

Exergy analysis of the performance of low-temperature district heating system with geothermal heat pump

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Abstract Exergy analysis of low temperature geothermal heat plant with compressor and absorption heat pump was carried out. In these two concepts heat pumps are using geothermal water at 19.5 °C with spontaneous outflow 24 m³/h as a heat source. The research compares exergy efficiency and exergy destruction of considered systems and its components as well. For the purpose of analysis, the heating system was divided into five components: geothermal heat exchanger, heat pump, heat distribution, heat exchanger and electricity production and transportation. For considered systems the primary exergy consumption from renewable and non-renewable sources was estimated. The analysis was carried out for heat network temperature at 50/40 °C, and the quality regulation was assumed. The results of exergy analysis of the system with electrical and absorption heat pump show that exergy destruction during the whole heating season is lower for the system with electrical heat pump. The exergy efficiencies of total system are 12.8% and 11.2% for the system with electrical heat pump and absorption heat pump, respectively.

Keywords: Exergy analysis; Low-temperature geothermal water; District heating system

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Nomenclature

a, b	–	coefficients
B	–	exergy, GJ
\dot{B}	–	exergy rate, kW
h	–	specific enthalpy, kJ/kg
HHV	–	high heating value, kJ/kg
L	–	work, kW
LHV	–	low heating value, kJ/kg
\dot{m}	–	mass flow rate, kg/s
s	–	specific entropy, kJ/(kgK)
T	–	temperature, °C
δ	–	loss
Δ	–	difference

Subscripts

AHP	–	absorption heat pump
ch	–	chemical
EL	–	compressor and transportation
EHP	–	electrical heat pump
GHE	–	geothermal heat exchanger
HD	–	heat distribution
HE	–	heat exchanger
i	–	number of elements
in	–	inlet
out	–	outlet
geo	–	geothermal water
0	–	reference state

1 Introduction

Utilization of geothermal water in the district heating systems is commonly used but it mainly concerns the water temperature over 60 °C. In Polish conditions the temperature of geothermal water resources varies from 17 to 90 °C, however, existing district heating systems are using the geothermal water with temperature of 40–90 °C. The geothermal heating plants were designed for existing buildings with high temperature radiator heating system and low thermal resistance of the walls. For that reason, the temperature of network supply water is relatively high (90–95 °C), thus the heating plants have to work in bivalent system with gas or oil boiler units [1,2]. This increases the investment and running costs of the heating system and makes it more harmful for environment.

Due to growing concern about low energy buildings and application of a low temperature space heating systems in the buildings, the utilization of low-temperature geothermal sources seems to be more attractive. The growing market of heat pumps and increasing of their coefficient of performance make this technology more interesting from economical and ecological point of view. However, to evaluate environmental benefits from these sources, not only energy but also exergy analysis should be carried out. Exergy analysis is a useful key to indentifying causes and locations of process inefficiencies. It is commonly used in assessment of heating systems, geothermal energy sources and other energy sectors as well [3–8].

2 Low-temperature geothermal district heating system

For the specific location in the Community of Poczesna in Częstochowa Region in southern Poland the district heating system based on low temperature geothermal source with water of 19.5 °C and spontaneous outflow 24 m³/h was proposed. It was assumed that after cooling down in the geothermal heat exchanger water runs into water supply system. The hot water is delivered into a heat pump, which supplies the buildings located near geothermal bore-hole with a heat during the heating season. The scheme of considered district heating system is shown in Fig. 1.

