lessons for post-brexit cities in the united kingdom. Resources 8(1): 7. doi:10.3390/resources8010007

Sedin V.L. & Grabovets O.N., 2018, Distribution of distructive underflooding in the territory of Ukraine. Bulletin of Prydniprovska State Academy of Civil Engineering and Architecture 5: 245-246. doi: 10.30838/J.BPSACEA.2312.271118.24.362

Seybold C. & Brunk M., 2017, Wastewater heat utilization. Heat pumps 1: 29-34.

Sirko Z.S., Korenda V.A., Vyshnyakov I.Y., Protasov O.S., Okhrimenko S.M. & Tsiren N.L., 2020, Use of heat pumps for heating and hot water supply of buildings of enterprises on the example of HELIOTERM installations. Scientific reports of NULES of Ukraine No. 5 (87). (in Ukrainian).

Tulaydan Y., Malovanyy M., Kochubei V. & Sakalova H., 2017, Treatment of high-strength wastewater from ammonium and phosphate ions with the obtaining of struvite. Chemistry & Chemical Technology 11(4): 463-468. doi: 10.23939/chcht11.04.463

Tymchuk I., Malovanyy M., Shkvirko O. & Yatsukh K., 2021, Sewage sludge as a component to create a substrate for biological reclamation. Ecological Engineering and Environmental Technology 22(4): 101-110. doi:10.12912/27197050/137863

Tymchuk I., Shkvirko O., Sakalova H., Malovanyy M., Dabizhuk T., Shevchuk O., Matviichuk O. & Vasylinych T., 2020, Wastewater a source of nutrients for crops growth and development. Journal of Ecological Engineering 21(5): 88-96. doi:10.12911/22998993/122188

Vranayova Z., Kaposztasova D. & Poorova Z., 2018, Water management of "Smart" buildings and cities. Czasopismo inżynierii lądowej, środowiska i architektury [Journal of Civil Engineering, Environment and Architecture, JCEEA], Vol. XXXV, No. 65 (1/18), Styczeń-marzec, p. 45-52.

Zakharov A.V., Zabalueva T.R. & Saud Ya.M., 2021, An economical way to ensure thermal comfort in the premises of cottages built in a subtropical climate zone, as exemplified by the city of Kasab (Syria) . "Innovation and investment" 4: 251-255. (in Russian).

Zhidovich I.S., 2017, The use of heat pumps in heat supply and hot water supply systems for multi-apartment housing on the principles of energy conservation. United Nations Development Program in the Republic of Belarus / Global Environment Facility / Energy Efficiency Department of the State Standard of the Republic of Belarus. Minsk, 30 pp. (in Russian).