EKSERGETSKA ANALIZA GREJANJA OBJEKTA GEOTERMALNOM TOPLOTNOM PUMPOM VODA–VODA

EXERGY ANALYSIS OF BUILDING HEATING WITH A GROUNDWATER SOURCE HEAT PUMP

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U radu je prikazana eksergetska analiza rada geotermalne toplotne pumpe voda–voda za potrebe grejanja objekta. Analiza je sprovedena na mesečnom novou, s obzirom na zavisnost eksergije od promenljivog stanja okoline. Analizirane su promene koeficijenta grejanja i eksergetskog stepena korisnosti grejnog sistema geotermalne toplotne pumpe u zavisnosti od uticajnih parametara: temperature podzemne vode u crpnom bunaru, promene temperature podzemne vode na isparivaču toplotne pumpe i temperature vode u grejnom sistemu. Dobijeni rezultati daju uvid u termodinamičke pokazatelje rada toplotne pumpe u zavisnosti od temperature podzemne vode i režima rada grejnog sistema objekta. Sprovedena analiza pruža smernice za projektovanje i optimizaciju rada toplotnih pumpi koje rade sa podzemnom vodom kao izvorom toplote.

Ključne reči: *Geotermalna toplotna pumpa voda–voda; eksergetska analiza; energetska analiza; grejanje*

The paper presents an exergy analysis of the groundwater heat pump operation for the needs of building heating. The analysis was conducted on a monthly basis, given the dependence of exergy on the changing state of the environment. Changes in heating coefficient and exergy efficiency of the geothermal heat pump heating system depending on the influential parameters were analyzed: groundwater temperature from the pumping well, changes in the groundwater temperature on the heat pump evaporator and water temperature in the heating system. The obtained results provide insight into thermodynamic indicators of heat pump operation depending on the groundwater temperature and the operation mode of the building heating system. The conducted analysis provides guidelines for the design and optimization of heat pumps that work with groundwater as a heat source.

Key words: *Groundwater heat pump; exergy analysis; energy analysis; heating*

1 Introduction

Ground source (geothermal) heat pump (GSHP) systems that use water from an underground aquifer as a heat source, which they return to the ground after heat recovery, are known as open-loop GSHP system or groundwater heat pump (GWHP) systems. From a thermodynamic point of view, GWHP systems have an advantage in terms of higher coefficient of performance compared to other GSHP systems. This is due to the characteristics of the groundwater, which is used directly: its large specific heat capacity and relatively high, almost constant temperature throughout the year. GWHP systems represent an attractive alternative to conventional heating systems in residential and commercial buildings, as they use a small amount of primary energy and have low greenhouse gas emissions [1,2]. An indicator that this type of heating system has gained in importance is the continuous increase in the number of these facilities in the previous more than two decades. The annual increase in the installed capacity of the GSHP systems in the period from 2010 to 2015 is over 10% [3].

The analysis of energy and exergy parameters of the GWHP system is the subject of many papers. Sartor and Dewallef [4] compared the energy and exergy needs of different heating systems on the example of four different types of buildings. Their results showed that the best heating system is a heat pump connected to the domestic heat network. Gojak and Bajc [5] also came to the conclusion that the use of the heat pumps is a much better choice for the building heating needs, than the use of high-quality energy sources. This is the result of an exergy analysis of various energy sources use (electricity, natural gas, district heating, coal and renewable energy sources) for the needs of building heating and sanitary hot water preparation. Energy and exergy analysis of different heating systems on the building adopted model and at given indoor and outdoor air temperatures was performed by Balta et al. [6]. They came to the conclusion that, after the heating system with solar collectors, the GWHP system has the highest total exergy efficiency and sustainability index. Sangi and Müller [7] performed an exergy analysis of the building energy system on the example of a GSHP system. Using the concept of an ideal heat source (not taking into account variations in ambient temperature), and for a different number of control volumes, they determined lower exergy losses for the heating and cooling regime, compared to the conventional approach. Based on that, they concluded that this approach may represent only a starting point for further analysis. Pitarch et al. [8] performed exergy analysis of each heat pump component separately and based on that, they performed optimization of heat pump operating parameters.