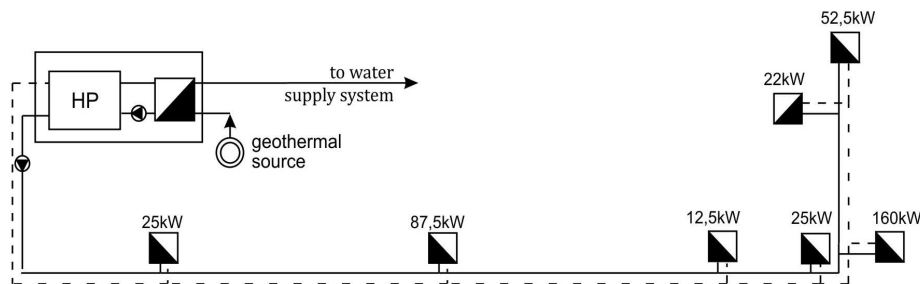


Figure 1. The concept of low temperature geothermal district heating system: HP – heat pump, white/black square – heat exchanger.

The design heat demand of the buildings is 400 kW and all buildings are equipped with space heating system. The supply and return temperature of circulation water is equal to 50/40 °C (for design outdoor temperature of -

20 °C), and is changing with outdoor temperature during the heating season (quality regulation). The outdoor temperature of the typical heating season for Czestochowa region was taken from Ministry of Transport, Construction and Maritime Economy database [9] and is shown in Fig. 2.

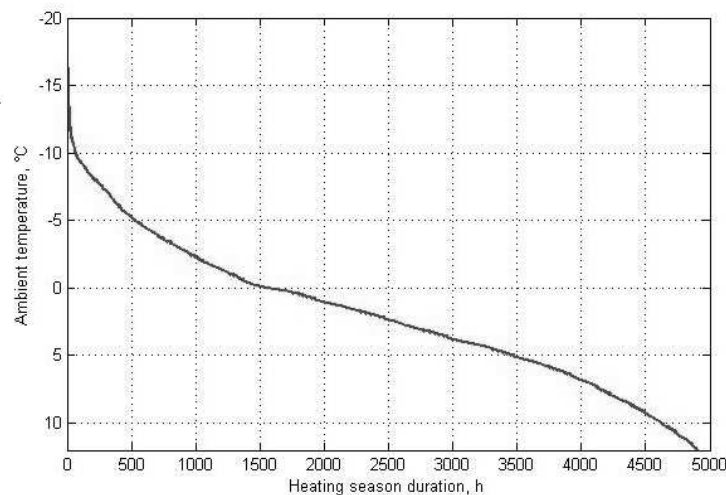


Figure 2. Ambient temperature time characteristic for typical heating season.

In this study two types of heat source were considered: compressor heat pump (EHP) and gas absorption heat pump (AHP). The concept of the small local low-temperature geothermal system is based on the assumption that heat pumps are working in monovalent system, meeting all the heat demand during the whole heating season. In most cases geothermal district heating system is working in bivalent mode but usually the heating network is more expanded and the supply temperature is higher (for example Pырzyce or Uniejów district heating systems). In small heating networks with low water supply temperature the use of monovalent system allows to avoid additional investment and running costs and consequently makes it cost-effective. The heat pumps were designed for the particular needs of the low-temperature geothermal heating system. Two stage water/water compressor heat pump with semihermetically sealed compact screw compressor and R134a as working fluid was proposed. In gas absorption heat pump (GAHP) the working fluid is a solution of ammonia in water. The internal gas burner heats the ammonia and water solution and then ammonia gas enters the condenser, where condenses and releases heat. The proposed GAHP is fired by natural gas. The relationship between water

temperature in condenser of heat pumps and its coefficient of performance (COP) is presented in Fig. 3.

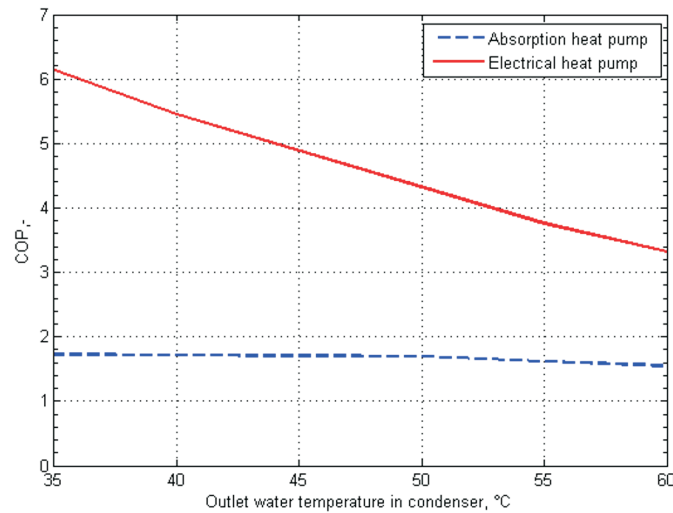


Figure 3. Influence of outlet water temperature of the heat pumps coefficient of performance.

3 Exergy analysis

Exergy analysis was carried out for all heating systems and its components as well. For the purpose of analysis, the heating system was divided into five components: geothermal heat exchanger (GHE), heat pump (HP), heat distribution (HD), heat exchanger (HE) and electricity production and transportation subsystem (EL) as well. Exergy flow rates in the system were illustrated in Fig. 4.

Exergy rate of water was determined using the following equation:

$$\dot{B} = \dot{m}[(h - h_0) - T_0(s - s_0)] . \quad (1)$$

It was assumed that the reference temperature, T_0 , is equal to ambient temperature and it is changing during a heating season with relationship presented in Fig. 2.

The exergy destruction in the district heating system components, i.e.: electricity production and transportation, geothermal heat exchanger, elec-

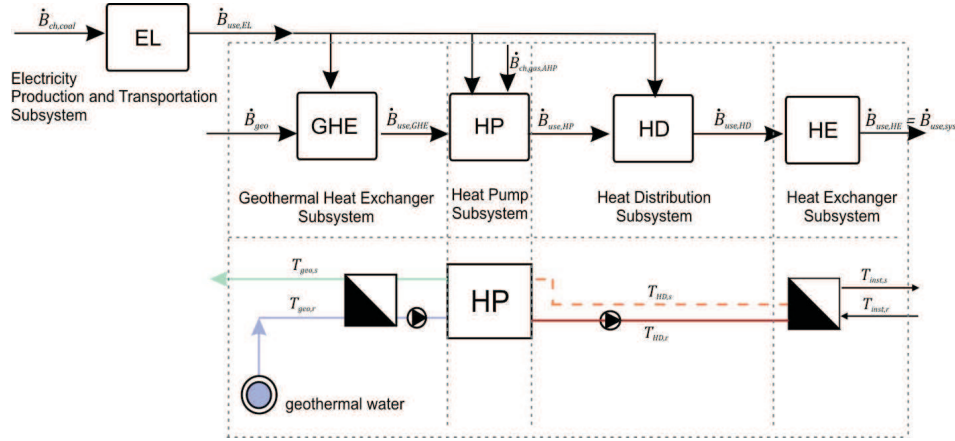


Figure 4. Schematic diagram of exergy flow in the heating system.

trical heat pump, absorption heat pump, heat distribution and heat exchanger as well as in total system were calculated using following equations:

$$\delta \dot{B}_{EL} = \dot{B}_{ch,coal} - \Delta \dot{B}_{out,EL} , \quad (2)$$

$$\delta \dot{B}_{GHE} = \dot{B}_{GHE} + \Delta \dot{B}_{in,GHE} - \Delta \dot{B}_{out,GHE} , \quad (3)$$

$$\delta \dot{B}_{EHP} = \dot{B}_{EHP} + \Delta \dot{B}_{in,EHP} - \Delta \dot{B}_{out,EHP} , \quad (4)$$

$$\delta \dot{B}_{AHP} = \dot{B}_{el,AHP} + \dot{B}_{ch,gas,AHP} + \Delta \dot{B}_{in,AHP} - \Delta \dot{B}_{out,AHP} , \quad (5)$$

$$\delta \dot{B}_{HD} = \dot{B}_{HD} + \Delta \dot{B}_{in,HD} - \Delta \dot{B}_{out,HD} + \delta \dot{B}_Q , \quad (6)$$

$$\delta \dot{B}_{HE} = \Delta \dot{B}_{in,HE} - \Delta \dot{B}_{out,HE} , \quad (7)$$

$$\delta \dot{B}_{total} = \delta \dot{B}_{EL} + \delta \dot{B}_{GHE} + \delta \dot{B}_{HP} + \delta \dot{B}_{HD} + \delta \dot{B}_{HE} . \quad (8)$$