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In this paper, an energy and exergy analysis of the influential parameters on the performance of the GWHP system was performed. The influence of the monthly final energy needs for heating the building and the operating mode of the building heating system was analyzed, as well as the influence of the groundwater temperature and the change of the groundwater temperature on the heat pump evaporator.

2 Thermodynamic (exergy and energy) analysis of GWHP system operation

2.1 Case study

Thermodynamic analysis of GWHP system operation was conducted on the model of a building - residential house of 180 m^2 with good thermal insulation, built after 2002 in the climatic region of Belgrade, Serbia. It has been adopted that the final energy use per square metre of the building (specific energy use) for the heating energy needs is 50 kWh/(m^{2}a) [9]. The GWHP system meet the final annual heating energy in the amount of 9.000 kWh/a. Figure 1. shows the monthly demand for indoor air heating, determined by applying an analysis based on the heating degree days.

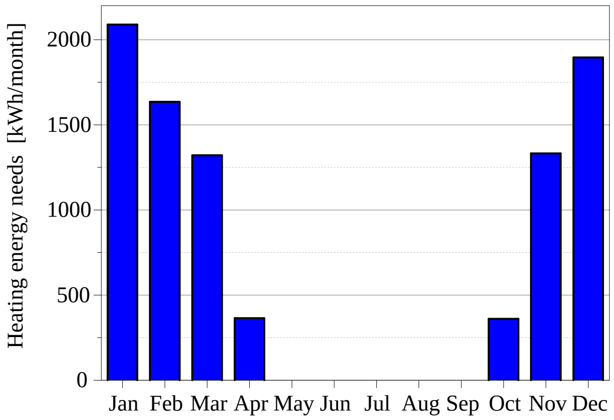


Figure 1. The monthly demand for building heating during the heating season

The entire GWHP heating system consists of three subsystems: the external subsystem of the facility, which represents the connection of the system with the ground, then the heat pump and the internal subsystem of the facility, i.e. the heating system of the building (Figure 2).

System connection with the ground is established by a pair of coupled wells - pumping and injection well. The external circuit of groundwater circulation from pumping to injection well is established by the operation of the circulating pump 1 - submerged pump in groundwater side. Groundwater flows through the evaporator, transfers heat to the working fluid of the heat pump, cools and returns to the injection well. On the other hand, the flow of heated water in the heating system of the building is established by means of a circulating pump 2 - heated water circulating pump. The return heating water from the building heating system flows through the condenser, receives heat from the working fluid of the heat pump and is heated. Thus heated water to the distribution temperature flows through the heating system and transfers heat to the building.

The characteristics of the comparative GWHP system, in relation to which the parametric analysis is performed, are: groundwater temperature regime - $t_{gw,in}/t_{gw,out}$ = 12/7°C ($t_{gw,in}$ - groundwater temperature that is pumped from the well and enters the control volume, $t_{gw,out}$ - groundwater temperature at the outlet of the control volume returning to the ground); the depths of the pumping and injection wells are 30 meters; temperature regime of the heating system - $t_{hw,out}/t_{hw,in}$ = 35/30°C, which corresponds to the floor heating system ($t_{hw,out}$ - temperature of distributive heating water, $t_{hw,in}$ - temperature of return heating water).

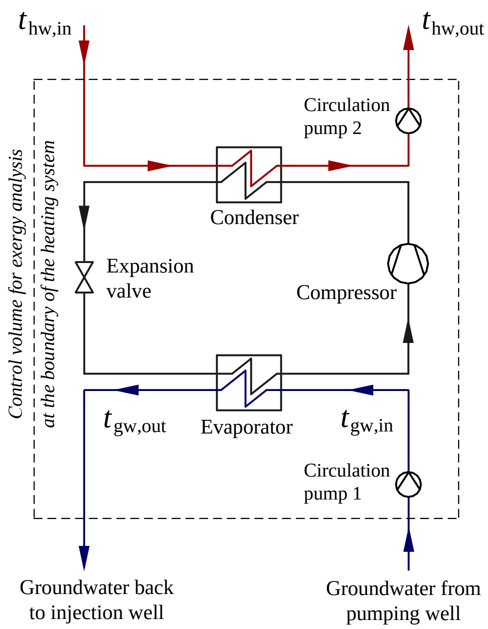


Figure 2. Schematic illustration of the GWHP system

The working fluid of the heat pump is R407C. The operating parameters of the heat pump are defined by the temperature regimes of the external and internal subsystem. It was adopted that the difference between the evaporation temperature of the heat pump working fluid and the groundwater temperature at the evaporator outlet is constant and is

5°C, while the condensing temperature of the heat pump working fluid is equal to the heating water temperature at the outlet of the condenser [10]. Compressor and circulation pumps efficiencies are 0,85.