Chemical exergy of the fuel was defined using relationship between specific chemical exergy and high heating value (HHV) or low heating value (LHV) of the fuel:

$$B_{ch} = aLHV = bHHV . \quad (9)$$

The coefficients a and b for selected organic fuels are shown in Tab. 1.

The exergy efficiencies of the district heating system components and the total system as well was determined from the following relationship:

$$\varepsilon_i = \frac{\dot{B}_{i,out}}{\dot{B}_{i,in}} . \quad (10)$$

Table 1. The ratio of specific chemical exergy of the fuel to its LHV (a) and HHV (b) [3].

Fuel	a	b
Hard coal	1.09	1.03
Lignite	1.17	1.04
Gas	1.04	0.94

4 Results

The exergy flow diagrams of systems with electrical heat pump (EHP) and absorption heat pump (AHP) are given in Figs. 5 and 6, respectively. In a system with EHP the highest exergy destruction occurs in electrical production and transportation subsystem and it amounts to 64.3% of total exergy input to the system. Exergy losses in electrical heat pump subsystem equal to 371 GJ during the heating season, i.e. 16% of the total exergy input. Exergy destruction in geothermal heat exchanger, heat distribution and heat exchanger is relatively low (sums up to 6.9%). In the system with AHP the highest exergy destruction occurs in the absorption heat pump subsystem and it equals to 1794 GJ, i.e. 67.3% of total exergy input. Exergy losses in EL (electricity production and transportation) subsystem amount to 16.1% of total exergy input.

The exergy efficiency of district heating system components and the total system as well is presented in Fig. 7. As it is shown, the efficiencies of the subsystems are mostly on the same level. The magnitude difference occurs in heat pump subsystem, the exergy efficiency of EHP is 47.0%, while for AHP is 15.6%. The total exergy efficiencies of systems with electrical and absorption heat pump are 12.8% and 11.2%, respectively.

The total exergy destruction, exergy efficiencies and total exergy inputs are given in Tab. 2. The exergy destruction during the whole heating season is equal to 2021 GJ and 2355 GJ for system with EHP and APC, respectively. The utilization of primary exergy of the fuel during the heating season is much higher for the system with absorption heat pump (2504 GJ) than with electrical heat pump (2092 GJ). The share of geothermal water exergy in total exergy input is higher for the system with EHP (about 10%), while for the system with AHP it is about 5.5%.

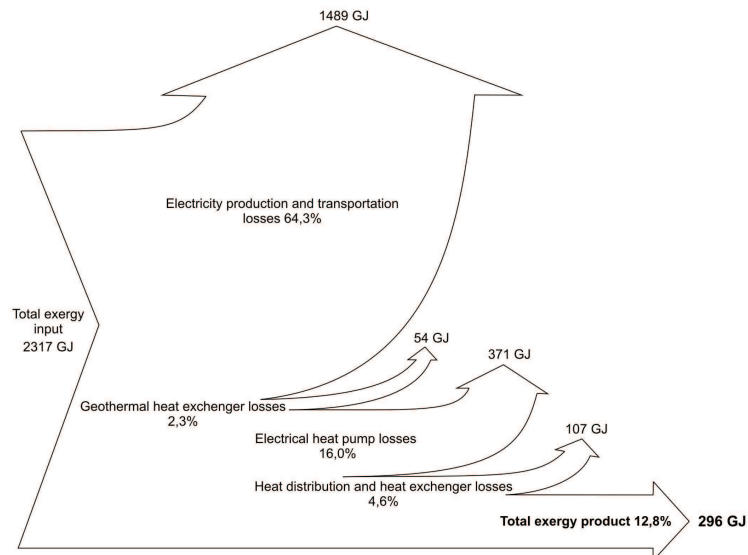


Figure 5. Exergy flow diagram of the system with electrical heat pump.