2.2 Theoretical basis

Based on the law of energy conservation applied to the geothermal heat pump system, heat transfered to distribution heating system in building, i.e. heat pump heating load $\dot{Q}_{\mathrm{h}}$, equal the sum of electrical consumption of compressor P_{comp} and heat extracted from groundwater $\dot{Q}_{\mathrm{evap}}$:

$$\dot{Q}_{\mathrm{h}} = \dot{Q}_{\mathrm{evap}} + P_{\mathrm{comp}} \quad . \tag{1}$$

The energy quality of the heat pump cycle is defined by the Coefficient of Performance (COP):

$$COP = \frac{\dot{Q}_{\mathrm{h}}}{P_{\mathrm{comp}}} \quad . \tag{2}$$

Overall heating coefficient of performance of the GWHP system, which considers the energy characteristic of the coupled heat pump cycle and the operation of circulating pumps, is defined by the Energy Efficiency Ratio (*EER*):

$$EER = \frac{\dot{Q}_{\mathrm{h}}}{P_{\mathrm{comp}} + P_{\mathrm{pump}}} \tag{3}$$

where $P_{\mathrm{pump}} = P_{\mathrm{building}} + P_{\mathrm{well}}$, of which P_{building} and P_{well} represents the electrical consumptions of heated water circulating pump and submerged pump in groundwater side, respectively.

Energy analysis is a method that evaluates the way energy is used in a system and determines how efficient the use of that energy is. According to the law of energy conservation, energy can neither be created nor destroyed, but can be converted from one form to another. This law does not recognize the quality of energy. All forms of energy are not of the same quality and are not mutually equivalent. They do not have the same possibilities of converting into other forms of energy and exploitation. Therefore, energy analysis does not provide information on the quality of energy flows in the system. For this reason, it is recommended by many scientists and engineers that in order to conduct a comprehensive thermodynamic analysis, it is necessary, in addition to energy, to conduct an exergy analysis [11]. Exergy or work ability is part of the system energy that can be converted into useful mechanical work as it comes to a state of thermodynamic equilibrium with a reference environment. No exergy is destroyed during a reversible process, but part of the exergy is destroyed during irreversible one. Exergy efficiency is an indicator of how much the quality of the process deviates from the ideal return process.

Equation (4) represents the total exergy of the fluid flow:

$$\dot{E}x = \dot{m} \cdot ex \tag{4}$$

where $\dot{m}$ represents the mass flow of fluid entering or leaving the system. For the exergy analysis in this study, exergies of macroscopic kinetic and potential energy of fluid flow were neglected. It follows that the specific exergy of a fluid flow (*ex*) is equal to its physical part of the exergy:

$$ex = h - h_0 - T_0 \cdot (s - s_0) \tag{5}$$

where h and s represent the specific enthalpy and entropy of a working substance, while h_0 and s_0 correspond to the specific values of working substance enthalpy and entropy at the state of reference environment. In this paper, the state of the outdoor air, defined by the average monthly temperature t_0 [12] and atmospheric pressure p_0 = 1atm was adopted for the reference state of the environment.

The exergy change rate gained by groundwater as a renewable energy source is given by:

$$\Delta\dot{E}x_{\mathrm{gw}} = \dot{m}_{\mathrm{gw}} \cdot (h_{\mathrm{gw,in}} - h_{\mathrm{gw,out}} - T_0 \cdot (s_{\mathrm{gw,in}} - s_{\mathrm{gw,out}})) \tag{6}$$

while the exergy change rate delivered to the water in the heating system is calculated by the following:

$$\Delta\dot{E}x_{\mathrm{hw}} = \dot{m}_{\mathrm{hw}} \cdot (h_{\mathrm{hw,out}} - h_{\mathrm{hw,in}} - T_0 \cdot (s_{\mathrm{hw,out}} - s_{\mathrm{hw,in}})) \tag{7}$$

where subscripts "in" and "out" refer to a fluid flow of groundwater or heating water at the inlet and outlet of the control volume (see Figure 2).

Exergy efficiency of the GWHP system at the boundary of the heating system can be determined on the basis of the expression:

$$\eta_{\mathrm{ex,hw}} = \frac{\Delta\dot{E}x_{\mathrm{hw}}}{\Delta\dot{E}x_{\mathrm{gw}} + P_{\mathrm{comp}} + P_{\mathrm{pump}}} \quad . \tag{8}$$

The exergy balance for a system whose control volume includes the entire heating GWHP system and the air inside the building may be written as follows:

$$\Delta\dot{E}x_{\mathrm{gw}} + P_{\mathrm{comp}} + P_{\mathrm{pump}} = \dot{E}x_{\mathrm{a}} + \dot{E}x_{\mathrm{dest}} \tag{9}$$

where $\dot{E}x_{\mathrm{dest}}$ represents the exergy losses of the system per unit time.

The exergy rate transferred to the air in the building by heating system, required to maintain the indoor air temperature at a value of 20°C (T_i = 293K), is given by:

$$\dot{E}x_{\mathrm{a}} = \dot{Q}_{\mathrm{h}}\left(1 - \frac{T_0}{T_{\mathrm{i}}}\right) \quad . \tag{10}$$

It follows that the total exergy efficiency can be defined as [13]:

$$\eta_{\mathrm{ex,a}} = \frac{\dot{E}x_{\mathrm{a}}}{\Delta\dot{E}x_{\mathrm{gw}} + P_{\mathrm{comp}} + P_{\mathrm{pump}}} \quad . \tag{11}$$

The total exergy efficiency calculated in relation to the primary energy is:

$$\eta_{\mathrm{ex,p}} = \frac{\dot{E}x_{\mathrm{a}}}{(P_{\mathrm{comp}} + P_{\mathrm{pump}}) \cdot F_{\mathrm{p}}} \tag{12}$$

where F_p is the primary energy factor for electricity (F_p = 2,5 [12]).

In the previous expressions, the operation of all circulating pumps was taken into account (as well as the pump that enables the circulation of groundwater from the pumping to the injection well), so it was taken that the groundwater energy is completely renewable energy (F_p = 0).

2.3 *Methodology*

The analysis was conducted through three series of independent calculations in which changes in the stated energy and exergy parameters of the system were analyzed. In relation to the comparative GWHP system in each series of calculations all but one operating parameter were fixed. Influential variable parameters, i.e. parameters whose impact on the efficiency were analyzed, were:

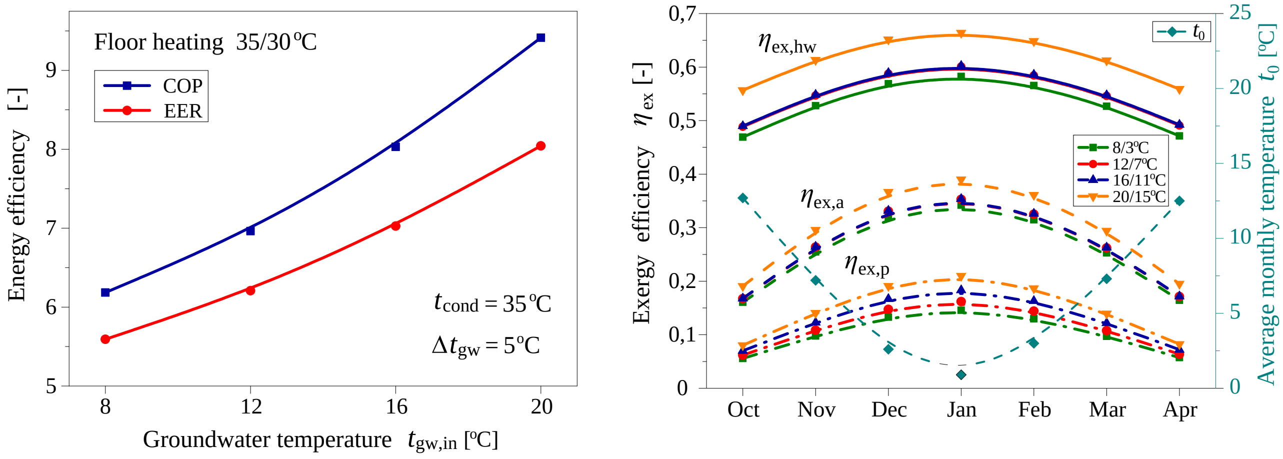
- groundwater temperature from the pumping well ($t_{gw,in}$),
- change in groundwater temperature on the heat pump evaporator (Δt_{gw}),
- temperature operation mode of the heating system ($t_{hw,out}/t_{hw,in}$).