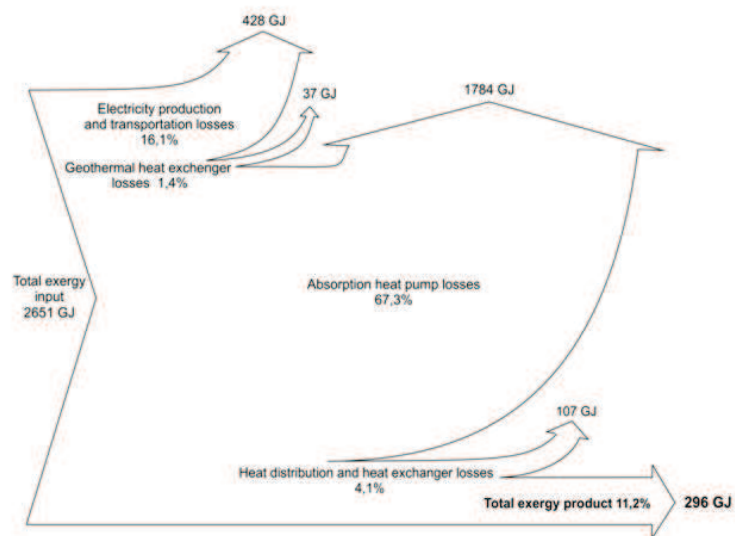


Figure 6. Exergy flow diagram of the system with absorption heat pump.

5 Conclusion

The exergy analysis of low temperature geothermal water heating system was presented. The results of the analysis show that higher exergy efficiency

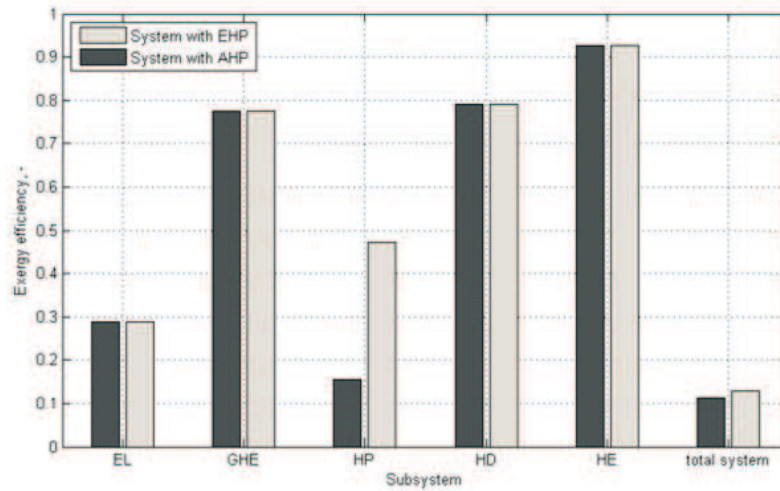


Figure 7. Exergy efficiency of district heating systems.

Table 2. The results of exergy analysis.

	Exergy destruction	Exergy input of the fuel	Exergy input of geothermal water	Total exergy input	Total exergy efficiency
	[GJ]	[GJ]	[GJ]	[GJ]	[%]
System with electrical heat pump	2021	2092	225	2317	12.8
System with absorption heat pump	2355	2504	147	2651	11.2

and lower exergy destruction were determined for the system with electrical heat pump. It is related to higher value of coefficient of performance (COP) of electrical heat pump than absorption heat pump. It is worth to notice that the value of heat pumps COP has a significant influence on the difference between EHP and AHP exergy efficiency value.

Increase of exergy efficiency of a system with EHP is achievable by increasing the efficiency of electricity production and transportation or by renewable energy sources share as well. The increase could also be achieved by utilization of renewable energy sources in micro-cogeneration systems.

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