Based on the known phase change temperatures of the heat pump working fluid (t_{cond} - condensation temperature and t_{evap} - evaporation temperature), its thermodynamic values in the characteristic states were determined. Knowing them and the values of the heat pump heating load, the operating parameters of the system were determined: mass flows of the heating water, groundwater and heat pump working fluid, then the electrical consumption of heat pump compressor and circulation pumps, next the exergy of groundwater and heating water flows, as well as the exergy rate transferred to the indoor air. Based on these quantities, the energy and exergy efficiencies of the analyzed system were determined.

3 Results and discussion

First, the impact of groundwater temperature from the pumping well ($t_{gw,in}$) on the change of energy and exergy parameters of the GWHP system was analyzed. The heating system of the building is floor heating (35/30°C) and the heat pump works with a constant change in groundwater temperature on the evaporator of 5°C. The calculation results are shown in Figure 3.

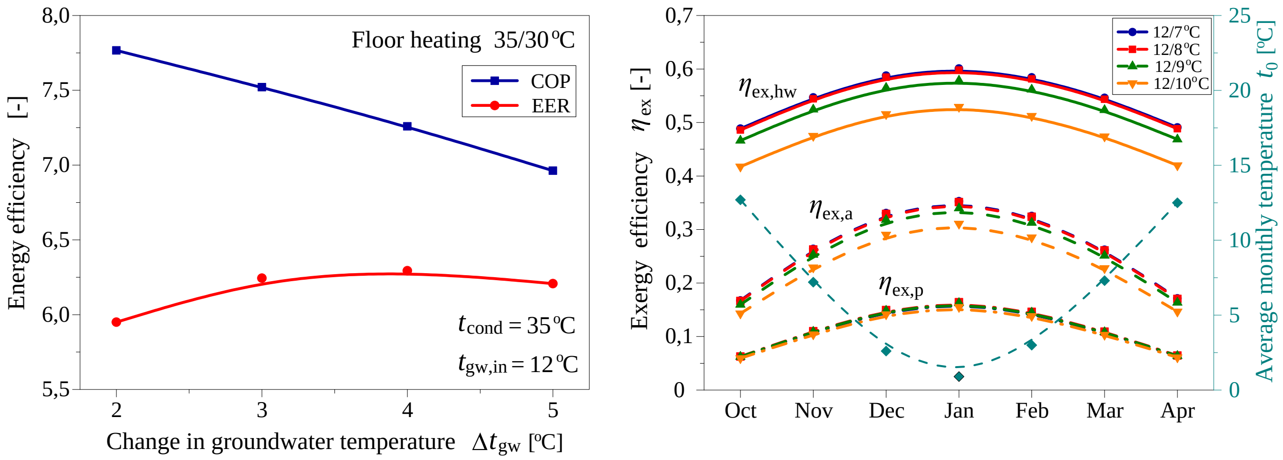
Figure 3.a shows that the increase in groundwater temperature leads to an increase in the COP and EER of the geothermal heat pump system. Namely, coupled with the increase in the groundwater temperature, there is an increase in the evaporation temperature of the heat pump working fluid, which leads to a decrease in the electrical consumption of heat pump compressor (P_{comp}). For the same heat pump heating load, this leads to an increase in the heat flow delivered by the groundwater, as the heat source. Simultaneously with the increase in the groundwater flow, the electrical consumption of submerged pump in groundwater side (P_{well}), also increases. Therefore, the percentage difference between the COP and EER increases with groundwater temperature $t_{gw,in}$.



a) *b)*

Figure 3. The impact of groundwater temperature on: a) COP and EER, b) differently defined exergy efficiencies of GWHP system

Then, the impact of the groundwater temperature change on the heat pump evaporator (Δt_{gw}) on the thermodynamic parameters of the GWHP system was analyzed. The heating system of the building is floor heating (35/30°C), while the groundwater temperature from the pumping well is $t_{gw,in}$ = 12°C. Figure 4 shows the results of the analysis.

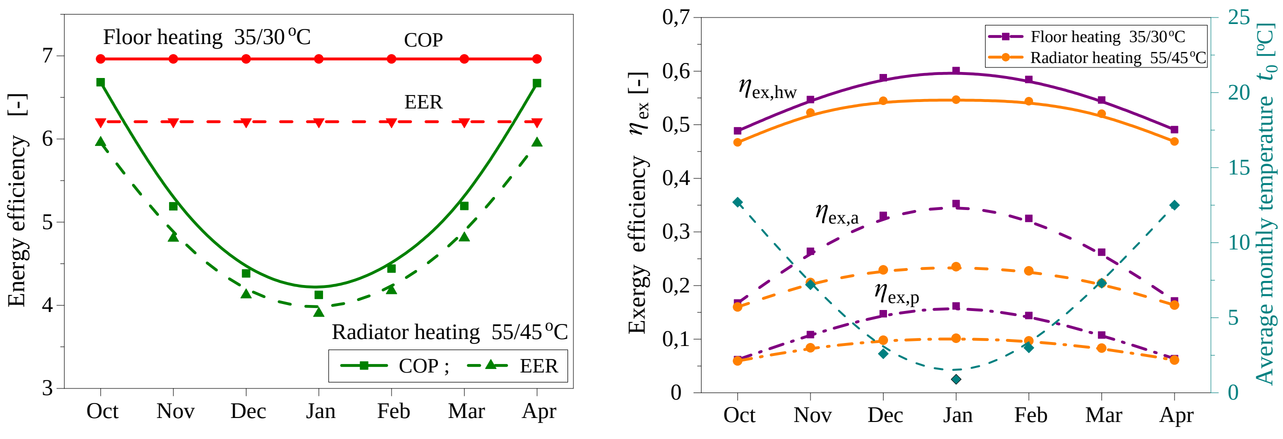


a) *b)*

Figure 4. The impact of change in groundwater temperature on: a) COP and EER, b) differently defined exergy efficiencies of GWHP system

An increase in the COP with a decrease in the groundwater temperature change on the heat pump evaporator is clearly seen in Figure 4.a. When it comes to the EER, it shows a different dependence. The EER first increases slightly and reaches a maximum, and with a further decrease in the groundwater temperature change the EER decreases. This can be explained by the fact that coupled with a decrease in Δt_{gw} there is an increase in the evaporation temperature. This, as in the previous analysis, with unchanged heat pump heating load, affects the reduction of the compressor electrical consumption P_{comp} and the increase in the electrical consumptions of the submerged pump in groundwater side P_{well}. The dependence of the P_{well} increase with the decrease of Δt_{gw} acquires a steep character, due to the large increase in the required groundwater flow, which causes a decrease in the EER.

Finally, the impact of heating system temperature regime on the change of GWHP system energy and exergy parameters was analyzed. The system operates at groundwater temperature regime 12/7°C and groundwater temperature change on the heat pump evaporator of 5°C. The analysis compared the temperature operating mode of the floor heating system ($t_{hw,out}/t_{hw,in}$ = 35/30°C) with the radiator heating system ($t_{hw,out}/t_{hw,in}$ = 55/45°C). In order to regulate the heat transfer to the room for the radiator heating system, the temperature values of the distribution and return heating water were adjusted with the change of the outdoor air temperature. The calculation results are given in Figure 5.



a) *b)*

Figure 5. The impact of heating system temperature operation mode on: a) COP and EER, b) differently defined exergy efficiencies of GWHP system (groundwater temperature regime 12/7°C, t_{evap}=2°C)

By analyzing the results shown in Figure 5.a, it can be concluded that an increase in the mean heating water temperature results in a decrease in both heating coefficients, COP and EER. This can be explained by the fact that combined with the increase of the distributive heating water temperature, there is an increase in the condensation temperature, which results in an increase in the compressor electrical consumptions P_{comp}. Simultaneously with the increase of P_{comp} and with unchanged heat pump heating load, the heat flow delivered by the heat source - groundwater decreases. This results in a groundwater flow reduction which causes a reduction in the electrical consumption of submerged pump in groundwater side P_{well}. The flow of water in the heating system of the building, and thus the electrical consumptions of heated water circulating pump $P_{building}$, with the increase of the mean heating temperature also decreases. For this reason, in January, at the lowest monthly outdoor air temperature and the highest heating water temperatures in the case of radiator heating, the energy parameters of the GWHP system, COP and EER, are the lowest.

Based on the analysis, it can be concluded that the increase in COP occurs with an increase in groundwater temperature, with a decrease in the groundwater temperature change on the heat pump evaporator and with a decrease in the mean water temperature within the heating system. This results in an increase in the energy that groundwater, as a renewable source, transmits to the GWHP system, at the same heat pump heating load. It is important to note that the groundwater energy delivered to the system during one heating season should be determined on the basis of the seasonal coefficient of performance (SCOP) [14]. In order to determine SCOP, it is necessary to conduct an hourly analysis of the demand for indoor air heating. However, the analysis conducted on a monthly basis is the first approximation in determining the energy from renewable source captured by the heat pump system.

The dependences of the GWHP system exergy efficiencies, defined for different control volumes, from the influential parameters are shown in Figures 3.b, 4.b and 5.b. The diagrams show that the changes in the exergy efficiency of the GWHP at the heating system boundary ($\eta_{ex,hw}$), then the total exergy efficiency of the system ($\eta_{ex,a}$) and the exergy efficiency calculated in relation to the primary energy ($\eta_{ex,p}$) correspond to the change of the overall heating coefficient of performance of the GWHP system (EER). Based on the large difference between the exergy efficiency $\eta_{ex,hw}$ and the total exergy efficiency $\eta_{ex,a}$ it can be concluded that the exergy losses in the heating system of the building, during the heat transfer to the air in the heated room, are high. This is a consequence of heat transfer at final temperature differences. The results shown in Diagram 5.b show that the total exergy efficiency of radiator heating is lower than the total exergy efficiency of floor heating. Heat transfer between the heating water and the indoor air during radiator heating is performed at a larger temperature difference. As a result, the irreversibility of the heat transfer process increases, i.e. the losses of exergy increase, so the total exergy efficiency is lower. Seasonal values of the total exergy efficiency, calculated in relation to the primary energy ($\eta_{ex,p}$), have values in the range of 0,11 to 0,16 in the case where the heat pump system is connected to the floor heating in the building and for all analyzed system operating parameters. In the case when the radiator heating in the building is an internal subsystem of the GWHP system, $\eta_{ex,p}$ has a value of 0,088. When it comes to seasonal values of the total exergy efficiency for systems that use conventional energy sources for heating (coal, gas, electricity), they are lower than 0,05 [5], i.e. they have lower values than the GWHP system.

4 Conclusion

Based on the conducted thermodynamic analysis of the GWHP system, used for the needs of heating the building, it can be concluded that:

- the EER and differently defined exergy efficiencies of GWHP system increase with the decrease of the temperature regime in the heating system and with the increase of the groundwater temperature;
- there is an optimal change in groundwater temperature on the heat pump evaporator at which the EER and exergy efficiency have a local maximum;

- proper selection of control volumes for which exergy analysis is performed can monitor exergy flows from groundwater, as a renewable heat source, to the air in the room, as a heat sink;
- there is a significant loss of exergy in the heating system of the building, which is a consequence of heat transfer at the final temperature difference;
- the total exergy efficiency of the system calculated in relation to the primary energy has small value because the heat pump is powered by electricity that is in Serbia predominantly derived from thermal power plants and whose primary energy factor is 2,5. The total exergy efficiency of the GWHP system could be increased if energy from renewable sources was used to drive the heat pump;
- seasonal values of the total exergy efficiency of the GWHP system are significantly higher than in cases when heating systems use conventional energy sources, thus confirming the validity of GWHP system for heating the building.

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